SULPHUR STATUS OF SOILS AND WHEAT PLANTS IN THREE REPRESENTATIVE AREAS OF THE CENTRAL HIGHLANDS OF ETHIOPIA

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EXTENDED ABSTRACT

In the last three decades, Ethiopian agriculture solely depended on imported fertilizers, mainly urea and di-ammonum phosphate (DAP), which supplied nitrogen (N) and phosphorus (P). The use of such high-analysis fertilizers lacking adventitious S, coupled with traditional farming and cropping systems that mine S from native soil, can lead to S deficiency. Thus, recently there has been a perception that the production of such high protein cereals like wheat, legumes and even oil crops can be limited by the deficiency of sulphur (S) and possibly other nutrients as well. To explore the extent of S deficiency, three sets of experiments were conducted in the 2012-14 cropping seasons. The major aim was to quantify S status of soils and plants vis-à-vis other soil fertility parameters in the Central Highlands (CHLs) of Ethiopia. Moreover, an investigation was made to explore the response of wheat to applied S in relation to N and P. The study was also aimed to assess the different S supply indices with the ultimate goal of setting the critical levels (CLs) in order to make rational fertilizer use. Finally, the study was also aimed at determining the optimum S rate for wheat.

In the first experiment four treatment combinations, namely: an absolute control (without any fertilizer) or CK = ($N_0P_0S_0$), N alone or N = N_1 = ($N_1P_0S_0$), nitrogen plus sulphur or NS = N_1S_1 = ($N_1P_0S_1$), and nitrogen plus phosphorus plus sulphur or NPS = ($N_1P_1S_1$) were tested in Arsi, East Shewa and Oromia Liyuu zones covering diverse agro-ecological zones (AEZs) and soil types. Two levels of each nutrient were tested, namely: sulphur (0 and 20 kg S/ha), phosphorus (0 and 20 kg P/ha), and nitrogen (0 and 69 kg N/ha). The nutrient sources were gypsum, triple super phosphate (TSP) and urea. The treatments were arranged in the randomized complete block (RCBD) design and replicated three times. In the second experiment meant for evaluating the different indices

of S supply, also four treatment combinations, namely: an absolute control (without any fertilizer) or CK = ($N_0P_0S_0$), N alone or N = N_1 = ($N_1P_0S_0$), nitrogen plus sulphur or NS = N_1S_1 = ($N_1P_0S_1$), and nitrogen plus phosphorus plus sulphur or NPS = ($N_1P_1S_1$) were tested in the similar three locations covering diverse AEZs. Similarly, two levels of each nutrient were tested, namely: sulphur (0 and 20 kg S/ha), phosphorus (0 and 20 kg P/ha), and nitrogen (0 and 69 kg N/ha). The nutrient sources were gypsum, TSP and urea. The treatments were arranged in the RCBD design and replicated three times. In this part of the experiments four indices of S deficiency (OC and SO_4-S in native soils; and total S and N/S ratio in grains at harvest) were evaluated to establish their association with yields with the ultimate goal of setting their critical levels (CLs). A third experiment aiming at establishing optimum rates of S was set at six sites in Arsi, East Shewa and Oromia Liyuu zones. The nutrient elements tested were combined in nine treatments namely: an absolute control (without any fertilizer), CK = ($N_0P_0S_0$); nitrogen alone or N = N_1 = ($N_1P_0S_0$); nitrogen and sulphur or N_1S_1 = ($N_1P_0S_1$); nitrogen and sulphur or NS_2 = ($N_1P_0S_2$); nitrogen and sulphur or NS_3 = ($N_1P_0S_3$); nitrogen and phosphorus or N_1P_1 = ($N_1P_1S_0$); nitrogen, phosphorus and sulphur or NPS_1 = ($N_1P_1S_1$); nitrogen, phosphorus and sulphur or NPS_2 = ($N_1P_1S_2$); and nitrogen, phosphorus and sulphur or NPS_3 = ($N_1P_1S_3$) were tested. The nutrient rates tested were four levels of S (S_0 = 0 = CK, S_1 = 5, S_2 = 10 and S3 = 20 kg S/ha); two levels of P (P_0 = 0 = CK and P_1 = 20 kg P/ha); and two levels of N (N_0 = 0 = CK, N_1 = 69 kg N/ha) were applied as gypsum, TSP and urea. The wheat variety "Kekeba" was used as test crop in all trials.

Wheat responded significantly to N application at all sites. While in the case of sulphur, about 50 % of the studied fields showed highly significant response and 22 % showed marginal-response to S. Similar to N, all the study fields tested low in available P, but 56 % showed highly significant response, and 22 % marginal-response to applied P. Good

relationship between soil-test values and crop response, especially for N and S was observed. In addition, the study revealed that light textured soils in the peripheries of the Rift-Valley and calcareous vertisols were more deficient in S than the rest of the soils. The results of the second study indicated that, the N/S ratio and S content in wheat grain were better correlated with S-uptake than the soil S indices i.e. OC and the SO_4-S. Which means that, plant analysis is more useful tool for diagnosing S supply from soils to plant than the soil analysis. The critical levels were found to be 0.118 % for total S in grain, 14.7/1 for the N/S ratio in grains and 11.3 mg/kg for the SO_4-S in soils. The results from the sulphur rate trial indicated that four sites: G/Silingo, Keteba, N/Suba, and Bekejo had highly significant response to S at all treatment levels. The other two sites: W/Gora and B/Tokofa gave marginal response to S. Based on this, the three sites namely: Keteba, Bekejo and N/Suba were categorized as having very low SO_4-S status, while G/Silingo was marginal. Whereas W/Gora and B/Tokofa were grouped under the category of sites with adequate SO_4-S in soils. Based on the extent of response to sulphur, optimum S rate for Keteba, Bekejo, N/Suba and Gora Silingo sites was about 20 kg S/ha, whereas at the W/Gora and B/Tokofa sites, where the SO_4-S rated as adequate, yet wheat responded to low rates, applying S at a rate of 5-10 kg/ha is recommended.

The present study confirmed that S deficiency is becoming one of the major problems of soil fertility in the Ethiopian crop production system. This low level of soil S status is due to nutrient depletion without replenishment. Therefore, fertiliser recommendations should include the optimum amount of S for wheat and/or other crops. The alternative management decisions may include improved management of natural nutrient re-cycling within an agro-ecosystem, and by the importation of nutrients into the system in the form of fertilizers mined (e.g. gypsum) or manufactured off-farm.

DECLARATION

I, Assefa Menna, do hereby declare to the Senate of Sokoine University of Agriculture that this is my original work done within the Period of Registration and that it has neither been submitted nor being concurrently submitted to any other Institution.

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LIST OF ABBREVIATIONS, SYMBOLS AND ACRONYMS

AAS	Atomic Absorption Spectro-Photometer
AEZs	Agro Ecological Zones
ANOVA	Analysis of Variance
AS	Ammonium Sulphate
BNF	Biological Nitrogen Fixation
C/N	Carbon Nitrogen Ratio
$Ca(H_2PO_4)_2$	Calcium Orthophosphate
$CaCl_2$	Calcium Chloride
$CaSO_4.2H_2O$	Calcium Sulphate (gypsum)
CEC	Cation Exchange Capacity
CLs	Critical-Levels
CSA	Central Statistical Authority
CTHs	Critical-Thresholds
CVs	Critical-Values
DAP	Di-ammonium Phosphate
EC	Electrical Conductivity
EPA	Environmental Protection Authority
FYM	Farm Yard Manure
GDP	Gross Domestic Product
GPS	Global Positioning System
IFPRI	Fertilizer and Soil Fertility Potential in Ethiopia
INM	Integrated Nutrient Management
LGP	Length of Growing Period
$N(NH_4\text{-}N)$	Ammonium Nitrogen

$N(NO_3\text{-}N)$	Nitrate Nitrogen
$NaHCO_3$	Sodium Bicarbonate
NH_4OAc	Ammonium Acetate
NUE	Nitrogen Use Efficiency
P	Phosphorus
PBS	Percent Base Saturation
RY (%)	Relative Yield Percentage
S	Sulphur
$SO_4\text{-}S$	Sulphate Sulphur
SOC	Soil Organic Carbon
SOM	Soil Organic Matter
SON	Soil Organic Nitrogen
SSP	Single Superphosphate
TN	Total Nitrogen
TS	Total Sulphur
TSP	Triple Super Phosphate
WFP	World Food Programme

CHAPTER ONE

1.0 General Introduction

1.1 Preamble

It is widely recognized that Ethiopia has struggled for many years to respond to the challenges of food insecurity and rural poverty arising from rapid population growth, low agricultural productivity and environmental degradation. However, there has been significant progress to ensure food security at national level, but long a way remains to ensure this at the household level (WFP, 2013). While the reasons for this state of affairs are many, one major factor keeping crop yields and productivity low is low availability of plant nutrients, due to the degradation of the major natural resource base, the soil/land.

Accelerated soil degradation has reportedly affected as much as 500 million hectare in tropics (Lamb *et al*., 2005). In addition to negatively impacting agronomic production, soil degradation (e.g., loss of soil fertility) can also dampen economic growth, especially in countries like Ethiopia, where agriculture is the engine for the economic growth. Soil degradation implies a decline in soil quality and/or soil health with an attendant reduction in the ecosystem functions and services. There are four types of soil degradation: physical, chemical, biological, and ecological (Lal, 2015), each of which is affecting respective properties of soils, leading to disruption in ecosystem functions such as elemental cycling, water infiltration and purification, perturbations of the hydrological cycle, and a decline in net biome productivity. The overall decline in soil quality, both by natural and anthropogenic factors, has strong negative feedbacks leading to a decline in ecosystem services and reduction in nature conservancy. Among the major soil degradation processes are accelerated soil erosion, depletion of soil organic carbon (SOC), loss in biodiversity, loss of soil fertility and disturbance of nutrient elements balance, acidification and salinization, which are affecting the sustainability of agriculture.

However, the nutrient limitations can be addressed by the management of natural nutrient cycling within agro-ecosystem (cropping systems, re-cycling of animal, plant and human wastes) and by importing nutrients into the system in the form of fertilizers, mined or manufactured. But, fertilizers are expensive inputs in terms of energy, soil conditions, environmental concerns, and the purchasing power of farmers. Hence, it is critical that the most suitable types of fertilizers are used in the most efficient manner and that they are to be used in the contexts of integrated soil fertility (Vanlauwe *et al*., 2012a). Among the major nutrients required by plants is the element sulphur.

In Ethiopia, sustainable agriculture is a major concern of the economic growth. From this it is believed that all stakeholders should focus in changing this sector towards attaining food security and/or gain export earnings. Although sustainability has many dimensions that remain the subject of debate in the development scene, it is widely accepted that the dynamics of major plant nutrients in the soils, like nitrogen (N), phosphorus (P), sulphur (S) and/or organic carbon (OC), which represent major soil quality indicators (Van Pham and Smith, 2014) are critically important in sustaining agricultural crop production, thereby contributing for food security. These and other soil health indicators are critically low in Ethiopia soils and agricultural outputs, hence, crop yields remained sub-optimal. Therefore, that aspect of sustainability of agricultural systems can be assessed by examining the consequences of current management practices and exploring alternatives on soil nutrient dynamics.

1.2 Strategies for Restoring Soil Quality

Restoring degraded soils is a challenge in Ethiopia, a country dominated by smallholding agriculture. Re-carbonization of depleted soil organic carbon (SOC) pool, which is essential to numerous functions, requires input of biomass carbon and elements like sulphur, nitrogen and phosphorus (Lal, 2014). Thus, restoration of soil quality necessitates a coordinated approach. Soil OC pool is a key soil quality indicator and an important driver of agricultural sustainability and probably the single most important soil property relating to soil health is, the OM content of the soil (Brevik, 2009). In addition to its amount, other parameters of SOC include its depth distribution, quality or attributes (physical, chemical, biological) and turnover rate or mean residence time (Brevik, 2009).

1.3 Soil Organic Carbon and Its Impact on Soil Quality

The SOC including its quantity and quality is the defining constituent of soil (Lal, 2015). Indeed, its pool is the most reliable indicator of monitoring soil degradation, like that caused by accelerated erosion (Rajan *et al*., 2012). This is because soil degradation depletes SOC along with N and other nutrients like S and P. Therefore, it is essential to improve SOC pool preferably maintained above the critical thresholds of 10-15 g/kg, which is essential for reversing degradation.

Integrated nutrient management (INM) is one strategy that embodies sustainable management of SOC and its dynamics (Vanlauwe *et al*., 2012b). Adoption of INM and others practices that create positive soil carbon-budget can increase productivity and sequester additional carbon-dioxide into SOC pool (Dlamini *et al*., 2014). In general, the widespread prevalence of degraded soils in Ethiopia is attributed to over-exploitation and improper management. In this context, enhancing SOC is important to sustain soil fertility and agronomic productivity (Vanlauwe *et al*., 2012b). Increased use of chemical fertilizers with improved varieties, if erroneously recommended, may not be enough and sound way for increasing production and productivity. Patrick *et al*. (2013) reported that SOC critical level, for sustaining soil quality is 2 %, below which soil structural stability will suffer a significant decline. In general, it is well recognized that, SOC which is key to sustainable agriculture, contributes significantly to sulphur, nitrogen, phosphorus, potassium and other essential nutrients, through mineralization and other soil functions (Eaton *et al*., 2012).

1.4 Sulphur and Some of its Forms in Soils

1.4.1 Inorganic soil sulphur

Sulphur (S) is increasingly being recognized as the fourth major plant nutrient after N, P and potassium (K) in crop production. Inorganic S is generally much less abundant in most agricultural soils (Tisdale *et al*., 1993). Sulphate (SO_4^{2-}) is the most common form of inorganic S and can be divided into SO_4^{2-} in soil solution, adsorbed SO_4^{2-} and mineral S (Scherer, 2001). Sulphur may precipitate in the form of SO_4^{2-} as calcium, magnesium or sodium sulphate. It also occurs as a co-crystallized or co-precipitated impurity with $CaCO_3$ and is an important fraction of the total S in calcareous soils (Tisdale *et al*., 1993).

Some reduced inorganic S forms (e.g., elemental S, thio-sulphate or sulphide) may be present in soils under predominantly anaerobic conditions (Scherer, 2001). The reduced S forms are reported to be transitory in aerobic soils and their concentrations are usually negligible (Eriksen, 1997). Solomon *et al*. (2001) studied S fractions of the sub-humid Ethiopian highlands as affected by land use changes, and reported that the inorganic SO_4-S ranging from 11-17 mg/kg soil at Wushwush site and from 11-16 mg/kg soil at Munesa site. These values accounted on the average for 2 % of the total S content of the bulk soils. The author further reported that, the clay size separates adsorb more (SO_4^{2-}) than the silt size separates.

According to Tisdale *et al*. (1993), sulphate in soil solution is in equilibrium with the solid phase forms and is like phosphate adsorbed to clay minerals and sesquioxides, whereby the binding strength for SO_4^{2-} is less strong. Increased solution SO_4^{2-} contents will increase adsorbed SO_4^{2-}. However, the observation that SO_4^{2-} adsorption and phosphate adsorption are closely correlated suggested that a similar adsorption mechanism for both anions (Barrow, 1967). Hence, according to the author the SO_4^{2-} is easily desorbed by phosphate. Any treatment causing a decrease in retention and a corresponding increase in soil solution SO_4^{2-} should increase SO_4^{2-} availability to plants (Serrano *et al*., 1999). For instance, it is reported that the joint application of limestone and gypsum results in increased availability of SO_4^{2} in acid soils (Serrano *et al*., 1999). The higher content of SO_4^{2-} in the soil solution of the uppermost soil layer (Eriksen, 1997) can be caused by the application of S containing fertilizers and other S inputs including lime.

1.4.2 Organic soil sulphur

Solomon *et al*. (2001) reported that the major proportion of total S in most agricultural soils in Ethiopia is present in organic forms mainly because, unlike inorganic SO_2-S, soil organic S, is mostly insoluble in water and not available to plants. Its amount has been reported to vary from 509 - 1065 mg/kg soil at two sites in Ethiopia namely: Wushwush and Munesa. On average organic sulphur constitutes 98 % of the total S in the studied bulk soils in Ethiopia (Solomon *et al*., 2001). Solomon *et al*. (2001) found close association of organic S with SOC and N in the soils due to the fact that SOM provides the major non-leachable reserve of S and N in most surface soils.

1.5 Sulphur Availability Indices

Even in the industrialized world, because of the decreasing S emissions, predicting S need of plants is becoming very important. The tools for diagnosing S are complementary. Usually, soil and plant analysis; and simulation models have been used (Eriksen, 1997). However, often plant analysis does not show deficiency, until it is too late for a corrective S application. In addition, S deficiency symptoms, in cereals are difficult to distinguish as they are confused with those of N (Singh *et al*., 2014).

1.5.1 Soil analysis

For evaluating S status of soils, methods that include extraction of bound forms, S released during incubation or microbial growths have been suggested (Jones, *et al*., 1986). However, contents of S in soils vary throughout the year (Ghani *et al*., 1991) and are the result of changes and balance between the activity of microorganisms, fertilizer use, plant senescence, atmospheric inputs, crop uptake and different losses. According to Haneklaus and Schnug (1994), any analytical value of S in soils is more or less only for the moment, i.e. the time the samples were taken to the time they were analysed.

To determine the availability of S in soils, numerous solutions have been proposed. To extract the most easily available form of soil S, i.e. SO_4-S, solvents like H_2O (Walker and Doomenbal, 1972) and solutions like $CaCl_2$ (Saalbach and Aigner, 1987) were proposed. Because of the dispersion problems with H_2O, salt solutions are preferred. However, Matula (1999) stated the limitation of $CaCl_2$, because of the possibility of sulphate precipitation, resulting in depression of S. The author found a better correlation between S in plants versus H_2O soil-test. Link (1997) extracted the soils with 0.05 M $CaCl_2$ and 1 M NaCl + 0.2 M $CaCl_2$, respectively, to determine the plant available SO_4^{2-} early in spring in the soil layer from 0 to 90 cm. Accordingly the author, the experimental fields planted with rapeseed, contained between 11 and 238 kg SO_4^{2-}/ha with a mean value of 68 kg/ha. Further, the author stated that, 60 kg SO_4^{2-}-S/ha in the soil layer from 0 to 60 cm covers the S demand of the rape crop. Timmermann *et al*. (1995), who extracted the soils with different extractants (H_2O; 0.03 M H_3PO_4; 0.01 M $CaCl_2$ + 0.02 M DTPA; 8 M $Ca(H_2PO_4)_2$ + 1 M CH_3COOH), could not find a relationship between S extracted by the different solutions and S uptake of rape.

For combined extraction of soluble and adsorbed SO_4-S, different methods have been recommended by different workers: $CaCO_3$ (Williams and Steinbergs, 1959), $NaHCO_3$ (Kilmer and Nearpass, 1960) and NH_4OAc (Bardsley and Lancaster, 1960). According to Tabatabai (1982), the distinction between soluble and adsorbed SO_4-S is important when a fractionation of TS in sub-soil with their greater amounts of adsorbed SO_4-S is desired. Furthermore, solutions containing P as KH_2PO_4 (Ensminger, 1954) or $Ca(H_2PO_4)_2$; (Fox *et al*., 1964) have been recommended for both forms of S. Both solutions contain enough phosphate to exchange adsorbed SO_4-S, though the amounts of adsorbed SO_4-S extracted by $Ca(H_2PO_4)_2$ can vary widely. Comparisons between both solutions revealed that both methods extract similar amounts of SO_4-S (Link, 1997). Wada *et al*. (1994) evaluated the $Ca(H_2PO_4)_2$ solution containing 500 mg/P for both forms of S. Their results showed that five extractions at a soil: solution ratio of 1/10 quantitatively recovered added SO_4-S and that air-drying of soils after SO_4-S application had no effect on its extractability. Warman and Sampson (1992) concluded that calcium ortho-phosphate [$Ca(H_2PO_4)_2$], is an ideal extracting solution for determining available soil S.

According to Haneklaus and Schnug (1994), the suitability of soil-test depends on its correlation to yield and plant S status is assumed to be a suitable parameter to calibrate soil test methods. According to Finck (1976), however, a minimum coefficient of correlation (r) of 0.84 on field data is required for a reliable method of S deficiency to ensure efficient use of S fertilizers. In general, inconsistencies between soil-tests and crop responses have been reported and seasonal effects on the availability of S to plants and losses of SO_4-S restrict usefulness of soil analysis to identify S responses (Robson *et al*., 1995).

1.5.2 Plant analysis

Plant analysis is accepted to offer a better tool than soil in predicting crop S need (Zhao *et al*., 1996) and several indices have been suggested. However, no general consensus has been reached as to which gives best results. Using plant analysis for diagnosing S deficiency is based on the condition that each essential element should be present in sufficient amounts for unrestricted growth (Scherer, 2001). According to Jones *et al*. (1986), total sulphur (TS) content in the above ground material or in specific parts is widely used to assess S status. In general, the critical S level depends on plant species, on sampled part, developmental stage and yield levels (Hahtonen and Saarela, 1995). To predict S status, the authors recommend younger parts and sampling during the period of highest S need, (i.e. stem extension to the start of flowering), while generative material is less suited for diagnostic purposes. In monocots like wheat, flag leaf or whole plant before appearances of second node was found to be the best choice to determine S status (Bergmann, 1992).

It is reported that, S concentration decrease with plant age (Robson *et al*., 1995). In dicots like faba bean, young fully expanded leaves are strongest sink for S and are recommended (Haneklaus and Schnug, 1994). Jones *et al*. (1986) suggested that, to reduce difficulties in interpreting data, plant part and time of sampling should be standardized. According to Schnug (1994) the most important argument against the use of TS as a diagnostic tool for

S is the dependence of S content on development stage. Freney *et al*. (1978) reported that TS content in whole wheat shoots at late seedling is about 2.5 g/kg dry matter (DM), decreasing to about 1.1 g/kg at mid-vegetative stage and 0.8 g/kg at heading when grain was in milk stage. In general, the critical total sulphur (TS) concentration is about 2 g/kg dry matter (DM) but may vary between 1 and 3 g/kg dry matter and even higher.

According to Freney *et al*. (1978), SO_4^{2-}-S in plants is more sensitive than total S as an index of S deficiency, because of the greater difference between the SO_4^{2-}-S concentration for non-deficient and deficient tissues. The sulphate sulphur (SO_4^{2-}-S) concentrations in plants have been shown to be related to the S status of soils for legumes, perennial ryegrass and rapeseed (Maynard *et al*., 1983). This problem is a general one and applies to all tissue analysis. Further after S deprivation SO_4^{2-} stored in roots and shoots is mobilized within a few days and there may even be an increase in SO_4^{2-} concentration of mature leaves at the same time that young leaves are becoming deficient (Maynard *et al*., 1983). In plant species with higher glucosinolate contents the concentration of SO_4^{2-} may increase during enzymatic cleavage of these compounds after taking plant samples (Schnug, 1994).

Further, the N/S ratio is used as an index to determine the response to N and more particularly to S. When growth factors other than S are optimum, the critical values of N/S ratio are assumed to be more stable with plant growth stages than TS (Jones *et al*., 1986). For this reason, Rasmussen *et al*. (1977) stated that N/S ratio is a better index to describe S status of vegetative tissue of wheat than TS. However, one problem with N/S ratio is that a surplus of one of these elements may be interpreted as a deficiency of the other. Another problem is that, S is rather immobile in plants and older leaves tend to be higher in S than young leaves, while N is mobile and young leaves tend to have higher N than old leaves (Pasricha and Fox, 1993). According to the author, therefore, it is not correct to assume that, N/S ratio is more stable with plant tissue sampled, stages of growth as compared with TS or SO_4-S. However, studies of Spencer and Freney (1980) on wheat and clover suggest that, critical N/S ratio is less affected by plant age and N supply than critical TS and is suggested to be a useful tool for diagnosing S deficiency in cereals and legumes.

1.6 Sulphur Deficiency in Crop Production

Sulphur is the most forgotten nutrient in African agriculture. The declining fertility of soils in Africa has been well documented in recent decades, with most of the attention being given to the so-called ‘macronutrients’ or ‘fertilizer elements’ N, P and K (Batiano *et al*., 2008). The deficiency of S is likely to be widespread in Africa, especially in sub-humid and semi-arid regions where annual burning results in losses to the atmosphere as SO_2 (Itanna, 2005). In countries like Ethiopia, such losses can be more severe, because of the rapid mineralization of OM by the tropical climate and the subsequent leaching of S due to high precipitation, particularly in highlands and mid-altitude zones.

The situation regarding S fertility has changed in recent decades. First, as OM has been depleted by continuous cropping and high-yielding varieties of crops have found wider use, the supply of S from OM has become inadequate in many instances. Secondly, there has been a rapid shift in African agriculture away from the use of low-analysis fertilizers such as ammonium sulphate (AS) and single superphosphate (SSP) to high-analysis fertilizers such as only urea or di-ammonium phosphate (DAP), which contain little or no S. Where these high-analysis fertilizers are in use with high yielding varieties, failure to supplement S in balanced fertilizer formulas, can be expected to rapidly deplete available sulphur supplies in the soils, especially on continuously cropped lands.

1.6.1 Sulphur status of Ethiopian soils

Sulphur in surface soils is usually associated with organic fractions and its supply to crops is largely regulated by OM decomposition (Nziguheba *et al*., 2006). Thus, the amount of labile OC is regarded as a good indicator of the amount of available S as well as N and P, in soils (Dlamini *et al*., 2014). Tekalign and Haque (1987) reported that 94 % of TS in surface soils of Ethiopia was in SOM, and indicated that 80 % of the studied highland agricultural soils had marginal to deficient NH_4OAc extractable SO_4-S (< 10 mg/kg). In some Ethiopian highland soils under natural vegetation, the TN/TS ratios in OM ranged from 11/1 to 3/1, suggesting that SOM of the studied pedons were well supplied with S (Fritzsche *et al*., 2007). This may be due to the relative effectiveness of forest vegetation to recycle S in surface horizons (Eshetu *et al*., 2004). The N/S ratio > 12 in organic materials was reported to be the best diagnostic indicator of S deficiency (Weil and Mughogho, 2000). A study of five soil pedons in the Rift-Valley of Ethiopia found adequate S in less weathered soils, but deficient levels in nitosol (Itanna, 2005). Another similar study showed that continuous cropping on deforested highlands in the country depleted about 50 % of total soil S over a period of 20-30 years, as OM decomposed (Solomon *et al*., 2001). However, their study did not include the analysis of any plant samples. This may indicate that the depletion of SOM will have significant negative effect on soils S status, particularly in annually cropped lands.

1.6.2 Sulphur in crop tissue and deficiency symptoms

Studies indicated that reproductive growth of wheat appears to be more sensitive to S than vegetative, with decreased grain size under S limiting conditions (Ryan *et al*., 1996). Sillanpaa (1982) cited the critical range of S for wheat in leaves to be 0.15-0.18 % for low yield and 0.32 % for high yield. Wheat tissue collected in Ethiopia contained in most cases < 0.13 % S and about half of the samples had < 0.18 % S (Sillanpaa, 1982).

Low S values (< 0.15 %) were reported from Shewa, Sidamo (southern zones) and Arsi (south eastern zone) (Weil, 2011). The author reported some foliar symptoms of S deficiency in farmers' fields in Oromia, Amhara and Tigray regions. Generally, for young wheat plants, S content of 0.15-0.40 % is considered sufficient but values < 0.15 % or a N/S ratio > 17 are considered to be deficient (Estefan *et al*., 2013).

The major problem with S deficiency on crops is that it is often mistaken for N. On maize and sorghum, S deficiency usually produces yellow and green stripes on younger leaves (Weil, 2011) as opposed to yellowing of old leaves in the case of N. Therefore, these foliar deficiency symptoms can be used as indicators that suggest severe plant S deficiency. Particularly, severe S deficiency causes plant foliar symptoms that look superficially somewhat like those of N (spindly, yellowish chlorotic plants), and therefore S deficiency on crops is often mistaken for N (Weil, 2011). However, the symptoms are relatively easy to distinguish, as chlorosis from N deficiency is always most severe and occurs earliest on lowest, oldest leaves. On contrary, the chlorosis from S deficiency is either more even distributed in the plant or most often is most severe in the upper, newer leaves (e.g., in wheat).

1.6.3 Yield response of crops to sulphur application

High protein crops such as alfalfa, canola and rape are known to be most susceptible to S deficiency though wheat, oats, barley and maize respond to applied S. For instance, a study in Ethiopia indicated that S fertilization and inoculants improved biomass and grain yield of faba bean on average by 2.2 and 1.2 Mg/ha (Kiros *et al*., 2007). This corresponds to 37 % and 50 % increases, respectively relative to controls. These results agreed with the general experience that N-fixing legumes are responsive to S alone or with P. Sulphur is one of the nutrients that play a major role in biological N-fixation (BNF)

(Kiros *et al*., 2007). However, cereals need substantial amount of N before they will respond to S. Application of S resulted in greater response to applied N, showing a positive synergy between N and S. Kiros and Singh (2009) reported yield increase of 0.8-2.4 Mg/ha of wheat with increased nitrogen use efficiency (NUE) of 28 % due to applied N and S in Ethiopia. The N content increased significantly from check (N_0) to fertilized (N_2).

Sulphur fertilization increased contents of cysteine and methionine by 27 % and 14 % respectively as compared with N alone (Kiros and Singh, 2009). Those studies conducted in northern Ethiopia illustrate the potential for yield and quality responses to applied S by both cereal and legumes. Salvagiott *et al*. (2009**)** in Argentina reported that at lowest S rate, N uptake was 42 %, but increased to 70 % as S fertilizer was increased. The authors reported that increased level of S resulted in higher cystine (110 %), cysteine (167 %) and metheonine (85 %) contents in rice crop. Järvan *et al.* (2008) reported that, sulphur applied (in two top dressings totalling 10 kg S/ha) increased yield of winter wheat, depending on weather and soil conditions in field trials by 0.47-1.48 t/ha (7.7-43.0 %) and in production trials by 1.35-2.44 t/ha (39.8-45.5 %).

1.7 Sulphur Fertilizers

In recent years, S deficiency especially in high S demanding crops such as the oilseed rape and legumes has increased considerably. Water-soluble sulphates, e.g. potassium sulphate, magnesium sulphate (18 % S) and ammonium sulphate (AS) (24 %S) are known to be effective for reversing S deficiency in growing crops. Ammonium sulphate (AS) has an acidifying effect can provide an added benefit on alkaline soils. Slow acting types such as gypsum (18 % S) or calcium sulphate (14 % S), a by-product of superphosphate can be used, if leaching is considered a problem (Weil, 2011). Elemental S (100 % S) may be applied either in powdered form or in the form of S-coated urea (10-20 % S). Availability coefficient ratios obtained from wheat indicated that elemental S, sodium sulphate and gypsum were 25, 99 and 100 %, respectively as effective as super-phosphate (Arora *et al.*, 1991), because elemental S is slow acting. In Uttar Pradesh, application of 90 kg S/ha gave significantly higher rice yield than 30 kg S/ha as gypsum (Ryan *et al.*, 1996). This report indicated that S use efficiency was greater with gypsum, irrespective of their levels of application.

Poongonthai *et al.* (1997) observed that S application enhanced S uptake and grain yield of rice and application of gypsum along with green manure increased S use efficiency and straw and grain yields on S-deficient Entisols. Aggarwal and Nayyar (1998) reported that a soil having an available S of 22.2 mg/kg positively and significantly correlated with S content in wheat and S uptake by wheat grain and straw. When wheat cultivar, LOK-1, was given 2-4 t/ha gypsum or 20 kg/ha elemental S, grain and straw yields of wheat were reported to increase significantly with increase in the levels of gypsum (Akbari *et al.*, 1999). According to the authors, applying 40 kg S/ha as elemental S gave significantly higher yields of rice, wheat, mustard and potato followed by the same level of gypsum.

1.8 Factors Influencing Sulphur Fertilizer Recommendations

Sulphur recommendations can be determined based on crops grown, yield goal, SOM levels including manure, and level of S in irrigation water and soil test S. Fertilizer S requirements depend on the difference between soil additions from precipitation, irrigation water, crop residues and fertilizers and soil losses through crop removal, leaching of SO_4-S, erosion and volatilization (Brady and Weil, 2002). At average or lower yield levels, much of the S needs can be met by additions through precipitation or irrigation water and from SOM mineralization (Lamond, 1997), the optimum yields may require supplemental S fertilizations. More generally fertilizer sulphur recommendations may depend on crop removal, soil and fertilizer considerations.

1.8.1 Crop removal

Sulphur requirement of crops differ not only between species, but also on the developmental stages for their yield and quality production. For example, the amount of S required to produce one ton of seed is about 3-4 kg S for cereals (range 1-6); 8 kg S for legume crops (range 5-13); and 12 kg S for oil crops (range 5-20) (Jamal *et al.*, 2012). The author reported that oil crops require about the same amount of S as, or more than, P for high yield or product quality. In general, crop plants are reported to require the same amount of S as P (Weil, 2011). Cereals generally remove 15-20 kg S/ha, forage crops 15-35 kg S/ha and crops belonging to the cruciferae family, brassicas (cabbage, broccoli) require high S, 22-45 kg S/ha (Singh *et al.*, 2014). Therefore, in intensive cropping systems that include oil and legume crops S uptake and/or removal can be high, especially when crop residues are removed from fields along with the produce, because S is critically important for protein synthesis and oil formation. This leads to considerable S depletion in soil, if the corresponding amount is not replenished through fertilizer for the next season. Weil (2011) reported that the need for S is associated with the amounts of nitrogen available to crops. This relationship is not surprising since both are the components of proteins and associated with chlorophyll formation. Significant economic forage and yield losses of grains can occur with S deficiency, even when deficiency symptoms are not obvious (Weil and Mughogho, 2000). This can be particularly true when high levels of N are not balanced with adequate S.

1.8.1.1 Sufficiency levels

Calibrating soil-test results is important, because fertilizer S recommendations are site or soil specific. The $CaCl_2$ extractable soil SO_4^{-2}-S as a critical limit of S deficiency for most crop species (e.g., in wheat) reported by Tandon (1991) is 10-13 mg/kg. In this system, a nutrient is applied, only if the soil-test level is below this critical or no-response level, because absolute minimum is necessary to support potential maximum yield. According to Saeed *et al*. (2012), however, there is no overt attempt to maintain optimum level every year by factoring crop removal. The emphasis is to maintain a sufficient level of each nutrient to support yield and no more. Sufficiency level is also commonly called fertilizing the crop. A certain uptake quantity of each nutrient into plant is critical in maximizing yield.

The sulphur rate for wheat is reported to be about 20 kg S/ha (Jamal *et al.*, 2012) for optimum yield. However, (Haneklaus *et al*., 1995) reported further increases in loaf volume when S rate was increased up to 100kg S/ha, while yield responses of wheat were limited to the application of 20kg S/ha. Zörb *et al*. (2013), suggested a modest amount of 15-35 kg S/ha for better quality and optimum yield of wheat. However, such a marked increase in wheat yield with additional S fertilizer is attributed to soils deficient in available S, when other factors are optimal. Where insufficiency is small, crop removal plus corrective additions can be done at one time. But, at severe deficiencies, a gradual approach several years can be more practical. Once an optimum soil level is attained, only crop removal quantities need to be applied to maintain this level (Estefan *et al*., 2013).

1.8.1.2 Minimum and maximum recommendations

As the critical levels separate the highs and lows of the plant and/or soil S contents, some medium levels are also expected above or below these ranges. Weil (2011), reported the importance of the minimum or maximum level fertilizer application approaches, and this will enable farmers to apply the minimum or supplemental amounts of fertilizers. The supplemental or partial dose aims at reducing any amounts of yield or quality loss. According to the author, for instance if the pre-soil test sulphur level is just above the critical levels, it is not considered sufficient, especially when the SOM levels are low. In such conditions, the author suggested applying a small dose of S below the crop's optimum level depending on the soil conditions. Such recommendations are especially meant for accounting a balance between soil content and crop removal and/or other losses. This limit is invoked when a nutrient tests near optimum and only crop removal or starter recommendations are made (Jamal *et al.*, 2012).

1.8.1.3 Excessive levels

When a soil contains an available nutrient at an excessive level, there is the potential for uptake competition with other nutrients. For certain nutrients, there may be a direct toxicity effect. For instance, a highly water soluble ammonium sulphate (AS), has a detrimental effect on low pH soils, like that of the Wolmera district in the Ethiopian highlands, especially when it is applied in excess. But, it has an added benefit on alkaline soils like that of in the Awash Valley in Ethiopia. It also decomposes to form colloidal elemental sulphur and ammonium sulphate. Likewise, ammonium thio-sulphate should not be used in starter fertilizers placed in direct seed contact, because of toxicity to seed.

The normal breakdown of excess SOM like farm yard manure can result in an overabundant supply of available nutrients (e.g., N) during growing season, resulting in excess foliar and height growth, very succulent tissue structure that result in delayed blossoming or ripening of fruiting crops (Estefan *et al*., 2013). The excess N will also lead to also to sulphur deficiency.

1.8.2 Soil Considerations

Sulphur (S) is usually present in relatively small amounts in soils in the available forms (Brady and Weil, 2008). As a result, pre-soil testing is considered an important tool for the fertilizer S budgeting. Sulphur deficient soils are often low in OM, coarse-textured, well-drained and subject to leaching. In recent years, an increasing number of finer textured soils have shown S deficiency (Jamal *et al*., 2012). However, much like N, sulphur tends to cycle in the soil environment (Lal, 2014). Since organic S is not plant available, sulphate must be released from the reserves of OM. Mineralization of sulphate from SOM is controlled by OM levels, temperature, and moisture. Generally, such factors that favour plant growth enhance S release from OM.

Sulphate is an anion and as such is mobile in the soil though not as free moving as nitrate or chloride (Lamond, 1997). Supply of sulphate in soils can vary greatly from year to year depending on many factors. The total sulphur (TS) of soil varies widely from about 50 to 50,000 mg/kg. As is the case with many other nutrients, however, TS is not necessarily a good predictor of a soil's ability to supply sulphur. Most soil tests measure extractable (SO_4-S) and using this value to make recommendations. Due to the importance of OM and soil texture in predicting fertilizer S needs, however, most laboratories also factor these into recommendations. Organic S is often estimated as the difference between TS and SO_4-S. For best S test interpretations Lamond, (1997) suggested attaching of both the SOM and texture analysis, as this information coupled with crop and yield goal allow for the best possible S recommendations. Like profile N samples, soil samples to be analyzed for S should be sampled deeper and air-dried before mailing. Since SO_4-S is mobile, sampling to a 60 cm depth is recommended for best results (Lamond, 1997).

1.8.2.1 Soil build-up

Plants take up S as SO_4 ion, and this form is easily leachable from soils. However, sulphur cycles in the soil environment, much like N. Soil organic matter (OM) is an excellent source of S and used as an important soil build-up application in agricultural soils (Lal, 2014). Such applications are particularly, important in the countries like Ethiopia, where the inorganic S fertilizer sources are hitherto forgotten. Soil OM is not only acting as the source of S, but also buffers the extremities of soil pH, and reduces the loss of available S form in soils. Its mineralization and immobilization process define the contents of plant available S in the soil system. The organic S sources are crop residues, household wastes and and/or animal manure, and their soil build-up application can be a gradual or one time practice. Solomon *et al*. (2001) reported the close association of organic S with SOC and N, due to the fact that SOM provides the major non-leachable reserve of sulphur and nitrogen in most surface soils. Soil build-up is also called corrective fertilization or fertilizing soils.

1.8.3 Fertilizer considerations

The incidence of S deficient soils has increased in recent years, likely due high analysis fertilizers lacking S; intensive cropping systems; less use of fallow; the use of higher yielding varieties and hybrids of crops; less atmospheric deposition; and declining levels of SOM. Due to these factors, the use of S fertilizers is expected to increase. Lamond (1997) reported a list 16 dry and five fluid sources of S fertilizer products. Growing plants receive their S from many sources. In soil, the main sources are sulphate ions released from the decomposition of OM and by dissolution of soil minerals. To supplement these sources, a number of S containing materials can be effectively used.

The most commonly used S fertilizer materials are ammonium sulphate AS), potassium sulphate, elemental S, gypsum, and livestock manure. Weil (2011), suggested AS and gypsum as the best supplement for soil fertility in Africa. But, the main disadvantage of AS is that, it is the most acid forming and should not be used in large amounts in acidic soils (pH < 6). Elemental S has the advantage of being highly concentrated in this element and also available in deposits in Ethiopia. However, it is a strong acid forming material and should only be used where soil acidification is desirable (e.g., in sodic soils). Animal manures also contain some S, but even if animal diets are sufficient in S, the amount of S in the manure will still be low enough that a great deal of bulk material must be handled and applied to supply the necessary S (Weil, 2011). The big advantage to using manure is that it supplies many other nutrients as well as OM.

Gypsum is commonly available in a hydrated form ($CaSO_4.xH_2O$). This material is found in plenty in the Ethiopian landscapes. This material is generally applied in a dry form and is available in a granulated form that can be blended with other materials. According to Weil and Mughogho (2000), there are many advantages in using gypsum (e.g., increased N use efficiency). It is important for addressing both S deficiency and ammonia volatilization (Weil and Mughogho, 2000; Weil, 2011). According to the authors gypsum has no deleterious effect, even when used at larger doses. In regions with acid soils (pH < 7.0), gypsum should be used with urea, rather than risk excessive acidification by S. Using the local material is also cost effective in terms of cash.

1.9 Problem Statement and Justification

Food insecurity is widespread in many areas of Ethiopia. One of the major reasons is the low crop yields due to inherently low soil fertility. Stoorvogel and Smaling (1990), reported Ethiopia to be one of the countries having highest rate of nutrient depletion, with aggregated national scale nutrient balances estimated to be -41kg N, -6 kg P and -26 kg K/ha. The main reason for these negative balances is greater outflows of nutrients through crop harvest, leaching or erosion and gaseous losses than inflows. However, solutions to the problems of nitrogen (N), phosphorus (P) and potassium (K) are apparently available in a form of recommended fertilizers, as they are subject to intensive investigations in the Ethiopian agricultural crop production systems.

Sulphur is one of the 17 essential elements in plant nutrition. However, S input to soils in Ethiopia is constrained by the use of high analysis N and P fertilizers with little or no S; low S returns with farmyard manure (FYM) or organic matter (OM); introduction of high yielding cultivars and hybrids of crops; crop residue removal; residue burning; and S losses such as through leaching. These factors are likely to contribute to S deficiency in soils. For instance, the amount of N fertilizer used in Ethiopia has increased by 22 % from 349 580 metric tons (MT) in 1996 to 424 521 MT in 2005, largely from urea. However, such increased use of high-analysis fertilizers was not supported with other essential nutrients like S, which has been found to be sub-optimal and deficient in the limited works and soils investigated in Ethiopia so far (Itanna, 2005).

Deficiency of S has been recognized as a limiting factor for crop production in many regions of tropical and sub-tropical Africa (Pasricha and Fox, 1993), and Ethiopia is no exception to this. Kiros and Singh (2009) reported yield response of wheat to applied S in northern Ethiopia. With respect to soil test results, Itanna (2005) reported soil SO_4-S ranging 0.2 to 9.1 mg/kg in a study made in Rift Valley soils in Ethiopia. Similarly, in a study made in the highland soils in Ethiopia, Tekalign and Haque (1987) reported low levels NH_4OAc extractable S of < 10 mg/kg.

Although some early reports recognized the problem of S deficiency (Blair *et al*., 1980), there are several reasons why S has not received adequate attention in Africa. First, the low-yield subsistence agriculture has been based on exploiting natural soil nutrient reserve, using S released as SOM decomposes. Second, during 1950s to 1980s, adequate S was commonly supplied to cropland from animal manures or from the then-popular low-analysis fertilizers such as ammonium sulphate (AS) and single superphosphate (SSP), which were applied for their N and P, but supplied more S than either N or P, thereby obscuring the occurrence of S deficiencies and responses, especially in research plots (Weil, 2011). In addition, certain technical issues have militated against research on S fertility. One was the lack of simple, inexpensive and reliable methods for analysing plant and soil S and sulphate (duToit and 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 to be free of S. However, TSP is reported to contain about 2-6 % by weight of S (Weil and Mughogho, 2000).

The situation regarding S fertility has changed in recent decades. First, as SOM has decreased substantially by continuous cropping, and as high-yielding varieties and hybrids have found wider use, the supply of S from OM has become inadequate in many instances. Secondly, there has been a rapid shift in African agriculture away from the use of low-analysis fertilizers like AS and SSP toward high-analysis fertilizers such as urea or di-ammonium phosphate (DAP), which contain little or no S. Where these fertilizers are used with high yielding varieties, failure to supplement S can be expected to rapidly deplete available S from soils. Therefore, it is not surprising that the deficiency of S could be a major problem, especially on continuously cropped lands.

Sulphur is an essential macro-nutrient that is taken-up by grain crops in amounts similar to and sometimes exceeding, those of P, namely 10-30 kg/ha (Weil, 2011). However, while P and many other plant nutrient elements have been subject to extensive investigations throughout Africa (Batiano *et al*., 2008), much less is known about S status of African soils and the response to S in crop production. Plants require S as a constituent of some amino acids which are essential for protein synthesis. Sulphur is also essential for N nutrient use efficiency (NUE) and ranks equal to N for optimum crop yield and quality. It is reported to be necessary for the formation of chlorophyll, vitamins, enzymes, and aromatic oils (Korb *et al*., 2002). However, accidental addition of S from low analysis fertilizers (e.g., AS and SSP) in Ethiopia is nil or minimal due to a shift to high analysis fertilizers (mainly urea and DAP). In such conditions, failure to supplement S in a balanced fertilizer management programme can be expected to rapidly deplete available native soil sulphur. Although S is an essential macronutrient that is used by plants in quantities similar to those for P, until recently very little research has been done on the status of this element in soils and crops in Ethiopia and the available data and information are quite scanty.

Furthermore, unlike N, P and K, S is not routinely analyzed in soils and plant tissue samples at EIAR laboratories in Ethiopia, nor did a recently prepared manual of standard methods for the Soil and Plant Analytical Laboratories Network of Ethiopia include a method for either soil or plant S. Therefore, there is relatively little documented data available on this element in Ethiopian soils and crops. From this, it is clear that protein rich cereals like wheat, legume crops like faba bean, and even oil crops are likely to respond to S application. Therefore, these are some of the compelling reasons for the need to assess the status of sulphur in some major crops (e.g., wheat) growing agro-ecological zones (AEZs) and soils of Ethiopia.

1.10 Research Objectives

1.10.1 Overall objective

To enhance increased agricultural crop production, productivity and quality produce through the integration of sulphur in balanced fertilizer recommendations for major wheat growing soils and agro-ecological zone (AEZs) of Ethiopia.

1.10.2 Specific objectives

The specific objectives of the research were to:

1. Quantify the sulphur status of some major soils and crops in relation to other soil fertility parameters in wheat growing areas of the Central HLs of Ethiopia.
2. Investigate the response of wheat to applied S along with N and P in different agro-ecological zones (AEZs) and soils in the central highlands of Ethiopia.
3. Evaluate the relationship among OC and SO_4-S, total S content and N/S ratio in wheat grain at harvest with yield or grain S uptake.
4. Establish critical levels for different sulphur indices.
5. Determine the optimum S rate for wheat production in the study areas.

1.11 Research Questions

1. Is there a response of wheat to applied nitrogen (N), sulphur (S), and/or phosphorus (P)?
2. Is there a combined effect of N, S, and P on wheat yield or yield components?
3. Are the native soil SO_4-S and/or OC; total S content and N/S ratios in wheat seed correlated with yield or sulphur uptake?
4. What is the best estimate of the critical levels for those that were found suitable?

5. Does the application of S increase yield and yield components of wheat? And if so, what is the optimum application rate of sulphur for wheat production in Ethiopia?
6. Is there sulphur deficiency in the crop production systems in the Central highlands of Ethiopia? And if so, how wide spread is the sulphur deficiency in the CHLs of Ethiopia?

1.12 Outline of the Dissertation

Chapter 1 is the general introduction, presenting the background information and literature review on: strategies for restoring soil quality and/or soil health; SOC and its impact on soil quality in relation to the elements N, P and S; S availability indices; the problem of sulphur deficiency in crop production; and fertilizer recommendations, and factors affecting it. Finally, the general introduction provides details of problem statement and justification, research objectives, research questions and the outline of the dissertation.

Chapter 2 discusses the results of wheat response to applied N, S and P in three representative areas of the central highlands (CHLs) of Ethiopia, from 18 explorative field experiments conducted in diverse agro-ecological zones (AEZs) and soil types.

Chapter 3 covers the results of the evaluation of different indices of S supply on wheat yield in the major wheat growing areas of the CHLs of Ethiopia from the 18 explorative field experiments.

Chapter 4 presents the results of field experiments conducted to determine the optimum S rate for wheat production from six field experiments conducted in the second season.

Chapter 5 presents the general conclusions and recommendations derived from the study.

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CHAPTER TWO

2.0 Wheat Response to Applied Nitrogen, Sulphur and Phosphorus in Three Representative Areas of the Central Highlands of Ethiopia

Abstract

A study was conducted in the three representative areas (Arsi, E/Shewa and Oromia Liyuu zones) in the Central Highlands of Ethiopia to assess S status of soils and wheat plants. Explorative field experiments were conducted in 18 sites to evaluate the response of wheat to applied S vis-à-vis N and P. A newly released "Kekeba" wheat cultivar was used as a test crop. Four treatment combinations, namely: an absolute control (without any fertilizer) or CK = ($N_0P_0S_0$), N alone or N = N_1 = ($N_1P_0S_0$), nitrogen plus sulphur or NS = N_1S_1 = ($N_1P_0S_1$), and nitrogen plus phosphorus plus sulphur or NPS = ($N_1P_1S_1$) were tested in diverse AEZs and soil types. The evaluated nutrients were two levels of sulphur (0 and 20 kg S/ha); two levels nitrogen (0 and 69 kg N/ha); and two levels of phosphorus (0 and 20 kg P/ha), applied as gypsum, urea and TSP, respectively. The treatments were arranged in randomized complete block design (RCBD) and replicated three times. The results showed significant response ($P < 0.001$) in grain and various yield components of wheat. All studied fields (100 %) showed response to applied N, and this is directly related to low soil-test TN in these fields. The SO_4-S of the studied soils ranged from 1.30 to 24.18 mg/kg. Based on the 10-13 mg/kg $CaCl_2$ extractable SO_4-S as a critical level of soil S deficiency for wheat cited in literature, over 70 % of the studied soils were low in available S. Wheat showed response to applied S in about 72.3 % of the sites. Similar to N, all fields had low plant 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 not for P in some fields. Pair-wise orthogonal comparisons did not show wheat yield response of S from TSP as impurity. In the study, it was evident that light textured and calcareous vertisols in the peripheries of Rift-Valley were found to be more deficient in S than other soils. There are strong indications that S deficiency can be much widespread, if assessments were made across the country. Therefore, it is important to include S in balanced fertilizer formula. Moreover, 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*: Sulphur response; gypsum; grain yield; sulphate sulphur; wheat cultivar.*

2.1 Introduction

Ethiopia is the largest producer of wheat in the sub-Saharan Africa (SSA), accounting for over 1.8 million hectares cultivated annually (Abeyo *et al*., 2012). Wheat ranks third in area coverage and total production after teff and maize, and after maize and sorghum for productivity. It is a major cereal, which triggered the green revolution in many parts of the world, having a unique protein and grown in diverse environments (Beena *et al.*, 2012). Ethiopia needs to increase agricultural production in order to provide food to its ever increasing population, estimated at over 91 million (CSA, 2012), based on the 2007 census. However, to ensure sustainable crop production including wheat, healthy soils are important, soils having good physical, chemical and biological fertility. In contrast, poor health/quality soils exhibit various dysfunctional attributes such as deficiencies in plant available nutrients, soil erosion, and various other problems. Adequate levels of plant nutrients are key components of good soil health/quality. But, if the levels are not adequate, replenishing it must be weighed against any economic activity.

For the last three decades, Ethiopian agriculture solely depended on imported fertilizer products, mostly urea and DAP, as the sources of only N and P. However, very recently it has been perceived that the production of such high protein rich cereals like wheat and even legumes can be limited by the inadequate supply of S and other related essential nutrients. The major prone areas of S deficiency are the central highlands (CHLs) of Ethiopia, because of their high crop production potential, which is driven by high market access for the harvested produce in the big towns and cities in the centre of the country. Some of the reasons that can lead to S deficiency in soils of these areas include: i) increased use of high-analysis fertilizers, only urea and DAP, that contain no sulphur, ii) intensive agriculture that leaves behind little organic matter (OM), and/or complete removal of organic materials/crop residues including farmyard manure (FYM) for alternative uses, iii) increased crop yields due to the use of high-yielding varieties, resulting in more S removal, iv) no or less deposition of S from atmosphere due to little or no industrial sector development, and less or no use of S containing pesticides, and v) intensive cropping systems that include legumes and oil crops that mine more S. All these reasons are more pronounced in areas with high crop production potential like those in the CHLs of Ethiopia.

Although sulphur is often overshadowed by N, P and K, it is an essential mineral nutrient best known for its role in the synthesis of proteins, oils, vitamins and flavored compounds in plants. The amino acids methionine (21 % S), cysteine (26 % S), and cystine (27 % S), which are the building blocks of proteins that impact nutritional value of human food and feeds, contain S (Chattopaddhyay and Ghosh, 2012). Sulphur is reported to be a macro-nutrient that is taken-up by grain crops in amounts similar to and sometimes exceeding those of P, 10-30 kg/ha (Jamal *et al*., 2012; Weil, 2011), and is 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 and quality (Brown *et al*., 2005; Zörb *et al*., 2013).

However, S is a nutrient element most overlooked in Ethiopian agriculture. In Ethiopia, there is little incidental addition of S from low analysis sources due to a shift to high analysis fertilizers. Farmers and extensions can aim at increasing crop yields only in quantity by applying significant amounts of N and P from urea and DAP. But, in such a condition, failure to supplement S in balanced programmes can be expected to rapidly deplete available soil reserve leading to S deficiency. Regardless of its importance, very little research has been done on the status of this element in soils and crops in Ethiopia and the available information and even data are quite scanty. Moreover, unlike N, P, K and several other nutrient elements, S is not routinely analyzed in soil and plant tissue at the laboratories in Ethiopia.

With the view of the above research gaps, this study was aimed at:

i. Quantifying the status of S in relation to other soil fertility parameters in wheat growing areas in the CHLs of Ethiopia.
ii. Investigating the response of wheat to applied S in along with N and P in different agro-ecological zones (AEZs) and soils.

Hence, the research questions intended to be answered by this study are: 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 or yield components?

2.2 Materials and Methods

2.2.1 Description of the study areas

The study was conducted in six districts (Tiyo, Hitossa, Gimbichu, Ada'a, Akaki and Welmera) in Arsi, E/Shewa and O/Liyuu zones. They are representative of the major wheat growing zones in the CHLs of Ethiopia.

In Arsi zone, average annual rainfall during the growing season is about 788-1200 mm. The mean annual potential evapo-transpiration, calculated by pan-evaporation is about 1300 mm. The mean annual maximum temperature is 23 °C and minimum is 10 °C. The monthly maximum values range between 21 to 25 °C, while monthly minimum values range between 8 to 12 °C. The rainfall is higher than the half potential evapo-transpiration (PEVT), thus endowing the area to have 200 to 240 consecutive days of long growing period (LGP). During the months of July to September, the rainfall is higher than full PEVT. Arsi has a low relief difference with altitude ranging from 1769 to 2418 m. In some places where the slope is very flat, flooding and water logging occur. In this study area a considerable proportions of vertisols exist. The geology of this area consists of pyroclastic rocks, mainly tuffs and ignimbrites of the recent volcanic eruptions. The upper soil layer consists of tephritic materials, whereas the substratum consists of calcareous material enriched through secondary precipitation over bedrock (Abayneh *et al*., 2001).

In the E/Shewa zone cantering Debre Zeit area, the average annual temperature ranges from 8-20 °C. The AEZs in this zone extends from sub-tropical and mid-highlands to highlands. This area also has a low relief difference with altitude ranging from 1874 to 2427 m. In general, the average annual rainfall during the growing season is about 800-1200 mm. The dominant soil types in this study area are vertisols (Abayneh *et al*., 2001; Damitew *et al*., 2012). The geology is typically alkaline basalt and trachyte of the Cenozoic volcanic eruptions.

In O/Liyuu zone, Welmera district, the altitude range is from 2124 to 2350 m above sea level. The mean annual rainfall is 1078 mm. The main rainy season extends from June to September which receives 70 % of the annual rainfall. The mean minimum and maximum temperatures are 6.2 °C and 22.1 °C respectively, with a mean relative humidity of 60.6 %. The major soil types of the area are nitosols and vertisols; and the major AEZs of Welmera district extend from extremely cool highlands to mid-highlands, 61 and 39 %, respectively.

In each zone, six sites/farmers fields were selected in each study area, and geo-referenced using Global Positioning System (GPS) GARMIN, model number GPS-60, USA 2007, assisted by Google Earth (2011) and were classified by elevation, and soil type. These sites were characterized and used for conducting trials to test response of sulphur to wheat. The specific locations and salient features of the selected sites are presented in Table 2.1.

Table 2.1: Geographic locations of the selected study sites in the central highlands of Ethiopia

District	Site/farmer field	Latitude (N)		Longitude (E)		Altitude	Soil type
		Degree	mm.mm	Degree	mm.mm	(m)	
Arsi zone							
Tiyo	A/Alko	7	49.454	39	1.661	2297.02	Light Vertisol
	Dosha	7	53.813	39	6.176	2418.32	Nitosol
	G/Silingo	8	0.792	39	8.436	2151.10	Light Vertisol
	C/Misoma	7	59.067	39	3.964	1768.98	Nitosol
Hitosa	B/Edo	8	3.507	39	17.184	2359.95	Light Vertisol
	B/Lencha	8	7.476	39	17.722	2186.37	Nitosol
E/Shewa zone							
Gimbichu	C/Donsa	8	57.113	39	6.087	2426.53	Pellic Vertisol
Ada'a	Keteba	8	53.553	39	1.913	2224.37	Pellic Vertisol
	Ude	8	40.767	39	2.197	1873.86	Pellic Vertisol
	Bekejo	8	38.376	38	55.322	1874.16	Pellic Vertisol
Akaki	Insilale	8	51.647	38	53.214	2211.30	Light Vertisol
	Kilinto	8	54.099	38	49.133	2204.00	Pellic Vertisol
O/Liyuu zone							
Welmera	N/Kersa	8	55.605	38	31.062	2123.74	Light Vertisol
	N/Suba	8	57.287	38	29.756	2229.54	Nitosol
	B/Tokofa	8	59.605	38	30.98	2252.64	Nitosol
	D/Lafto	8	59.147	38	26.92	2173.60	Nitosol
	W/Harbu	9	1.457	38	28.731	2335.63	Nitosol
	T/Harbu	9	2.571	38	28.817	2349.62	Nitosol

The soils are classified as characterized by Abayneh *et al*. (2001); Damitew *et al*. (2012).

2.2.2 Experimental treatments and design

During the first cropping season (2012-13), 18 explorative field experiments were conducted in 18 farmers' fields, six in each study area: Arsi, East Shewa and Oromia Liyuu or West Shewa administrative zones covering different AEZs and soils. A newly released wheat cultivar, known as "Kekeba" was used as a test crop. Four treatment combinations, namely: an absolute control (without any fertilizer) or CK = ($N_0P_0S_0$), N alone or N = N_1 = ($N_1P_0S_0$), nitrogen plus sulphur or NS = N_1S_1 = ($N_1P_0S_1$), and nitrogen plus phosphorus plus sulphur or NPS = ($N_1P_1S_1$) were tested in Arsi, East Shewa and Oromia Liyuu zones covering diverse agro-ecological zones (AEZs) and soil types. The evaluated nutrients were two levels of S (0 and 20 kg/ha), two levels of P (0 and 20 kg/ha); and two levels N (0 and 69 kg/ha). Nitrogen supplied as urea (46 % N), phosphorus as TSP (46 % P_2O_5) and sulphur as gypsum (18 % S) were applied as per experimental treatments. The treatments were arranged in randomized complete block design (RCBD) and replicated three times. The plot size was 3 m x 5 m = 15 m^2 and there were a total of 4 experimental plots per block. One third of N source was incorporated into soils within rows just before seeding to enhance its use efficiency, whereas the remaining 2/3 was top dressed at tillering stage. But, the entire amount of S and P sources were drilled (5 cm depth) within rows and incorporated (mixed with soils) just before seeding. Then, the whole was covered with the soil.

The agronomic spacing for wheat between rows and plants was 25 cm x 5 cm (175 kg/ha seed rate). There were a total of 12 rows of wheat plants per plot. There were two border rows in each side and another one row consisting of (a 25 cm x 5 cm size) was used for plant tissue sampling. The remaining centre rows (a 4 m x 1.5 m = 6 m^2 net plot) were used for agronomic/yield data and seed sample collection. Whenever needed, hand weeding was used to control weeds as required. During the crop's growing stage or before/after harvest the 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), grain yield (GY), stover yields (SY) and number of seeds per panicle (NSsPP) were recorded. Harvesting was commenced when the grain and stover samples were reached average grain moisture content of about 13.5 %.

2.2.3 Soil sample collection, preparation and analysis

Just before planting seeds, composite surface soil samples representing each block from 10 spots were taken at 0-20 cm depth and bulked and further composited to represent one sample per field. Then, soils were air dried immediately in dry rooms to avoid sulphate formation from OM in transit. The dried samples were ground and sieved to pass through a 1-mm sieve for evaluating physico-chemical fertility status. The dried/sieved samples were transported to the Department of Soil Science (DSS) laboratory of SUA, Tanzania, for analysis. The soil samples were analyzed for different physico-chemical parameters, as follows.

The soil samples were analyzed for pH in water at 1:2.5 soil: water ratio solution using a combined glass electrode pH meter as described by Van Reeuwijk (2002). Electrical conductivity (EC) was determined in water at 1:2.5 soil: water suspension ratio by electrode method (Klute, 1986). For exchangeable bases, Na^{+1} and K^{+1} determination, soil samples were extracted with, 1M NH_4OAc (pH: 7.0). The Na^{+1} and K^{+1} content in the extract were quantified using flame photometer as described by Rowell (1994). Also Ca^{+2} and Mg^{+2} were extracted in 1M NH_4OAc (pH: 7.0) and measured by atomic absorption spectro-photometer (AAS) as described by Van Reeuwijk (2002). The PBS was calculated as described in Van Reeuwijk (2002). Similarly, CEC was determined by 1 M NH_4OAc solution at pH = 7.00 as described by Van Reeuwijk (2002). To determine the CEC, soil sample were saturated with 1 M NH_4OAc solution at pH 7, followed by repeated washing with alcohol to remove excess NH_4^+ ions in the soil solution. The ammonium saturated soil samples were then leached with KCl and NH_4^+ ions which were displaced by K were measured using the method described by Van Reeuwijk, (2002).

The TN was determined by Kjeldahl digestion and distillation method as described by Okalebo *et al*. (2002). Soil OC was estimated in soil samples by the procedure used by Walkley-Black as described by Nelson and Sommers (1996). In this method OC in soil samples were oxidized with potassium dichromate ($K_2Cr_2O_7$) in H_2SO_4 solution. A measured amount of $K_2Cr_2O_7$ was used in excess of that required to destroy OM and this excess was determined by titration with ferrous sulphate, using diphenylamine indicator, to detect the first appearance of un-oxidized ferrous iron.

Available P was determined by Bray-1 method using NH_4F extraction solution (Bray and Kurtz, 1945) for soils with pH < 7. Whereas, the Olsen method using $NaHCO_3$ extraction solution (Olsen *et al*., 1954) was used for soils with pH > 7. The available sulphur, SO_4-S was extracted by calcium orthophosphate ($Ca(H_2PO_4)_2$), and quantified by turbidimetric analytical method as described by Rowell, (1994). Soil texture was determined by the hydrometer method as described by Bouyoucos (1962).

2.2.4 Statistical data analysis

Data were statistically analyzed using SAS statistical package version 9 (SAS Institute Cary, NC, USA, 2012). Similarly, PROC UNIVARIATE procedure in SAS was used to test normality assumptions of variables, besides analyzing residuals distribution. In this respect, grain yield in all fields is normally distributed, because p-value from Kolmogorov-Smirnov test was > 0.05 for all sites, implying that there was no significant departure from normality. Analysis of variance (ANOVA) was done using a PROC MIXED of Generalized Linear Model (GLM) of SAS protocols to evaluate differences among treatments as per experimental design. When differences between treatments on yield and its components were significant, least significant difference (LSD) was used to separate means at 0.1 %, 1 % and 5 % probability levels. The variables like yield were 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. The SAS GLM statement for the analysis of RCBD in field experiment is indicated as:

$$\mathbf{Y}_{ij} = \mu + \mathbf{T}_i + \rho_j + \mathbf{e}_{ij}$$

Where treatment (i = 1, 2, … t) and block (j = 1, 2, … r).

Y_{ij} = wheat yields; μ = grand mean; T_i = treatment effect; ρ_j = block effect; β = regression of Y_{ij} on X_{ij}; e_{ij} = normally independently distributed (NID) error with (0, 2^2_e) or residuals, deviations of each observation from their expected values. The model will also include blocks that are nested within farms, and also need P factors. In addition to this, analysis such as regression of yield and S uptake against SO_4-S in soil etc were performed.

2.3 Results and Discussion

2.3.1 Some selected physical and chemical properties of the soils of the study sites

Table 2.2 presents some physico-chemical properties of soils of the study fields before planting. The results show that the studied sites varied widely in their physico-chemical properties of soils, particularly pH, CEC, PBS and soil SO_4-S. The variation can be attributed to specific agro-climatic conditions of the areas. It is evident that these variations can affect plant nutrient availability, particularly S.

Soils provide 13 of the 16 essential elements necessary for crop production. Soil testing will provide information on the level of total or available nutrients and, based on the information thus obtained, thus it is possible to formulate suitable fertilizer recommendations to correct any nutrient deficiencies or amendments to rectify any toxicity problems.

Soil pH is a chemical property that significantly influences the availability of plant nutrients, and it showed a wide range of values from 5.1 to 8.1 (Table 2.2). The pH ranges from strongly to moderately acidic (5.1 to 6.7) in sites of O/Liyuu zone, Welmera district. It was strongly acidic to near neutral pH (5.3 to 7.0) in Arsi zone; while in the E/Shewa zone the pH ranged from neutral to moderately alkaline (7.1 to 8.2). In the majority of fields in the E/Shewa zone, the soils were calcareous with visible fragments of $CaCO_3$, making them alkaline in reaction. Such sites include Chefe Donsa, Keteba, Kilinto and partly Bekejo, which make up about 67 % of the sites in the zone. In general, in all the studied areas, the pH values fall within a range 4.5 to 8.5 reported by Thiagalingam (2000) for agricultural soils, with the values of 5.5 to 7.0 preferred by most grain crops and pastures. According to the author, the pH of most agricultural soils falls within the range of 4.5 to 8.5. Below pH 5.5, acid tolerant plants (coffee, tea and sweet potato) will grow but as the pH decreases from 5.5 to 4.5 excessive aluminium, iron and manganese will usually be present and will be toxic to legumes, cereals and other crops. If the pH values are in excess of 8.5 to 9.0, this will indicate high levels of exchangeable sodium and poor soil physical conditions.

From all the studied areas, in only two of the sites, i.e. Dosha (in Arsi zone) and Berfeta Tokofa (in Oromia Liyuu zone), the pH was slightly below 5.5. Their values were 5.3 and 5.1 respectively, but both are still in a tolerable range for growing wheat crop based on the criteria by Thiagalingam, (2000).

Table 2.2: Some physico-chemical features of the soils of the study areas cultivated for wheat before planting

Study Area	District	Farmer Field	Soil Type	pH (1:2.5) Soil:H_2O ratio	EC (dS/m)	Exchangeable Bases [(cmol(+)/kg)]				CEC (Cmol(+)/kg)	PBS (%)	TN (%)	OC (%)	Av.P (mg/kg)	SO_4-S (mg/kg)	Soil Textural Class
						Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}							
Ar	Ti	AA	Cv	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	Ti	Do	Ni	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	Ti	GS	Cv	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	Ti	CM	Ni	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	Hi	BE	Cv	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	Hi	BL	Ni	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	Gi	CD	Pv	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	Ad	Ke	Pv	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	Ad	Ud	Pv	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	Ad	Bk	Pv	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	Ak	In	Ni	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	Ak	Ki	Pv	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	We	NK	Cv	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	We	NS	Ni	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	We	BT	Ni	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	We	DL	Ni	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	We	WH	Ni	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	We	TH	Ni	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); Districts (Ti = Tiyo, Hi = Hitosa, Gi = Gimbichu, Ad = Ada'a, Ak = Akaki, and We = Welmera); Farmer fields (AA = Abosara Alko, Do = Dosha, GS = Gora Silingo, CM = Chefe Misoma, BE = Boneya Edo, BL = Boru Lencha, CD = Chefe Donsa, Ke = Keteba, Ud = Ude, Bk = Bekejo, In = Insilale, Ki = Kilinto, NK = Nano Kersa, NS = Nano Suba, BT = Befeta Tokofa, DL = Dawa Lafto, WH = Wajitu Harbu, and TH = Tulu Harbu); 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 (for pH > 7.0, by Olsen; and for pH < 7.0, by Bray-1 method used).

The EC ranges from 0.05 to 0.25 (dS/m) indicating that the studied soils were salt free or low in soluble salts based on the criteria developed by Thiagalingam (2000). The results of this study show no detrimental effect of soluble salt for agricultural crops.

The CEC of about 38.9 % of the studied soils was ranged from 15 to 47.8 cmol (+)/kg, and falls within a range 15 to 25 cmol (+)/kg soil suggested as medium; whereas 61.1 % falls in a range, 25 to 40 cmol (+)/kg considered to be high based on the criteria developed by Landon (1991) for tropical soils. The sequence of exchangeable cations was $Ca^{+2} > Mg^{+2} > K^{+1} > Na^{+}$. Which means that Ca was dominating the exchange site followed by Mg, and it is largely controls the base saturation and pH. Such a case is more prominent in areas of East Shewa zone, whose soils were found to be calcareous in nature, but it was not to the level that can significantly affect the availability of plant nutrients like phosphorus for arable crops. In general, the pH of the soils fall within the range of 5.1 to 8.1 with values of 5.5 to 7.0 reported to be preferred by most crops and pastures (Thiagalingam, 2000). According to the author, below pH 5.5 acid tolerant plants (e.g., coffee, tea and sweet potato) will grow, but as the pH decreases from 5.5 to 4.5 excessive aluminium, iron and manganese will usually be present and will be toxic to cereals, legumes and other crops.

The PBS of the soils at Arsi zone, which constitutes 33.3% of studied soils ranged from 42.48 to 71.83 %; and for a similar proportion of soils in O/Liyuu zone, the PBS ranges from 41.60 to 66.98 %. The soils in both study zones falls within a range that is considered to be medium to high based on the criteria developed by (Landon, 1991; Thiagalingam, 2000) for tropical soils. Whereas the PBS of soils at E/Shewa zone that ranges from 90.80 to 96.64 % falls within a range considered to be high. According to Landon (1991), the PBS that range between 20 to 60 % is considered medium, and considered to be less fertile, whereas that above 60 %, is considered to be high, implying better fertility of soils.

The TN, which ranged from 0.06 to 0.25 % falls in a range that is considered to be very low to low, based on the criteria developed by Landon (1991) and Thiagalingam (2000) for tropical soils. This low TN content can be attributed to the alarmingly low levels of soil OC in the studied sites soils. In such soils crop yields are expected to be adversely affected.

The available P content extracted by Olsen *et al*. (1954) for E/Shewa zone ranged between 7.55 to 10.99 mg/kg. This falls far below 10 to 20 mg P/kg, a range considered being low as per Thiagalingam (2000); and less than 20 mg P/kg considered being low by Horneck *et al*. (2011). Similarly, Bray-1 extracted P for soils from Arsi and O/Liyuu zones that ranged from 0.22 to 5.12 mg/kg are far below the low level of the Bray-1 P of less than 20 mg P/kg according to Horneck *et al*. (2011). According to Landon (1991) fertilizer responses are most likely expected in such low P soils. But, in the calcareous soils of E/Shewa zone, the availability of P can be limited, because of the expected fixation of P by high Ca content in such soils. This is also true for more acidic soils with low pH, in the areas like O/Liyuu zone where P would be fixed by Al. But, the pH was in acceptable range for optimum crop growth as suggested by Thiagalingam (2000).

The extractable SO_4-S ranged from 1.30 to 24.18 mg/kg (Table 2.2). Based on the 10 mg/kg $CaCl_2$ extractable SO_4-S critical threshold (CTH) for S deficiency for most soils reported by Srinivasarao *et al.* (2004), over 50 % of the studied soils were below this CTH and may be S limiting. In such soils, the responses to applied S are most likely expected. Moreover, as these CTHs separate only low and high levels, some marginal levels are also expected above the suggested critical levels, which soon can go to low levels, unless remedial measures are taken in advance.

The soil organic carbon (SOC) content of the studied soils ranged from 0.90 % to 2.99 % (Table 2.2). This falls in a range considered to be very low to low and/or marginal based on the criteria developed by Thiagalingam (2000). The SOC of most studied sites, about 78 % are far below the CTH of 2 %, suggested by other workers (Horneck *et al*., 2011; Patrick *et al*., 2013). The OC at Dosha site (Arsi zone) was 2.04 %, which is just equal to the critical level. From all the studied sites, in only Chefe Misoma and Boneya Edo sites (in Arsi) and Wajitu Harbu in (O/Liyuu zone), was the OC slightly above the critical levels, with the values of 2.75 %, 2.77 % and 2.79 % respectively. Indeed, it is important to note that, as this CTH separates only low and high values, the marginal/medium ranges can stretch up some points above 2 %. Considering this, therefore, about 83.3 % of the studied sites can be regarded as low in SOC, which indicates that some of the key soil quality/health indicators like structural stability of the study areas' soils would be at risk.

It is well recognized that SOM is a core component to sustainable agriculture, contributes significantly to C, S, N, P and K and other essential plant nutrients and other soil functions. Soil OC provides integrative benefits in protecting the environment and sustaining agriculture. Solomon *et al*. (2001) studied S fractions in particle-size separates of sub-humid Ethiopian highlands as influenced by land-use changes and reported that up to 98% of the total soil S may be present as organic S compounds. The authors further stressed that this TS can be associated with a heterogeneous mixture of plant residues, animals and soil microorganisms. The profile of this organic S concentration was generally reported to follow the pattern of OM contents in soils, even with depth. The soil organic carbon is reported to be a promising indicator for guiding N fertilizer management and/or use, given its integrative benefits that lead to high N supply and soil quality/health under challenges of soil heterogeneity among smallholder farming systems (Patrick *et al*., 2013).

Some authors link hunger in Africa to unhealthy soils and unhealthy people (Sanchez and Swaminathan, 2005). Furthermore, in Africa three quarters of farmland is severely degraded (Stocking 2003; Eswaran *et al*., 2012). As a result, the continent cannot produce enough food to keep pace with its needs, and the per capita food production is declining (Lal, 2015) largely due to the loss of soil health/quality, which is largely controlled by SOM. Some scientists have described SOC as a 'universal keystone indicator' in soil fertility management (Loveland and Webb, 2013). This makes it a good candidate and an appropriate tool for managing soil fertility heterogeneity among farmer fields in sub-Saharan Africa (SSA), which have the lowest fertilizer use levels in the world (Kiros *et al*., 2013; Juan *et al*., 2016) and agronomic N use efficiency (Vanlauwe *et al.*, 2012).

As indicated from the present study, in about 83.3 % of the studied sites had very low SOC. Therefore, it is not surprising that the studied soils are deficient in plant available N, S and/or P. From plant nutrients supply point of view, particularly N, S and P, SOM is critically important. However, the SOC in the studied soils is alarmingly low to the extent that it can negatively affect the soil health or its quality. This is because SOC and plant nutrient status are among the key indicators of soil quality and are critically low. Hence the soil health/quality of the studied sites can be regarded as being at risk.

Another root cause of the low SOC in the studied soils is that, from a transect survey study conducted in over 350 farm households and farm fields in the same season (unpublished data), it was observed that the crop residues which are the potential sources of plant nutrients have alternative uses, primarily cattle feed and fuel. Even during crop growing periods, there is a continuous removal of large amounts of plant biomass in the form of weed/feed and through defoliation of plant leaves. This reduces OM return to the soils and could affect soil's nutrient and eco-system dynamics. Such practices in Ethiopia are especially common in fields of cereals like maize, teff, wheat, sorghum and finger millet. Therefore, it is not surprising that the studied soils can be deficient in S, N and P. This indicates that restorative measures are needed to rectify the problem, especially at smallholding farmer level, to sustainably build the soil OC to an acceptable minimum level, close to the critical thresholds to revert the condition of SOM decline.

The soil textures as determined by the hydrometer method are indicated in Table 2.2. It is noticeable that in most studied areas, the proportions of clay soils dominate. But, whenever there is sandy clays dominate as in the case of sites like Gora Silingo and Boru Lencha (in Arsi zone) and Bekejo (E/Shewa zone), the responses to applied S were pronounced as the available SO_4-S levels were inherently low.

2.3.2 Response of wheat to applied nitrogen, sulphur and phosphorus

With the history of soil fertility management for crop production in Ethiopia, in relation to the past and present fertilizer use, cropping and farming systems and the consequent nutrient mining through continuous cultivation calls for better knowledge of soil nutrient status, particularly for those hitherto forgotten elements like S. The present study focused on making assessments on the status of S in soils and plants in the CHLs of Ethiopia. The results on the grain yield for the on-farm experiments conducted in diverse AEZs and/or soil types as affected by S nutrition along with NP fertilizers on the wheat are presented in Figs. 2.1, 2.2 and 2.3.

Number of tillers per plant (NTsPP), plant height (PH), spike/panicle length (SPL), spike/panicle weight (SPW), total above ground biomass (TAGB) dry matter yield, forage/stover yields (SY), number of seeds per panicle (NSsPP) and the grain yield (GY) all showed highly significant response ($P < 0.001$) to the applied N, S and P individually or in combinations. The obtained wheat grain yield response is also better related to other yield attributes and soil test values. For instance, the GY is well correlated to TAGB yield ($r = 0.88$; $P < 0.0001$), SY ($r = 0.82$; $P < 0.0001$), SPW ($r = 0.76$; $P = 0.0003$), SPL ($r = 0.65$; $P = 0.0034$), PH ($r = 0.53$; $P = 0.0246$), NTsPP ($r = 0.67$; $P = 0.0023$), NSsPP ($r = 0.40$; $P = 0.051$), and sulphur uptake in grain ($r = 82$; $P < 0.0001$). The grain yield (GY) is also positively correlated to the native soil's plant available S and TN in the soils before planting ($r = 0.69$; $P = 0.0033$), and ($r = 0.51$; $P = 0.0327$).

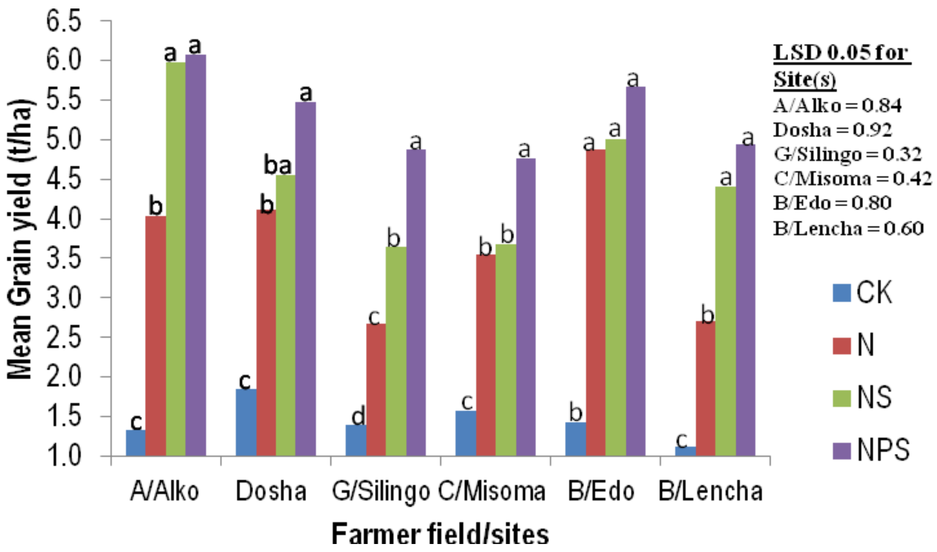

Figure 2.1: Wheat grain yield at Arsi zone in response to the applied N, S and P.

Means bearing the same letter(s) on bars within a field/site are not significantly different at $P < 0.01$ % probability level analyzed by T-test.

The results showed that wheat showed highly significant response (100 %) to applied N in all studied sites, which is directly related the low TN soil test values (Table 2.2). In about, 56 % of the fields' wheat showed highly significant response to applied P and about 22 % showed partial/marginal response. Similarly, all the studied areas (Arsi, E/Shewa and O/Liyuu zones) were tested low and/or marginal in plant available P. In some 22 % of the fields and soils wheat did not show response to P, despite their low available soil P before planting. The sites which did not show any response to applied P in relation to the next lower level treatment (i.e., NS) were Abosara Alko, Boneya Edo and Boru Lencha in Arsi zone, which constitute (16.7 %); and Kilinto in E/Shewa zone (5.6 %). But, those with marginal P response were Dosha in Arsi zone, Ude in E/Shewa and Dawa Lafto in O/Liyuu zones, which making a total of about 22 % of studied sites/fields. But, it is important to note that all the fields were responsive to P when compared with the check treatment (without any fertilizer) and/or with only N treatments.

Moreover, with the applied S, there can also be negative interaction between applied P and S. This may indicate that P may need better management for instance rate, method of placement, fertilizer source and timing of application, including soil build up applications to ensure better crop response, as there is a possibility of improving wheat yield from the addition of higher level of this element. However, this collectively may need further investigations, as the 20 kg P/ha applied P might be relatively lower than the wheat crops' P need in those sites. The low P rate used might have even obscured the chance of response of applied S beyond 20 kg S/ha. Infect, wheat yield can be increased by many folds as compared to the unfertilized checks, if all other nutrients and factors of crop production are non-limiting.

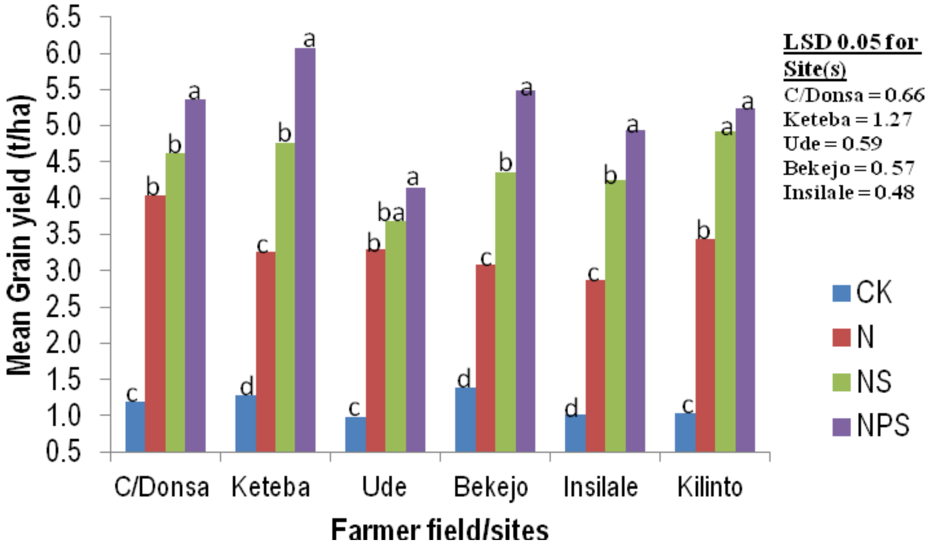

Figure 2.2: Wheat grain yield at East Shewa zone in response to the applied N, S and P.

Means bearing the same letter(s) on bars within a field/site are not significantly different at *P* < 0.01 % probability level analyzed by T-test.

From the 18 studied fields, maximum wheat grain yield obtained was 6.6 t/ha, from only one field, in the Tulu Harbu site in O/Liyuu zone (Fig. 2.3). However, the average grain yield of wheat can go over 8.5 t/ha when major nutrient elements like N, P K and S and others like micro-nutrients are interacting (Zhao *et al*., 1999). This may indicate that the potential attainable grain yield of the tested crop can still be higher, when other major crop management inputs and decisions are optimized including best fertilizer management practices such as rate, placement methods, source and timing of application of fertilizers.

With respect to sulphur, about 50 % of the study sites gave highly significant response to applied S from gypsum and 22 % had partial/marginal response, and about 30 % did not show any response.

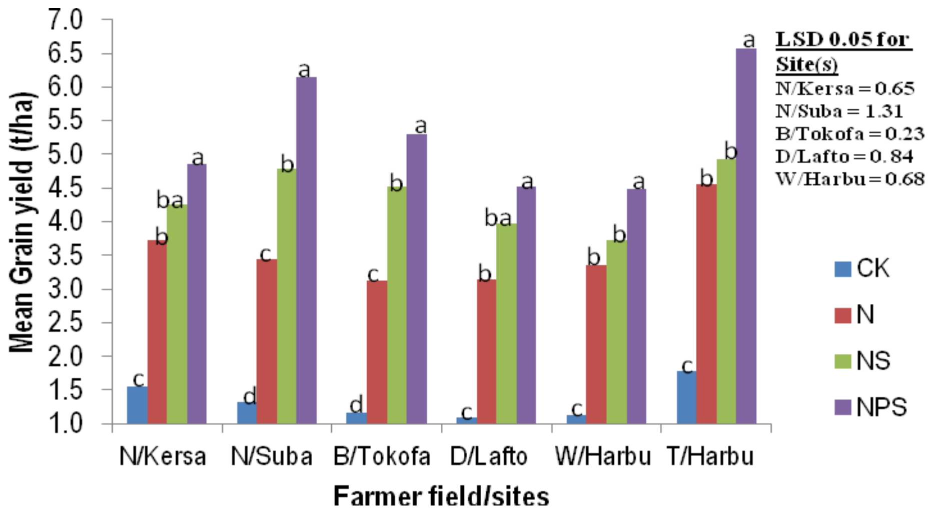

Figure 2.3: Wheat grain yield at Oromia Liuu zone in response to the applied N, S and P.

Means bearing the same letter(s) on bars within a field/site are not significantly different at *P* < 0.01 % probability level analyzed by T-test.

Following N, there observed better response to sulphur as directly related to soil test values. This was evidenced by the fact that, whenever the soil test value showed quantities below the critical level and/or was marginal; there was a corresponding wheat yield response. The least yield response to applied fertilizers was observed for P (Table 2.2; and Figs. 2.1, 2.2 and 2.3). As a direct link to this result, the SO_4-S in the studied soils ranged from 1.30 to 24.18 mg/kg. Based on 10 mg/kg $CaCl_2$-extractable SO_4-S as the critical limit of S deficiency for most crop species reported by Srinivasarao *et al*. (2004), 50 % of the studied sites were found to be S deficient.

But, more interestingly, in relation to S need for wheat, Tandon (1991) suggested a more crop specific critical level range, 10-13 mg/kg SO_4-S, which is now commonly being reported for cereals (e.g., wheat, maize) and oilseed (e.g., mustard). In agreement, Menna *et al.* (2015) reported critical level for the soil SO_4-S, 11.3 mg/kg. Considering these critical limits, however, about 72.2 % of the studied soils can be regarded as S limiting for wheat crop production. The sites which did not show response to applied S relative to the next lower level treatment (N alone), were Chefe Misoma and Boneya Edo in Arsi zone (which are making 11.1 % of the sites); Chefe Donsa in E/Shewa zone (5.6 % of the sites); and Wajitu Harbu and Tulu Harbu in O/Liyuu zone (11.1 % of the sites) making them a total of 27.8 % of the sites. Those sites with partial/marginal response to S were Dosha in Arsi; Ude in E/Shewa; and Nano Kersa and Dawa Lafto in O/Liyuu zone, a total of about 22.2 % of the sites. From the results, it is noticeable that most of the studied soils (about 72 %) were found to be S limiting. It may follow that; the S deficiency of soils can be much more severe, if such assessments were made across the country, particularly far into the out fields.

Figures 2.1, 2.2 and 2.3 also show the synergies that exist between applied N, S and P. For example, it is noticeable that, the grain yield curve in all the studied sites was always increasing and there observed to be yield advantage at any given point with any additional type and level of fertilizer added. But, the increases may or may not be always be statistically significant. This may indicate that, this was not necessarily the economic optimum level probably for N and P, because the yield plateau or nutrient response curve was not obtained. It is also important to note that in all the studied sites, the absolute control (treatment without any fertilizer) gave the least, the NPS treatment being the highest in affecting the yield of wheat.

When looking at specific examples: at the Abosara Alko, Dosha and Boru Lencha fields in Arsi zone, the effects of NPS and NS on wheat yields are comparable. This implies that the application of 20 kg P/ha did not increase wheat yield significantly. In these fields, NPS and NS led to higher grain yields than N alone, while CK has the lowest yield. At Chefe Misoma, the best treatment in increasing grain yield was NPS followed by NS and N. The N alone and NS were equally good in increasing wheat grain yield, while the CK gave the lowest grain yield. In Boneya Edo, all the applied fertilizer rates are equally good as far as wheat grain yield is concerned, and are superior to the CK. In Gora Silingo, each treatment has its own mean group and thus, the best treatment was NPS followed by NS and N, and the CK had the least effect on wheat grain yield. In general, the E/Shewa zone had better response to S, followed by O/Liyuu and Arsi had the least response. Moreover, it was in E/Shewa (Bekejo site) that the lowest plant available SO_4-S of 1.3 mg/kg (Table 2.2), was recorded. Even at Arsi, with a relatively low S response, a very low SO_4-S in the tested soil, (4.32 mg S/kg) was recorded in the Boru Lencha site (Hitossa district). Indeed, both of these sites are found in the periphery of the rift valley.

Moreover, the soils of both sites were sandy clay in texture. This may indicate that the calcareous soils, low in OM, and in the peripheries of the rift valley are expected to be much deficient in plant available S. In agreement with this, Withers *et al*. (1997) reported significant yield responses of wheat to S fertilization, particularly in areas of low S deposition and with light textured or shallow calcareous soils in England. Itanna (2005) also reported S deficiency in some highly weathered nitosols in the rift valley of Ethiopia. With respect to crop response, Kiros and Singh (2009) reported a strong N and S interaction in impacting wheat yield in northern Ethiopia. For example, the authors reported wheat yield increase of 0.8 to 2.4 Mg/ha with increased nitrogen use efficiency (NUE) of 28 % due to applied N and S.

Pair-wise orthogonal comparisons among treatments using SAS contrast statements or the difference between means at 95 % confidence limits (CLs), are presented in Tables 2.3a to 2.5b. The purpose of this part of statistical analysis was to see the effect of S impurity from TSP on wheat yield. This can be seen by looking at only the S responsive, but non-P responsive sites, such as A/Alko and B/Lencha (in Arsi zone), Kilinto (E/Sheea zone), and D/Lafto (O/Liyuu zone) (Tables 2.3a to 2.5b). In those sites the wheat responded well to the applied S at 20 kg/ha levels from gypsum, but not to the applied P from TSP. As indicated in the Tables, the pair-wise orthogonal comparisons showed non-significant negative CLs at 95 %, which is indicative of the fact that there was no wheat response to S impurity from TSP. If a site is responsive to applied S from gypsum, but non-responsive for P from the applied TSP, then any increase in wheat yield due to the applied TSP beyond 20 kg S/ha can be regarded as the response of wheat due to S coming from TSP, if all other factors are kept constant.

Table 2.3a: Pair-wise orthogonal comparisons among treatments in Arsi zone, at A/Alko, Dosha and G/Silingo sites (2012-13)

Treatment		**A/Alko site**				**Dosha site**				**G/Silingo site**		
comparisons	**DBM**	**95 % CL**			**DBM**	**95 % CL**			**DBM**	**95 % CL**		
NPS-NS	0.09	-0.75	0.93	ns	0.92	-0.01	1.84	ns	1.22	0.91	1.54	***
NPS-N	2.04	1.20	2.88	***	1.35	0.43	2.27	***	2.19	1.87	2.50	***
NPS-CK	4.73	3.89	5.57	***	3.63	2.71	4.56	***	3.48	3.16	3.80	***
NS-N	1.95	1.11	2.79	***	0.43	-0.49	1.36	ns	0.96	0.65	1.28	***
NS-CK	4.65	3.81	5.49	***	2.72	1.79	3.64	***	2.26	1.94	2.57	***
N-CK	2.69	1.85	3.53	***	2.28	1.36	3.21	***	1.29	0.98	1.61	***

Key: DBM = difference between means; CL = confidence limits; N = nitrogen; P = phosphorus; S = sulphur and; CK = Check (without any fertilize); ns = not significant at 95 % CL.

Comparisons significant at 0.01 levels are indicated by ***.

It has been reported that responses to sulphur are easily overlooked when a basal dressing of P is applied as TSP, a high analysis fertilizer which contains agronomically significant quantities of S (2-6 % by weight) (Weil and Mughogho, 2000). However, though the wheat cultivar gave highly significant response to applied S from gypsum in over 72 % of the sites, there was no wheat response to S impurity from TSP.

Table 2.3b: Pair-wise orthogonal comparisons among treatments in Arsi zone, C/Misoma, B/Edo and B/Lencha sites (2012-13)

Treatment	C/Misoma site				B/Edo site				B/Lencha site			
comparisons	DBM	95 % CL			DBM	95 % CL			DBM	95 % CL		
NPS-NS	1.09	0.67	1.52	***	0.66	-0.14	1.46	ns	0.55	-0.07	1.14	ns
NPS-N	1.22	0.80	1.64	***	0.79	-0.01	1.59	ns	2.24	1.63	2.84	***
NPS-CK	3.20	2.78	3.62	***	4.24	3.44	5.04	***	3.83	3.23	4.44	***
NS-N	0.13	-0.30	0.55	ns	0.13	-0.66	0.93	ns	1.70	1.10	2.30	***
NS-CK	2.11	1.69	2.53	***	3.58	2.78	4.38	***	3.30	2.69	3.90	***
N-CK	1.98	1.56	2.40	***	3.45	2.65	4.24	***	1.60	0.99	2.20	***

Key: DBM = difference between means; CL = confidence limits; N = nitrogen; P = phosphorus; S = sulphur and; CK = Check (without any fertilize); ns = not significant at 95 % CL.

Comparisons significant at 0.01 levels are indicated by ***.

This might be because of the low levels of plant available P in all the tested soils, which might have obscured the chance of wheat responses to S, that is expected to have come from TSP (Table 2.2).

Table 2.4a: Pair-wise orthogonal comparisons among treatments in E/Shewa zone, C/Donsa, Keteba and Ude sites (2012-13)

Treatment	C/Donsa site				Keteba site				Ude site			
comparisons	DBM	95 % CL			DBM	95 % CL			DBM	95 % CL		
NPS-NS	0.74	0.08	1.40	***	1.31	0.04	2.58	***	0.44	-0.15	1.04	Ns
NPS-N	1.32	0.65	1.98	***	2.81	1.54	4.08	***	0.84	0.25	1.44	***
NPS-CK	4.16	3.50	4.83	***	4.79	3.52	6.06	***	3.15	2.56	3.75	***
NS-N	0.58	-0.09	1.24	ns	1.50	0.23	2.77	***	0.40	-0.19	0.99	Ns
NS-CK	3.42	2.76	4.09	***	3.48	2.21	4.75	***	2.71	2.12	3.30	***
N-CK	2.85	2.18	3.51	***	1.98	0.71	3.25	***	2.31	1.72	2.90	***

Key: DBM = difference between means; CL = confidence limits; N = nitrogen; P = phosphorus; S = sulphur and; CK = Check (without any fertilize); ns = not significant at 95 % CL.

Comparisons significant at 0.01 levels are indicated by ***.

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 are indicated by the non-significant negative confidence limits at 95% (Tables 2.3a through 2.5b).

Table 2.4b: Pair-wise orthogonal comparisons among treatments at E/Shewa zone, Bekejo, Insilale and Kilinto sites (2012-13)

Treatment	Bekejo site				Insilale site				Kilinto site			
comparisons	DBM	95 % CL			DBM	95 % CL			DBM	95 % CL		
NPS-NS	1.11	0.54	1.69	***	0.69	0.21	1.17	***	0.32	-0.02	0.67	ns
NPS-N	2.39	1.82	2.97	***	2.06	1.58	2.54	***	1.80	1.46	2.15	***
NPS-CK	4.10	3.53	4.67	***	3.93	3.41	4.41	***	4.21	3.87	4.56	***
NS-N	1.28	0.71	1.85	***	1.37	0.89	1.85	***	1.48	1.13	1.83	***
NS-CK	2.99	2.41	3.56	***	3.24	2.76	3.72	***	3.89	3.54	4.24	***
N-CK	1.71	1.13	2.28	***	1.86	1.38	2.34	***	2.41	2.06	2.76	***

Key: DBM = difference between means; CL = confidence limits; N = nitrogen;
P = phosphorus; S = sulphur and; CK = Check (without any fertilize);
ns = not significant at 95 % CL.

Comparisons significant at 0.01 levels are indicated by ***.

Table 2.5a: Pair-wise orthogonal comparisons among treatments in O/Liyuu zone, N/Kersa, N/Suba and B/Tokofa sites (2012-13)

Treatment	N/Kersa site				N/Suba site				B/Tokofa site			
comparisons	DBM	95 % CL			DBM	95 % CL			DBM	95 % CL		
NPS-NS	0.59	-0.06	1.25	Ns	1.36	0.05	2.67	***	0.78	0.54	1.01	***
NPS-N	1.13	0.48	1.79	***	2.70	1.39	4.01	***	2.17	1.94	2.41	***
NPS-CK	3.30	2.65	3.96	***	4.82	3.51	6.13	***	4.14	3.91	4.38	***
NS-N	0.54	-0.11	1.19	ns	1.35	0.04	2.66	***	1.40	1.16	1.63	***
NS-CK	2.71	2.06	3.36	***	3.46	2.15	4.77	***	3.37	3.13	3.60	***
N-CK	2.17	1.52	2.82	***	2.12	0.81	3.43	***	1.97	1.74	2.20	***

Key: DBM = difference between means; CL = confidence limits; N = nitrogen;
P = phosphorus; S = sulphur and; CK = Check (without any fertilize);
ns = not significant at 95 % CL.

Comparisons significant at 0.01 levels are indicated by ***.

Table 2.5b: Pair-wise orthogonal comparisons among treatments in O/Liyuu zone, at D/Lafto, W/Harbu and T/Harbu sites (2012-13)

Treatment comparisons	D/Lafto site DBM	95 % CL			W/Harbu site DBM	95 % CL			T/Harbu site DBM	95 % CL		
NPS-NS	0.56	-0.28	1.40	ns	0.74	0.06	1.42	***	1.65	1.13	2.17	***
NPS-N	1.39	0.55	2.23	***	1.12	0.44	1.80	***	2.01	1.49	2.52	***
NPS-CK	3.42	2.58	4.26	***	3.36	2.68	4.04	***	4.78	4.26	5.29	***
NS-N	0.83	-0.01	1.67	ns	0.38	-0.30	1.06	ns	0.36	-0.16	0.87	Ns
NS-CK	2.87	2.03	3.71	***	2.62	1.94	3.30	***	3.13	2.61	3.64	***
N-CK	2.04	1.20	2.88	***	2.24	1.56	2.92	***	2.77	2.25	3.29	***

Key: DBM = difference between means; CL = confidence limits; N = nitrogen; P = phosphorus; S = sulphur and; CK = Check (without any fertilize); ns = not significant at 95 % CL.

Comparisons significant at 0.01 levels are indicated by ***.

From the Tables 2.3a through 2.5b; and Figs. 2.1, 2.2 and 2.3, it is also shown that in all the studied sites, with the applied N alone, there was a sharp rise in the wheat grain yield curves when compared with other treatments, including at B/Edo, the site that was non-responsive to both S and P. This sharp rise in the grain yield graphs with the applied N indicates that, N is the most limiting nutrient element in the studied areas followed by P as compared with S. This can be attributable to the low SOM content of the soils, vis-à-vis the inherently high mobility of N in the tropical climate and soil conditions. After sharp rises due to applied N, the graphs are still rising whether there was a response to S and/or P or not, indicating an interaction effect between applied nutrients one over the other, to produce a combined effect greater than the sum of their separate effects. In general, with applied N, S and P, there is always wheat grain yield advantage in combined treatments as compared to the preceding treatment, though in some sites the increase was not at an increasing rate (i.e., not statistically significant).

2.4 Conclusions and Recommendations

2.4.1 Conclusions

- The present study revealed that the wheat crop responded well to nitrogen, sulphur and phosphorus nutrients from the applied fertilizers, namely urea, gypsum and triple super phosphate (TSP), as evidenced by the existence of significant response of grain yield and other yield components. The yield responses were found to relate directly to the soil test values, especially for nitrogen and sulphur followed by phosphorus. Also, there observed a positive synergy between applied fertilizers, particularly N and S in increasing yield with each level and kind of fertilizer added, as evidenced by the progressively increasing yield advantage at any given fertilizer level and/or type.

- Furthermore, the yield response correlates well with the soil-test values, especially of N, OC, S and/or P. In the study, all the 18 tested field/sites (100 %) showed highly significant response to applied N, as related to the low soil test TN values in all the tested sites. Similar to N, all the 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 applied S, and there appeared to be a direct relationship to the soil test values.

- In general, there are strong indications that the S response/deficiency which is now observed in the central highlands of Ethiopia can be more widespread, if similar assessments were made across the country, especially far into the out fields.

2.4.2 Recommendations

- Based on the results obtained so far, therefore, it important to integrate sulphur in a balanced fertilizer programs.

- In addition, it is also important to improve SOM to sustainably build the SOC stocks close to critical levels. Improving OM can not only act as the source of essential plant nutrients through mineralization, it can also buffer other plant nutrients to enhance better S synergy, and can also reduce S loss through leaching and/or soil erosion.

- Finally, it is also important to augment inorganic and organic fertilizers with local sulphur sources (e.g., gypsum) to take advantage of their integrative benefits and/or to economize on fertilizer use.

2.5 References

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CHAPTER THREE

3.0 Evaluation of different indices of sulphur availability in soils for wheat (*Triticum aestivum* l.) production in Ethiopia

Abstract

Sulphur deficiency symptoms are not easily identifiable under field conditions particularly in cereals because they are usually mistaken with those of nitrogen. Hence, sulphur availability indicators are necessary for rational sulphur fertilizer use. Eighteen explorative field experiments were conducted in 2012-13 seasons in the Central Highlands (CHLs) of Ethiopia with the purpose of evaluating sulphur deficiency indicators in wheat, with the ultimate aim of setting the critical-thresholds (CTHs). A newly released wheat cultivar, "Kekeba" was used as a test crop. Four treatment combinations, namely: an absolute control (without any fertilizer) or CK = ($N_0P_0S_0$), N alone or N = N_1 = ($N_1P_0S_0$), nitrogen plus sulphur or NS = N_1S_1 = ($N_1P_0S_1$), and nitrogen plus phosphorus plus sulphur or NPS = ($N_1P_1S_1$) were tested in diverse agro-ecological zones (AEZs) and soil types. The evaluated nutrients were two levels of sulphur (0 and 20 kg S/ha), two levels of phosphorus (0 and 20 kg P/ha); and two levels nitrogen (0 and 69 kg N/ha). Sulphur was applied as gypsum, nitrogen as urea and phosphorus was applied as triple super phosphate (TSP). The treatments were arranged in randomized complete block design (RCBD) and replicated three times. From the indices considered in this study, N/S ratio and total S in grain showed better association with S-uptake and/or yield, with the r of -0.84 and 0.86, respectively both significant at $P < 0.001$. However, still the TS in wheat grain showed better sensitivity, whereas N/S ratio was marginal. The CTHs were about 0.12 % for TS, 14.7/1 for N/S ratio in grains, and 11.3 mg/kg for SO_4-S in native soil. In general, the results suggest that plant analysis (in this case wheat grain), found to be a better tool for assessing S supply of soils or wheat crop than the soil analysis. Therefore, this preliminary result could be used as the basis for S research and as a provisional recommendation for wheat growers in Ethiopia.

Keywords: *Sulphur; availability/deficiency indices; total sulphur; N/S ratio;* SO_4*-S and organic carbon.*

3.1 Introduction

For more than two decades, crop production in Ethiopia has increased tremendously, primarily due to the growing food need triggered by the growing population pressure. To maintain soil fertility for sustainable crop production and productivity, however, small holding farmers use intensive cropping systems (crop rotations, mixed cropping and/or intercropping etc) that mainly include legumes and oil crops with cereals. In such traditional agricultural practices, therefore, nutrient uptake and/or removal including that of S can be significantly high, especially when crop residues are removed from fields along with the edible produce. Organic matter (OM) such as crop-residues and farm yard manure (FYM), which are the possible sources of plant nutrients, have many alternative uses like fuel and fodder.

It is widely recognized that sufficient sulphur to meet crop requirements can be obtained from frequent incidental additions of sulphur (S) to soils from ammonium sulphate (AS) and single superphosphate (SSP) as nitrogen (N) and phosphorus (P) fertilizers (Saeed *et al*., 2012). However, the inorganic fertilizer materials available in markets and used solely for crop production in Ethiopia are only urea and di-ammonium phosphate (DAP), high-analysis fertilizers that contain little or no sulphur. This can lead to considerable S mining and depletion from soils, if a corresponding amount is not replenished through fertilizer.

Continuous removal of S from soils through plant uptake without replenishment has led to widespread S deficiency and affected soil S budgets in countries all over the world (Imran *et al*., 2014). Sulphur deficiency can occur, even including the industrialized countries, areas where industrial pollution can contribute substantial amounts of S for plant needs through aerial deposition such as from coal combustion (Echeverr´ıa, 2005; Lal, 2014).

However, under field conditions S deficiency symptoms, particularly in cereals, are not easily identifiable, because they can be confused with those of N and yield losses may occur in crops with marginal deficiency showing no visual symptoms (Zhao *et al*., 1996). Consequently, S availability indicators are needed for making fertilizer recommendations to small-holding farmers, to avoid yield and quality losses due to visible and/or hidden S deficiency.

To diagnose S deficiencies in wheat, methods based on soil and plant analysis including simulations models have been used and/or proposed (Blake-Kalff *et al*., 2001). Some of the candidate indices include organic carbon (OC), TS, organic sulphur, and SO_4-S in soils. Also SO_4^{2-}S, TS content, N/S ratios, sulphate: total S ratio, malate: sulphate ratio, and glutathion in plant or plant parts at various vegetative growth stages including leaves and grains can be used as S indices (Reussi *et al*., 2012b). However, critical values determined for these indices show wide variations depending on stage of plant growth, part of the plant analyzed, experiment conditions (field or greenhouse) and chosen method of analysis, all of which limit their use for routine recommendations (Zhao *et al*., 1996).

For instance, according to Calvo *et al.* (2008), the N/S ratio in plant showed better sensitivity and stability at one distinguishable node and visible flag leaf ligules stages, stages in which S fertilization corrected S deficiencies. Consequently, the N/S ratio has been suggested to be a useful method for S deficiency diagnosis from end of tillering to flag leaf in spring red wheat. But, the same authors reported the lack of sensitivity of N/S ratio in growth stages between two to four tillers. In accordance with this (Reussi *et al*., 2012b) reported that, in appropriate N and S availability conditions, N/S ratio is not stable during periods from the beginning of tillering to the end of stem elongation in wheat, due to a lower S dilution in relation to N, which is related to a lower initial accumulation rate of this nutrient. Regardless of all such disparities (Calvo *et al.*, 2008), however, recommended N/S ratio to be a reliable method to detect S deficiencies in advanced stages of crop cycle for the spring red wheat.

Some of the other proposed indicators, like TS, sulphate and glutathion in wheat share a characteristic lack of stability for their critical values, and thus are not considered to be reliable methods for S deficiency diagnosis in wheat (Blake-Kalff *et al.*, 2001). In line with this, Scherer (2001) made a review of S indices for soils and plants, and concluded that plant tissue analysis was better than soil testing for the prediction of the need for S application and several diagnostic indices have been suggested, but there was no general consensus as to which index gives the best results.

In view of the above research gaps, in the present study the OC, SO_4-S in native soils; and the TS and N/S ratio in wheat grain at harvest as indices of S supply in plants were considered. Therefore, the specific objectives of this work were:

i. To evaluate the relationship of OC and SO_4-S, TS and N/S ratio in wheat grain at harvest with yield or grain S uptake, and
ii. For those different indices found suitable, to set critical levels based on site (the native soil condition or unfertilized plots).

The research questions intended by this study are therefore: a) Is the native soil SO_4-S and/or OC; and grain TS content and N/S ratios best correlated with sulphur uptake?

b) What is the best estimate of critical value for those that were found suitable?

3.2 Materials and Methods

3.2.1 Description of the study areas

Eighteen explorative experiments were conducted in 2012-13 cropping seasons on farmers' fields in the Central Highlands (CHLs) of Ethiopia, representing major wheat growing districts in Arsi, E/Shewa and O/Liyuu zones, or study areas covering different agro-ecological zones (AEZs) and soil types. More description of the study areas can be referred to in chapter 2 (Menna *et al*., 2015). The soil types in the study areas are typically vertisols and nitisols. Some of the relevant physico-chemical properties of soils sampled before planting are presented in chapter 2, (Menna *et al*., 2015).

Briefly, the pH of soils ranged from 5.1, which are more acidic in some sites in O/Liyuu zone, followed by pH near neutral in Arsi to about 8.1 (alkaline) in E/Shewa zone. The calcium orthophosphate $Ca(H_2PO_4)_2$ extractable SO_4-S ranged from 1.30 and 24.18 mg/kg. The total nitrogen (TN), ranged from 0.06 to 0.25 %. The available Olsen P content extracted for E/Shewa zone ranged from 7.55 to 10.99 mg/kg, while Bray-1 P for Arsi and O/Liyuu zones, ranged from 0.22 to 5.12 mg/kg. The OC contents of the soils ranged from 0.90 % to 2.99 % (Menna *et al*., 2015; Chapter two).

A newly released wheat cultivar, "Kekeba" was used as a test crop. Four treatment combinations, namely: an absolute control (without any fertilizer) or CK = ($N_0P_0S_0$), N alone or N = N_1 = ($N_1P_0S_0$), nitrogen plus sulphur or NS = N_1S_1 = ($N_1P_0S_1$), and nitrogen plus phosphorus plus sulphur or NPS = ($N_1P_1S_1$) were tested in diverse AEZs and soil types. The evaluated nutrients were two levels of S (0 and 20 kg/ha), two levels of P (0 and 20 kg/ha); and two levels N (0 and 69 kg/ha). Sulphur was applied as gypsum, nitrogen as urea and phosphorus was applied as TSP. The treatments were arranged in randomized complete block design (RCBD) and replicated three times. A 3 m x 5 m

(= 15 m^2) plot was used and there were four plots per block. There were 12-rows of wheat per plot, two border rows in each side and another one row was used for plant tissue sampling. The remaining net middle rows of a 4 m x 1.5 m (= 6 m^2) were used for agronomic or yield data and seed sample collection. One third of N was incorporated into soils within rows (5 cm depth), just before seeding to enhance its use efficiency. The remaining, 2/3 of the N was top-dressed at the stage of tillering. But, the entire sources of S and P were drilled within rows (5 cm depth) and incorporated into soils just before seeding. The agronomic spacing for wheat between rows and plants used was 25 cm x 5 cm. During the crop's growing stages or just before and after harvest the agronomic parameters such as number of tillers per plant (NTsPP), plant height (PH), spike/panicle length (SL/PL), spike weight (SW), total above ground biomass dry matter yield (TAGB), number of seeds per panicle (NSsPP), grain yield (GY), and stover yield (SY) were recorded.

3.2.2 Collecting shoot and grain samples

Representative plant shoot samples were collected from each plot at booting stage for laboratory analysis. In doing so, wheat shoot tissues were collected by hand picking from the upper 1/3 of each of the 25 plants from a row next to one of the two borders. After sampling wheat tissues were rinsed quickly in distilled water right in the fields and shaken to remove the water and placed in paper bags and air-dried in dust-free rooms. Then, in the laboratory the plant samples were oven dried at 65-70 °C to constant weight at least for 48h. At maturity, harvesting was commenced when average wheat grain moisture content was about 13.5 %. Similarly, grain samples were collected at harvest from each plot and oven dried at 65-70 °C to constant weight at least for 48h. All oven dried samples (plant shoot tissue, grain) were finely ground using Tecator CYCLOTEC-

1093 sample mill and analyzed for total nitrogen (TN) and total sulphur (TS). Then after, the TN/TS ratios and S uptake were calculated.

3.2.3 Analysis of shoot and grain samples

In laboratory, finely ground plant materials (seed/shoot samples) were wet-digested (using 68 % HNO_3-30 % H_2O_2 for TS determination). Then the S was quantified using a spectrophotometer. Whereas, TN was extracted by Kjeldahl wet-digestion method (using conc.H_2SO_4) as described by Okalebo *et al*. (2002) and determined by back titration. The relative yield (RY) of wheat grain was calculated with levels of S as percentage of maximum yield obtained as: RY = [N/(N+1)]*100, as described by (Cate and Nelson, 1965), where: N is check treatment without S, and (N+1) is the next higher level treatment containing S. Finally, the S uptake in wheat grain was calculated as the product of the dry weight of grain by the TS content in grain, then dividing the whole by 100.

3.2.4 Statistical data analysis

Four indices for assessing S supply, namely SO_4-S and OC in native soil; TS and N/S ratio in wheat grain were correlated with S-uptake and slopes were compared through parallelism and coincidence test using PROC REG procedure of the SAS statistical package version 9 (SAS Institute, Cary, NC, USA, 2012). For those indices found suitable on the basis of the correlation and coefficient of determination (R^2), critical levels were determined using the Cate and Nelson method (Cate and Nelson, 1965). The method involves plotting values of a particular index of S status, e.g. TS content in grain against RY. The horizontal and vertical lines were then positioned on scatter diagram to maximize number of points in the positive or negative quadrants depending on the relationships of the respective variables to the RY to obtain the critical values (CVs). This can be verified statistically from the values of total variance (R^2) of observed values with the postulated CVs, where R^2 peaks at the CV. In this set of experiments the CVs were set at a RY of 90 %.

3.3 Results and Discussion

Table 3.1 presents some selected indices of sulphur supply, namely SO_4-S, OC and TN in the native soils sampled just before planting; and TN, TS, N/S ratio and S uptakes in wheat grains at harvest for comparisons. The study areas comprise six districts, namely Tiyo, Hitossa, Gimbichu, Ada'a, Akaki, and Welmera in the Arsi, E/Shewa and Oromia Liyuu zones representing some 18 sites. The sites are representatives of the major wheat growing areas of the Central Highlands of Ethiopia.

Table 3.1: Relative yield of wheat grain and some selected indices of S deficiency in wheat in native soil condition

Study Area/zone	Study District	Site/Farmer Field site	Total N in Grain (%)	Total S in grain (%)	N/S ratio in grain	S uptake in grain (kg/ha)	Grain RY (%)
Arsi	Tiyo	A/Alko	1.637	0.08	19.95	1.09	67.39
Arsi	Tiyo	Dosha	1.657	0.11	15.19	2.04	90.35
Arsi	Tiyo	G/Silingo	1.670	0.09	19.37	1.21	73.42
Arsi	Tiyo	C/Misoma	1.533	0.12	12.46	1.92	96.47
Arsi	Hitossa	B/Edo	1.377	0.13	10.62	1.85	97.21
Arsi	Hitossa	B/Lencha	1.357	0.06	22.12	0.68	61.45
E/Shewa	Gimbichu	C/Donsa	1.963	0.13	15.53	1.50	87.45
E/Shewa	Ada'a	Keteba	1.320	0.07	19.90	0.86	68.55
E/Shewa	Ada'a	Ude	1.683	0.11	16.10	1.03	89.16
E/Shewa	Ada'a	Bekejo	1.447	0.06	23.13	0.88	70.64
E/Shewa	Akaki	Insilale	1.240	0.06	19.12	0.65	67.53
E/Shewa	Akaki	Kilinto	1.563	0.08	20.91	0.78	69.92
O/Liyuu	Welmera	N/Kersa	1.790	0.12	14.98	1.85	87.32
O/Liyuu	Welmera	N/Suba	1.637	0.07	23.05	0.94	71.82
O/Liyuu	Welmera	B/Tokofa	1.493	0.07	23.25	0.75	69.25
O/Liyuu	Welmera	D/Lafto	1.587	0.08	20.25	0.88	79.09
O/Liyuu	Welmera	W/Harbu	1.380	0.12	11.25	1.37	90.08
O/Liyuu	Welmera	T/Harbu	1.403	0.12	11.43	2.19	92.68

3.3.1 Correlation of different sulphur indices with sulphur up-take in wheat grain

The relationship between a response variable, yield or S-uptake in wheat grain and different indices for assessing S status are presented in Table 3.2. Though the indices for evaluating S status in grain and/or native soil contents considered varied widely in their degree of association, all were well correlated with S-uptake. In the association: the total sulphur (TS) in grain > its N/S ratio > SO_4-S in native soil > OC in the native soil, with their coefficients of correlations being 0.86, -0.84, 0.77 and 0.44, respectively (Table 3.2).

Table 3.2: Pearson Correlation Coefficients (r), between S-uptake in wheat grain and different indices of S deficiency in wheat plants and native soil as related to the check treatment (n = 18)

	Site	**Farmer field**	**SO_4-S, (soil)**	**OC, (soil)**	**TN, (soil)**	**TN, (grain)**	**TS, (grain)**	**N/S, (ratio), grain**	**Total S Uptake (grain)**
Site	1.00000	0.00000	0.06135	-0.03656	-0.28725	0.01920	-0.02680	0.07268	-0.11014
		1.0000	0.8089	0.8855	0.2478	0.9397	0.9159	0.7744	0.6635
Farmer field	0.00000	1.00000	0.25918	0.29265	0.08469	-0.68671	-0.11533	-0.13255	-0.10304
	(1.0000)		0.2990	0.2386	0.7383	0.0016	0.6486	0.6001	0.6841
SO_4-S, (soil)	0.06135	0.25918	1.00000	0.62671	0.37945	0.00405	0.86757	-0.94230	0.76378
	(0.8089)	(0.2990)		0.0054	0.1204	0.9873	<.0001	<.0001	0.0002
OC, (soil)	-0.03656	0.29265	0.62671	1.00000	0.60892	-0.26894	0.46977	-0.59705	0.43848
	(0.8855)	(0.2386)	(0.0054)		0.0073	0.2805	0.0492	0.0089	0.0687
TN, (soil)	-0.28725	0.08469	0.37945	0.60892	1.00000	-0.08742	0.35005	-0.43154	0.51562
	(0.2478)	(0.7383)	(0.1204)	(0.0073)		0.7301	0.1544	0.0737	0.0285
TN, (grain)	0.01920	-0.68671	0.00405	-0.26894	-0.08742	1.00000	0.40187	-0.02416	0.25828
	(0.9397)	(0.0016)	(0.9873)	(0.2805)	(0.7301)		0.0983	0.9242	0.3008
TS, (grain)	-0.02680	-0.11533	0.86757	0.46977	0.35005	0.40187	1.00000	-0.91060	0.85547
	(0.9159)	(0.6486)	(<.0001)	(0.04920	(0.1544)	(0.0983)		<.0001	<.0001
N/S, ratio, (grain)	0.07268	-0.13255	-0.94230	-0.59705	-0.43154	-0.02416	-0.91060	1.00000	-0.83767
	(0.7744)	(0.6001)	(<.0001)	(0.0089)	(0.0737)	(0.9242)	(<.0001)		<.0001
Total S uptake	-0.11014	-0.10304	0.76378	0.43848	0.51562	0.25828	0.85547	-0.83767	1.00000
	(0.6635)	(0.6841)	(0.0002)	(0.06870	(0.0285)	(0.3008)	(<.0001)	(<.0001)	

Key: OC = organic carbon; TN = total nitrogen; TS = total sulphur; N/S ratio = total nitrogen and total sulphur ratio; and SO_4-S = sulphate sulphur.

3.3.2 Soil sulphur availability indices

From the results, it is evident that the TS, SO_4-S and OC had direct relationship with S-uptake, whereas N/S ratio had an inverse relationship. From the indices considered, the

TS in grain and N/S ratios were highly significantly correlated P < 0.0001) with S-uptake than SO_4-S and OC in soils. Though had nearly equal degree of association, the TS in grain was more strongly related to S-uptake than N/S ratio based on the criteria set by Finck (1976). The details of the correlation results are discussed in the following sub-sections.

3.3.2.1 Organic carbon (OC)

Organic carbon (OC) is well correlated with S-uptake with the coefficients of correlations ($r = 0.44$ and $P = 0.0687$). But, it had weak degree of association as compared with other indices considered in this study (Table 3.2). Furthermore, its association to S-uptake or yield was not significant at the $P = 0.05$. This weak association of OC to S-uptake can be best explained by the unpredictable quantity of available plant nutrients that can be released through mineralization of OM in relation to the crop's S demand throughout its growth stages.

It is reported that, S in surface soils is usually associated with organic fractions and its supply to crops is largely regulated by organic matter (OM) decomposition. Thus the amount of labile OC is considered to be a good indicator of the amount of available S (Verma *et al*., 2012). It is also widely recognized that OC is not only the indicator of the supply of essential elements like N, P, K and S, but also considered to be one of the key indicators of the overall soil health/quality (Lal, 2014; Lal, 2015). However, controversies exist in setting OC's critical lower threshold for sustained soil functions and in quantifying plant available S that can be supplied to growing plants (Loveland and Webb, 2013). This is because, during the course of all crop growth stages, the process of OM mineralization can be slow and the amount of S released during critical S requiring growth stages of crops may not be sufficient enough to meet the crops S demand.

Moreover, it will be too late to satisfy crops S need from SO_4-S that is coming through late OM mineralization vis-à-vis the early stages of crop growth, a stage where the crop is in greatest S need. In line with this, Scherer (2001) reported the difficulty of predicting the amount of plant available SO_4-S that can come from added organic sources of S, because of the complicated dynamics in the soil environment.

Table 3.3: Mean, STD deviation and the range of variables considered in correlation relationships (n=18)

Variable	N	Mean	STD Dev	Sum	Minimum	Maximum	Range
SO_4-S, (native soil)	18	11.23	7.17	202.19	1.30	24.18	22.88
OC,(native soil)	18	1.60	0.63	28.73	0.90	2.99	2.09
TN,(native soil)	18	0.12	0.05	2.15	0.06	0.25	0.196
TN,(grain)	18	1.54	0.18	27.74	1.24	1.96	0.72
TS,(grain)	18	0.09	0.03	1.68	0.06	0.13	0.07
N/S, ratio (grain)	18	17.70	4.33	318.61	10.62	23.25	12.63
S uptake,(grain)	18	1.25	0.51	22.47	0.65	2.19	1.54

Key: SO_4-S = sulphate sulphur; OC = organic carbon; TN = total nitrogen; TS = total sulphur; N/S = total Nitrogen to total sulphur ratio; STD Dev = standard deviation.

With respect to measuring the exact amount of S and/or other essential plant nutrient elements that can be supplied through OM decomposition, it is likely that, even more controversies can exist under tropical climatic and soil conditions. It is widely reported that, tropical climate and soil conditions have significant influences on the turn-over effects of SOM (Berbeco *et al*., 2012; Leon and Osorio, 2014; and Vanlauwe *et al*., 2012). All these conditions support the relative weak association of OC to S-uptake in wheat grain from the present study. Apart from its unpredictable quantity of plant available nutrients that are released through mineralization, the quantity of OC itself in the studied soils was very low, including TN and available P. This may indicate that the depletion of the SOM, particularly in the tropical soils can have significant effect on soils S status in relation to its relative weaker association to S supply in soil and/or S-uptake as evidenced from this study.

3.3.2.2 Sulphate Sulphur (SO_4-S)

It is widely accepted that SO_4-S in soils can also be the indicator of S supply to crops. In this study, the SO_4-S in native soils was found to be positively related to the S-uptake in wheat grain, with the coefficient of correlation being 0.77 (P = 0.0002) (Table 3.2). Moreover, it had a higher level of significance of association (P = 0.0002) than OC, but to a lesser degree than N/S ratio and TS in grains (Table 3.2). Its level of significance can be explained by the fact that plant available S in soils can be affected by many factors, mainly by erosion and leaching losses before it can be absorbed by plant roots and/or cause of losses other than plant uptake.

Despite its relative better correlation with S-uptake in this study, inconsistencies between soil-test S and crop performances have been reported widely and seasonal effects on the availability of S to plants and the leaching of SO_4-S restrict the usefulness of soil analysis to identify S responsive sites (Robson *et al*., 1995). Similarly, Ghani *et al*. (1991) made a similar observation in that the concentration of inorganic S in soils can vary throughout the year and it is the result of changes and balances between microbial activity, leaching and surface run-off, fertilizer used, plant senescence and atmospheric inputs and crop uptake. Schnug and Haneklaus (1998) share a similar idea in that any analytical value on SO_4-S content of a soil sample to be more or less only for the moment or the time the sample was taken.

In relation to the result of the present study, in the case of S, plant S status is assumed to be a suitable parameter to calibrate different soil-test methods. However, the suitability of any index depends on the degree of correlation to crop yields. In line with this, Finck (1976) reported that a minimum coefficient of correlation of r = 0.84 on field data is required for a reliable method and diagnosis of S deficiency to ensure efficient use of

S fertilizers. Therefore, the obtained relationship (r = 0.77) for SO_4-S is somewhat below this criterion to declare its usefulness.

Most importantly, this critical level approach for native soil $CaCl_2$ and/or $Ca(H_2PO_4)_2$ extractable SO_4-S was questioned by Tandon (1991). According to this author, SO_4-S may not be adequate to assess S supply, as its availability is governed by a number of other soil properties. To overcome this shortcoming in assessing S status the author recommended considering OM of the native soil. By considering the OM content of native soil along with SO_4-S content, Donahue *et al.* (1977) proposed an S availability index. According to this concept, if a soil containing SO_4-S content is just above the critical limit and low in OM content, it cannot be considered as sufficient in available sulphur. This because, since there is less OM to support the inorganic fraction in case of any depletion, as soil S is continuously cycled between inorganic S and organic forms of sulphur (Pasricha and Fox, 1993). Similarly, organic S is also in equilibrium with inorganic counterpart and, if there is any decline in the inorganic SO_4-S level by means of crop uptake or leaching loss, it will be adequately replenished by the organic fraction.

3.3.3 Plant sulphur availability indices

3.3.3.1 N/S ratio in wheat grain

The total N/S ratio in wheat grain was found to be better and inversely related to its yield or S-uptake with high coefficient of correlation ($r = -0.84$, $P < 0.0001$) (Tables 3.2 and 3.3). It is well recognized that the useful tools for the diagnosis of S deficiency are soil as well as plant analysis. Plant S status is assumed to be a suitable parameter to calibrate soil-test methods, and the suitability of any index depends on the degree of correlation to crop yields. Interestingly, the coefficient of correlation for the N/S ratio, though it was slightly marginal was very close to the minimum data set by Finck (1976). As a result, the N/S ratio in grain can be considered as a satisfactory tool for S deficiency in wheat.

Reussi *et al*. (2012b) reported that N/S ratio is not an appropriate diagnostic tool for S deficiency in the early stages of wheat growth. The authors affirmed that in appropriate N and S availability conditions, N/S ratio is not stable during the period going from the beginning of tillering to the end of stem elongation in wheat. They further explained this lack of stability to be due to the lower S dilution in relation to N, which is related to a lower initial accumulation rate of this nutrient. From the report, therefore, it can be assumed that the later stages of wheat plant tissue samplings can give better index of S deficiency, and this is in conformity to the results from the present study. Randall *et al*. (1981) proposed the use of TS and N/S ratio in grain to be satisfactory indicators and tool of S availability for wheat based on the thresholds 0.12 % for TS and 17/1 for the N/S ratios, they determined. But, recently, Reussi *et al*. (2012a) modified these thresholds to be 0.15 % total S and 13.3/1 for N/S ratio.

However, controversial views and arguments emerged regarding the suitability of the N/S ratio and TS in plants as diagnostic tools. According to Scherer (2001), one of the problems using N/S ratio is that a surplus of one of these elements may be interpreted as a deficiency with the other. Another problem with N/S ratio is the fact that S is a rather immobile nutrient in plants and older leaves tend to be higher in S than young leaves, while N is mobile and young leaves tend to have higher N content than old leaves (Pasricha and Fox, 1993). Therefore, the authors argued (by opposing the N/S ratio concept) that it is not correct to assume that N/S ratio is more stable with plant tissue sampled, stage of maturity or plant age as compared with TS or SO_4^{2-}.

In general, from the results obtained in the present study, it can be said that the N/S ratio could be used as a satisfactory index of S status in wheat when grain analysis is considered. This is because, though the value obtained was marginal, it was closely above the minimum criteria set in literature. However, for making complete conclusions and recommendations, it might be necessary to consider all candidates of S indices, by optimizing all factors that might be affecting plant growth and nutrient uptake. This can be done by possibly considering some of the most S deficiency/sufficiency sensitive crops in parallel experiments at field and glass/greenhouse levels.

3.3.3.2 Total sulphur (TS) in wheat grain

The total S in wheat grain was much better related to yield or the S-uptake, with the coefficient of correlations ($r = 0.86$; $P < 0.0001$) than the rest of the variables considered in this study, including the N/S ratio (Tables 3.2 and 3.3). Jones *et al*. (1986) reported that the TS concentration in the above ground plant material or in specific parts is widely used to assess S status of plants. However, different workers reported that critical S concentration depends mainly on the plant species, sampled part of plants, developmental stage and yield level (Schnug and Haneklaus, 1998). To predict the S nutritional status of plants, these authors recommended younger plant parts and sampling during the period of the highest S demand. The best sampling period suggested is from stem extension to the start of flowering, while the generative material is less suited for diagnostic purposes (Gupta, 1976).

Randall *et al*. (1981) proposed the use of TS content followed by N/S ratio in grain to be a reliable indicator and tool of S availability for the wheat crop based on the thresholds they developed (0.12 % for TS and 17/1 for N/S ratio in grains). But these thresholds were recently modified by Reussi *et al*. (2012a) to be 0.15 % for TS and 13.3/1 for the total N/S ratio as suggested to be showing a good indication.

In general, from the above discussions and from the results obtained in this study, it can be said that the plant analysis offered a better tool than soil-testing (SO_4-S and OC) in predicting S deficiency in wheat and/or the studied soils. The most probable explanation could be that as the plant growth advances and the plant matures, possibly at the grain stage, the uniformity of partitioning of the nutrient elements might have reached to completion regardless of its deficiency in native soils. Hence, the stability of both S and N contents at maturity (grain), as they are important and act synergistically for the synthesis of proteins and improve the quality of the harvested produce. Another likely argument can be that at the time of S deficiency, S in plants accumulates in lower part of plant leaving upper/younger parts deficient, while in the case of N the reverse process happens. Therefore, plant sampling from any part in the early or vegetative stage of growth may not be a suitable way to get good balance between N and S to get the required result.

3.3.4 Critical levels for the selected indices

3.3.4.1 N/S ratio in wheat grain

The scatter diagram of relative yield percent and N/S ratios in wheat grain is presented in Fig.3.1. The N/S ratio in wheat grain varied over sites depending on the native soil's S supply (Fig. 3.1). Unlike other variables considered in this study the N/S ratio was inversely related to the relative yield (RY) or native soil's S supply. All the scatter points in the diagram lie in a straight line and nearly all are in negative quadrants indicating that there was no abnormal case in the behaviour of the RY in relation to the soil's S supply. The RY was decreasing when the N/S ratio was increasing and/or the soil's S supply was increasing. The coefficient of determination was R^2 = 82.3 % and the regression equation was Y = -2.449X +122.7. Inal *et al*. (2003) reported similar trends of inverse relationship where they determined that the N/S ratio in grain decreases when S availability increases. The regression line indicates that the maximum relative yield of 90 % was obtained when the N/S ratio was 14.7/1 in the grain, and it was increased to about 23.25/1 as the severity of S deficiency increased. This critical value for the N/S ratio (14.7/1) can now be used to separate the sulphur responsive sites or treatments from non-responsive ones.

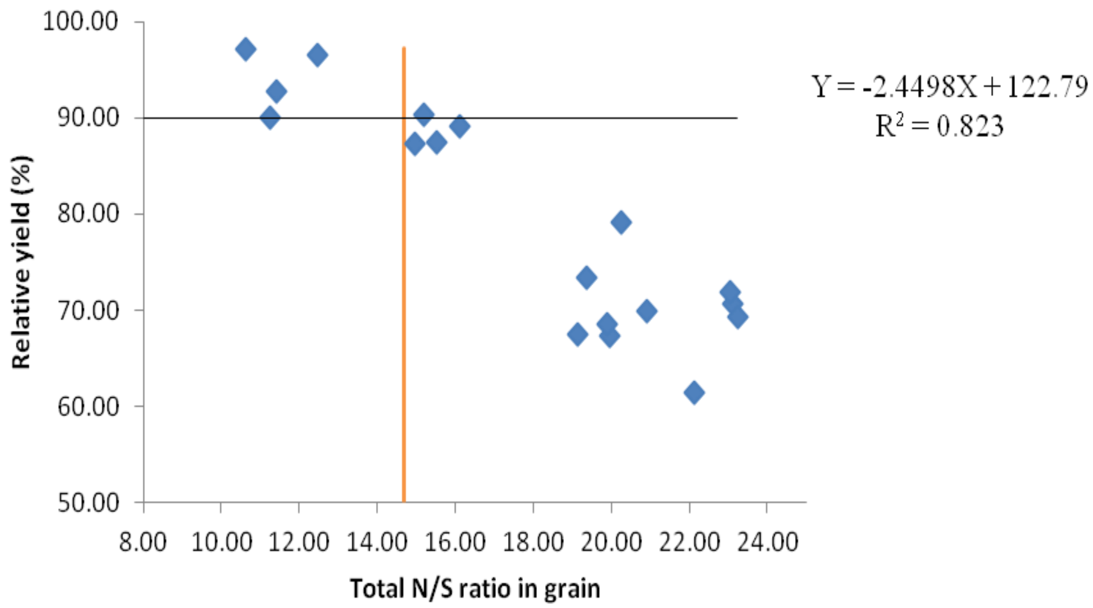

Figure 3.1: Relationship between relative yield and N/S ratio in wheat grain for the unfertilized treatments.

Regarding the N/S ratio as an indicator of S deficiency analysis in wheat, a wide range of values and critical thresholds have been reported in literature. Zhao *et al*. (1999) reported N/S ratio values of wheat grains of less than 10 to greater than 20. Similarly, with respect to critical N/S ratio in grains of wheat, different values were reported by other authors, but were comparable to that obtained in the present study.

For instance, though the N/S ratio obtained in the present study (14.7/1) is lower than (17/1) that determined by Randall *et al*. (1981), it is comparable to that reported by Bergmann (1992), which was 14.8/1. Reussi *et al*. (2012a) reported a critical N/S ratio value of 13.3/1. Though, this ratio (13.3/1) is lower than the one determined by Randall *et al*. (1981), but it is close to (14.8/1) that determined by Bergmann (1992), which was 14.8/1.

In the diagram, the horizontal line depicts 90 % maximum grain yield and the vertical line depicts N/S ratio threshold. Regarding the suitability of N/S ratio as an indicator of S deficiency in wheat different views have emerged. For instance, Blake-Kalff *et al*. (2001) questioned the usefulness of the N/S ratio concept as it reflects the relative proportions of N and S, rather than the actual magnitude of either nutrient. According to these authors, a low N/S ratio suggests S sufficiency when both nutrients might be deficient, whereas a high N/S ratio might mean excessive N instead S deficiency. Furthermore, TS concentration is less sensitive to S availability variations in soil in relation to plant sulphate levels at the early stages of growth (Blake-Kalff *et al*., 2000), all of which would limit the use of N/S ratio for that stage. However, in a four year experiment carried out in England, Blake-Kalff *et al*. (2004) determined that about 78 % of the samples were accurately diagnosed using N/S ratio in plant material. Continued in opposing the ideas, the same authors reported that, in wheat grain 'protein', the ratio of N/S was not constant with increasing sulphur supply and thus there was no fixed N/S ratio, which could be used as a reference value for determining the sulphur status of grain. Consequently, as a final remark, they suggested that the critical value of N/S ratio be determined empirically.

However, as a conclusion from the present study though marginal based on the minimal criteria set in literature, the N/S ratio in the wheat grain was found to be a satisfactory index of S deficiency/sufficiency in the soils of the study areas for wheat production. As a result, wheat grain from S responsive soils can be distinguished from unresponsive ones in which case much S response is expected for soils or sites with the N/S ratio above 14.7/1.

3.3.4.2 Total sulphur (TS) in wheat grains

The scatter diagram of relative yield percent and total sulphur contents in grain are shown in Fig. 3.2. The relative yield is always increasing with TS and/or native soil's S supply, with the regression equation of Y = 427.3X + 39.63. All the scatter points in the diagram lie in a straight line and nearly all are in positive quadrants, which mean that there was no abnormal case in the behaviour of RY in relation to the soil's S supply. In the diagram, the critical level of total S in wheat grain was estimated to be 0.118 %. In general, as compared to the other variables considered in the present study, the TS content in the grain with a coefficient of determination R^2 = 89.3 % was found to be a better index of S deficiency based on the criteria set in literature (Finck, 1976). Gyori (2005) determined a critical concentration of TS in grain of about, 0.15 %. However, this value is higher than, the 0.12 %, that reported by Randall *et al*. (1981), but equals to that reported by Reussi *et al*. (2012a). Randall *et al*. (1981) reported that the onset of S deficiency in the glasshouse experiment was earlier and the magnitude of response to added S was considerably greater than that encountered in the field. The yields at 90 % of maximum corresponded to grain TS values of 0.11 % for "Olympic" wheat cultivar, and 0.12 % for "Teal" and "Condor" cultivars, indicating that the critical level was varied with cultivar. Randall *et al*. (1981) thus recommended that the grain analysis can be used to diagnose, retrospectively, the S status of plants from which that grain came from. It was suggested that the information derived can be used to decide fertilizer applications to the succeeding crop.

Randall *et al*. (1981) reported that, the critical grain TS value for yield was 0.12 % in treatments adequately supplied with N, but plots with low N (S-unresponsive) had grain TS values < 0.12 % showing the important synergy between N and S in determining not only the yield and quality of wheat, but also estimating the critical TS value in grain. In a similar field experiment, Moss *et al*. (1981) reported that, the relative proportion of the albumins in the extracted protein falling sharply at flour S values below 0.11 %, but only in material well supplied with N. And this value for flour corresponds to a grain TS content of 0.125 %, nearly close to the value reported by Randall *et al.* (1981) to be the critical value for grain TS when fertilizer treatments deficient in N were excluded. The same authors made an analysis of grain from fresh harvests having shown that samples from a number of areas in Australia have TS content at or below 0.12 % and suggested them to be deficient in sulphur for increased yield.

In the (Fig. 3.2), the horizontal line depicts 90 % maximum grain yield and the vertical line depicts N/S ratio threshold. From the discussion so far and the results thus obtained, therefore, it is important to note that, the TS content of wheat grain is found to be a better candidate as a diagnostic tool from this study, and the critical level of TS in grain, 0.118 %, could be used as a provisional recommendation for wheat production in Ethiopia (Fig.3.2).

As the critical level determined by Cate and Nelson procedure (1965) divides only the low and high levels, it is important to note that the marginal/medium levels of TS in wheat grain can stretch up to 0.125 % or even higher.

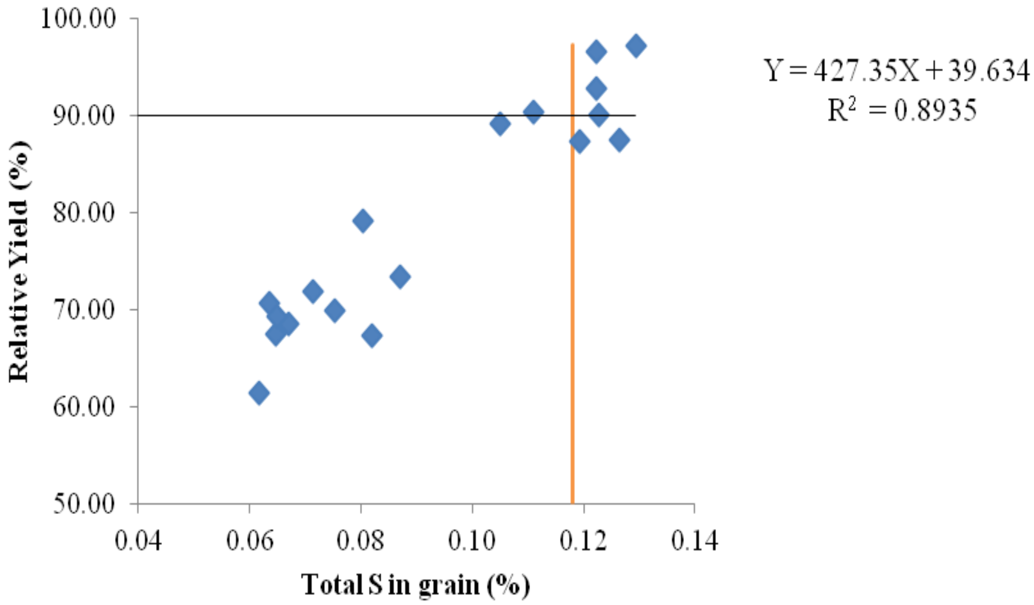

Figure 3.2: Relationship between relative yield and total S in wheat grain for the unfertilized treatments.

However, these slight variations in the total S contents in grains as reported by different authors and that obtained from the present study can be attributed by varietal differences, the differences in methods of extraction and/or the experimental conditions or other.

3.3.4.3 Sulphate sulphur (SO_4-S) in soils

It is worth mentioning that, soil testing before planting in advance is critically important for monitoring soil nutrients and fertilizer budgeting. The scatter diagram of RY percent and SO_4-S contents in native soils are presented in Fig.3.3. In the diagram, the critical level of SO_4-S was estimated to be about 11.30 mg/kg with a coefficient of determination R^2 = 77.0 %. But, it is evident that the SO_4-S was an inferior index of S supply based on minimum criteria set by Finck (1976). Furthermore, the coefficient of determination was lower than those for N/S ratio and TS in wheat grain.

The SO_4-S concentration in the studied soils ranged between 1.30 mg/kg and 24.18 mg/kg. Based on the critical level determined in the present study, about 66.7 % of the studied soils are below this critical level. However, as the critical level determined by Cate and Nelson procedure divides only the low and high levels, it is important to note that the medium/marginal levels can stretch up some levels above 11.30 mg/kg or even higher. This implies that the percentage of S deficient sites/soils can be higher than 66.7 %. Considering this medium/marginal level approach and the critical limit 10-13 mg/kg SO_4-S proposed by Tandon (1991), over 70 % of the studied soils can be regarded as sulphur limiting, specifically for wheat production in Ethiopia.

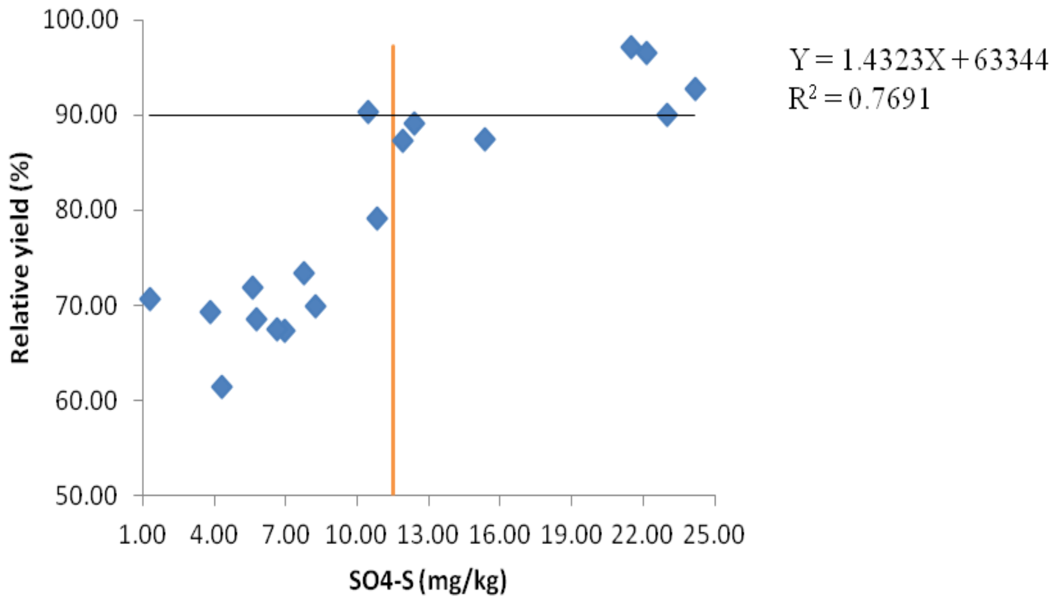

Figure 3.3: Relationship between relative yield and SO4-S in native soil condition.

In the (Fig. 3.3), the horizontal line depicts 90 % maximum grain yield and the vertical line depicts SO_4-S ratio threshold. Though the SO_4-S was found to be not a good index, the RY is always increasing with the native soil's S supply, with the regression equation of Y = 1.432X + 63.34.

Similar to the other indices considered in this study, all the scatter diagram points lie in a straight line and nearly all are in positive quadrants, which means that there was no much abnormal case in the behaviour of RY in relation to the soil's S supply.

In general, the obtained result is slightly higher than the critical level, 10 mg/kg $CaCl_2$ extractable SO_4^{-2}-S, as a critical limit of S deficiency for most crop species reported by Srinivasarao *et al.* (2004), but within the range of 10-13 mg/kg SO_4-S, determined Tandon (1991), which is now commonly being reported for cereals (e.g., wheat, maize, etc). Therefore, this critical level of SO_4-S for the native soil can be used routinely to make provisional fertilizer recommendations as a soil-test based fertilizer recommendation for the wheat growing farmers.

3.4 Conclusions and Recommendations

3.4.1 Conclusions

- From the present study, it is learnt that the plant analysis, total sulphur and N/S ratio in grain, offered better sensitivity of S supply for wheat plant than the soil variables, i.e. SO_4-S and the organic carbon. Within the plant variables, also the total sulphur in grain was still found to be a better index or tool in predicting S status in wheat plants than the N/S ratios.

- The critical level for the total sulphur in wheat grain was 0.118 % and that of the N/S ratio was 14.7/1, whereas, that of the SO_4-S in the native soils was 11.3 mg/kg. Hence, wheat grain from S responsive sites/soils and/or treatments can be distinguished from those unresponsive ones in which case much response is expected for sites or treatments with TS less than 0.118 %; N/S ratio greater than 14.7/1; and native soils SO_4-S below 11.3 mg/kg.

3.4.2 Recommendations

- In general, the critical levels obtained for the different variables were in close agreement with those reported by other workers, but standardizing the values as well as setting the best index of S supply may need further investigations. It is also important to note that, the indices of S availability considered in this study as well as the various candidate indices proposed by various other workers have comparative usefulness or advantage and, therefore, much should be done to locate the most suitable indicator for wheat and/or other crops in Ethiopia.

- In summary, therefore, as this critical level approach is the first work in cereals in Ethiopia (only one cultivar considered), the obtained preliminary results could be used as the basis for further sulphur research and could be used as provisional recommendation for wheat growers in the country.

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CHAPTER FOUR

4.0 Estimation of optimum rate of sulphur for application in soils for wheat production in Ethiopia

Abstract

Six on-farm experiments were conducted in 2013-14 cropping seasons, representing major wheat growing areas in the Central Highlands (CHLs) of Ethiopia. Three study sites, namely G/Silingo, Keteba and N/Suba were selected based on previous season's wheat response to S and soil-test results. The rest, W/Gora, Bekejo and B/Tokofa sites were randomly selected new sites on areas some miles (0.5 to 3.0 km) away from last season's S responsive sites, without pre-soil testing to further evaluate wheat response to applied S. The wheat cultivar, "Kekeba", was used as a test crop. The fertilizer elements were applied in nine treatments combinations as: absolute control, CK (without any fertilizer), nitrogen alone or N, nitrogen and sulphur or NS_1, NS_2, NS_3, nitrogen and phosphorus or NP, NPS_1, NPS_2 and NPS_3. The elements used were four levels of S (S_0 = 0 = CK, S_1 = 5, S_2 = 10 and S_3 = 20 kg S/ha); two levels of N (N_0 = 0 = CK, N = 69 kg N/ha); and two levels of P (P_0 = 0 = CK and P = 20 kg P/ha) as gypsum, urea and TSP respectively. The experimental design used was randomized complete block (RCBD), and it was replicated three times. The results showed that the grain, total above ground biomass (TAGB) dry matter yield and number of tillers per plant (NTsPP) of wheat showed highly significant response ($P < 0.001$) among treatments with applied N, S, and P individually or in combinations. In the study, it is shown that G/Silingo, Keteba and N/Suba sites showed highly significant response to applied fertilizers, especially S at all levels. From the other sites only Bekejo showed highly significant response to N, S and P. W/Gora and B/Tokofa sites showed marginal response, especially for the target element S at a critical level of lower concentration, 5-10 kg S/ha. In trying to make optimum S rate for wheat, it was learnt that the response to applied S was varied over sites and/or soil conditions. From the S response and/or soil-test values, therefore, sites like Keteba, Bekejo and N/Suba sites can be categorizes as very low; G/Silingo to be medium/marginal; whereas W/Gora and B/Tokofa can be grouped under sites adequate for plant available SO_4-S. Based on this, therefore, site/soil specific S recommendations were made. In this respect, in Keteba, Bekejo and N/Suba sites optimum S rate can be slightly higher than 20 kg/ha, for initial soils tested very low in S. Moreover, since the nutrient response curve, for the moment farmers can be advised to apply 20 kg S/ha together with the recommended full dose of N and P. At G/Silingo, since the initial soil-tested marginal for SO_4-S, applying S at a rate of 20 kg/ha with the recommended dose of N and P is advisable. Whereas at the W/Gora and B/Tokofa, since the initial soils tested adequate for SO_4-S, but wheat showed response to S at lower level, because of the observed yield response at the lower levels applying S at a rate of 5-10 kg/ha is reasonable. In general, because, in all the studied sites, maximum attainable potential wheat yield ceiling, about 8.0-8.5 t/ha was not achieved, it is important to make further investigations by controlling all other factors of production.

***Keywords**: Wheat cultivar, sulphur deficiency, optimum S rate, gypsum and triple super phosphate.*

4.1 Introduction

Globally, wheat (*Triticum aestivum* L.) is considered as the king of cereals and the nature’s unique gift to mankind as it produces excellent source of nutrition in terms of carbohydrates, minerals and proteins (Saeed *et al*., 2011; Inamullah and Ali, 2014). Wheat is one of the major cereals produced in Ethiopia, widely adapted to diverse soil conditions and agro-ecological zone (AEZs) ranging from less than 1500 to 3200 m above sea level. Because of this wide range of adaptations, given the major resource base, the soil together with its water resources 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 conditions, farmers hardly obtain wheat grain yield above 1.0 t/ha (personal observation from unpublished data). It is apparent that, this low yield is due to low soil fertility and/or nutrient depletion as a result of continuous cultivation without replenishment. From this survey it was also found out that all the farmers in the studied areas practice free grazing on farm fields after crop harvest until the next season land preparation. Grazing cattle, however, may actually mine nutrients from outfields and bring to areas directly around villages, if the cattle are kept overnight at the homestead. The farm yard manure (FYM), which is the by-product of livestock feed, is used as fuel and/or organic fertilizer only in homestead fields, leaving outfields without organic matter (OM), the potential source of plant nutrients N, P, K and S. This will adversely affect the nutrient balance and/or the next season crop yields and their quality. Sanchez *et al*. (1997) reported that soil nutrient depletion under smallholder farmers' condition is the fundamental root cause for declining per capital food production in sub-Saharan Africa.

The quantity of nutrients removed by a crop is a good index of fertilizer needs. However, the efficiency with which a nutrient is taken up is considered to vary with soil, plant type, weather conditions and other losses (leaching, immobilization, de-nitrification, fixation and volatilization etc) from the soil system. Hence, fertilizer addition to soils must be calculated to replace all those losses. Moreover, the significance of nutrients like sulphur should not be weighed only in terms of quantity of harvested produce, but also on its nutritional quality. Sulphur is now recognized as the fourth major element in balanced plant nutrient management programs, next to N, P and K. Currently, S is recognized as one of the most limiting element in wheat production, second only to N in importance (Lutcher *et al*., 2005). It is best known for its role in the synthesis of proteins, oils, vitamins and flavoured compounds in plants. Three amino acids, namely methionine (21 % S), cysteine (26 % S) and cystine (27 % S) contain S, which are the building blocks of proteins that impact nutritional value of human food and animal feeds (Chattopaddhyay and Ghosh, 2012). About 90 % of sulphur is present in these amino acids (Tandon and Messick, 2002).

It is frequently being reported that without adequate S, crops cannot reach their full potential in terms of yield and quality aspects; nor can they make efficient use of applied N (Sahota, 2006). From this, it is clear that protein rich cereals like wheat are likely to suffer from hidden S deficiency. It is a macro-nutrient element, whose deficiency is reported to reduce yield significantly, (Lošák *et al*., 2012) and changes the quality of wheat (Steinfurth *et al*., 2012). However, wheat requires only modest amounts of S, about 15-35 kg/ha (Zörb *et al*., 2013; Zhao *et al*., 1999b) for optimum growth.

From 18 explorative on-farm experiments conducted in 2012-13 in a wide range of AEZs and soil types, it was found out that over 72 % of the sites have shown either highly significant or marginal response to the applied S (Menna *et al*., 2015). It is evident that fertilizer requirements of crop plants should be on the basis of soil-test and/or crop responses. The objective(s) of this study were therefore:

i. To further evaluate the response of wheat to applied N, S and P, and;
ii. To determine the optimum sulphur rate for wheat production in the study areas.

The possible questions intended by this set of experiment are therefore: a) Does the application of sulphur increase yield and yield components of wheat, and if so, b) What is the optimum application rate for S?

4.2 Materials and Methods

4.2.1 Description of the study areas

Six on farm experiments were conducted in 2013-14 season in the central highlands of Ethiopia (CHLs) of Ethiopia, representing major wheat growing area in Arsi, E/Shewa and O/Liyuu zones, covering different soil types and AEZs. Three study sites, namely G/Silingo, Keteba and N/Suba were selected based on pre-soil test results and previous season wheat crop responses, which were highly responsive to applied N, S and P in the first season. Furthermore, the sites were tested to be very low in calcium orthophosphate $Ca(H_2PO_4)_2$ extractable SO_4-S as an additional criterion for selecting the sites (Menna *et al*., 2015). Whereas W/Gora, Bekejo and B/Tokofa were selected on areas, some miles (0.5 to 3.0 km) away from the last season's S responsive sites, namely Dosha, Bekejo and B/Tokofa, respectively to further evaluate wheat response to S in randomly selected sites and also to capture soil diversity, without pre-soil testing. All selected sites were geo-referenced using Global Positioning System (GPS) assisted by Google Earth (2011) and were classified by elevation, size and/or soil type.

Additional details about the study areas and soil types are found in chapter 2 and Menna *et al*. (2015). In Arsi zone, the upper soil layer consists of tephritic materials, whereas the substratum consists of calcareous material enriched through secondary precipitation over the bedrock. In the E/Shewa zone (Debre Zeit areas), dominant soil types in this study area are vertisols. In O/Liyuu zone, Welmera district, the major soil types of the area are nitosols and vertisols.

4.2.2 Experimental treatments and design

In 2013-14 cropping season, the test crop used was also the wheat cultivar known as "Kekeba". The nutrient elements tested were combined in nine treatments namely: an absolute control, CK (without any fertilizer) = ($N_0P_0S_0$); nitrogen alone or N = N_1 = ($N_1P_0S_0$); nitrogen and sulphur or NS_1 = ($N_1P_0S_1$); nitrogen and sulphur or NS_2 = ($N_1P_0S_2$); nitrogen and sulphur or NS_3 = ($N_1P_0S_3$); nitrogen and phosphorus or NP = N_1P_1 = ($N_1P_1S_0$); nitrogen, phosphorus and sulphur or NPS_1 = ($N_1P_1S_1$); nitrogen, phosphorus and sulphur or NPS_2 = ($N_1P_1S_2$); and nitrogen, phosphorus and sulphur or NPS_3 = ($N_1P_1S_3$) were tested in Arsi, East Shewa and Oromia Liyuu zones covering diverse AEZs and soil types. In this set of experiments, the fertilizer rates used were four levels of sulphur (S) (S_0 = 0 = CK, S_1 = 5, S_2 = 10 and S_3 = 20 kg S/ha); two levels of nitrogen (N) (N_0 = 0 = CK, N = 69 kg N/ha); and two levels of phosphorus (P) (P_0 = 0 = CK and P = 20 kg P/ha), whereby the fertilizer sources were S as gypsum, N as urea and P as TSP. The experimental design used was the randomized complete block (RCBD) with three replications. Each replication was sub-divided into a 3 m x 5 m (= 15 m^2) experimental units or plots and there were four experimental units or plots per block.

The agronomic spacing for wheat between rows and plants, 25 cm x 5 cm (175 kg/ha seed rate) was used. There were a total of 12 rows of wheat plants per plot. There were two border rows in each side and another one row (a 25 cm x 5 cm size) was used for plant tissue sampling. The remaining centre rows (a 4 m x 1.5 m = 6 m^2 net plot) were used for agronomic/yield data and seed sample collection. Whenever necessary, hand weeding was used to control weeds as required. One third of N was incorporated into the soils within rows just before seeding to enhance its early use efficiency, whereas the remaining 2/3 was top dressed at the stage of tillering. But, the entire sources of S and P were drilled within rows and incorporated into soils just before seeding. During the crop's growth cycle, a number of agronomic parameters as number of tillers per plant (NTsPP), plant height (PH), spike/panicle length (SL/PL), spike/panicle weight (SW/PW), total above ground biomass (TAGB) dry matter yield, grain yield (GY) and stover yield (SY) and number of seeds per panicle (NSsPP) were recorded.

4.2.3 Soil sampling and analysis

Just before planting, composite soil samples representing each block, from 10 spots, of 0-20cm depth were taken and bulked together for analysis. Then the soils were air dried immediately in dry rooms to avoid sulphate formation from OM decomposition in transit. The dried soil samples were ground and sieved through a < 2 mm sieve and analyzed for pH, OC, EC, TN, available PO_4-P, available SO_4-S, soil texture, exchangeable bases (Na, K, Ca and Mg), CEC and PBS as per method summarized in Table 4.1. The micro-nutrient elements analyzed were Fe, Mn, Cu and Zn. The selected soil physico-chemical properties were analyzed in the Department of Soil Science (DSS) laboratory at the Sokoine University of Agriculture (SUA), Morogoro, Tanzania, using the methods shown in Table 4.1. The details of procedures are found in Chapter 2 (Menna *et al*., 2015) above**.**

Table 4.1: Analytical methods of some selected soil parameters 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	Van Reeuwijk(2002)
EC	mS/cm	1:5 soil: water suspension	Klute (1986)
Exch. Bases	Cmol(+)/kg	1 *M* NH4OAc solution at pH =7.00	Van Reeuwijk (2002)
CEC	Cmol(+)/kg	1 *M* NH4OAc solution at pH =7.00	Van Reeuwijk (2002)
PBS	%	Calculation from exch. Bases	Van Reeuwijk (2002)
TN	%	Kjeldlehl as described in	Okalebo *et al*., (2002)
OC	%	Walkley-Black as described in	(Nelson and Sommers 1996)
Av. P	mg/kg	Bray 1 and Olsen	Bray and Kurtz. (1945); Olsen,*et al.* (1954)
SO_4-S	mg/kg	Calcium orthophosphate, Turbidimetric	Rowell (1994)
Soil texture	% (sand, silt & clay)	Hydrometer method	Bouyoucos (1962)

Key: EC = Electrical conductivity; Exch. = Exchangeable; CEC = Cation exchange capacity; PBS = Percent base saturation; TN = total nitrogen; OC = organic carbon; Av.P = Available phosphorus; SO_4-S = sulphate sulphur.

4.2.4 Statistical Data Analysis

Yield data were analyzed using SAS statistical package version 9 (SAS Inst, Cary, NC, USA, 2012). Similarly, the PROC UNIVARIATE procedure in SAS was used to test the normality assumptions of evaluated variables, besides analyzing residual distribution. In this set of experiments, the analysis of variance was done using PROC MIXED procedure in the SAS program protocols to evaluate differences between treatments or variables evaluated. The SAS linear model statement for analysis of RCBD considers replications and treatments as fixed effects. When differences between treatments on yield were significant, the least significant difference (LSD) test was used to separate the means, with a significant level of 5 %, 1 % and 0.1 % probability levels. This was done through the GLM procedure. Some variables like yield and yield 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 using the SAS contrast statements were performed to determine the significance of treatments at each level and to determine the effect of S as an impurity from TSP on wheat yield. The analysis of variance (ANOVA) was performed to evaluate the effects of treatments (N, S and P rates) on yield and yield components of the wheat.

4.3 Results and Discussion

4.3.1 Some physico-chemical properties of the soils of study sites before planting

Some physico-chemical properties of soils of the study sites before planting are presented in Table 4.2. Soil pH ranged from acidic in some sites of O/Liyuu zone, Welmera district, followed by pH near neutral in Arsi to higher pH (calcareous with visible fragments of $CaCO_3$) in E/Shewa zone, Keteba and partly at Bekejo sites.

Extractable SO_4-S ranged from 4.03 mg/kg to 35.83 mg/kg. Based on the10-13 mg/kg $CaCl_2$ extractable SO_4^{-2}-S as a critical limit of S deficiency for most crop species (Tandon, 1991) and Srinivasarao *et al.* (2004), 66.7 % of the studied sites were found be sulphur deficient. But, two sites (W/Gora and B/Tokofa) were found to be adequate for plant available sulphur (Table 4.2).

The total nitrogen (TN) content, which ranged from 0.05 to 0.21 %, falls within the range considered to be very low to low, based on the criteria developed by Thiagalingam (2000) for tropical soils. This signifies that, the Ethiopian agricultural soils are inherently low in plant available nitrogen, which will significantly be affecting the sustainability of crop production, and thereby negatively affecting food security. The indirect effects the low plant available nitrogen can be through the synergetic beneficial effects that are expected from the applied sulphur. In chapter 2, Menna *et al*. (2015) reported similar alarmingly low levels of total soil nitrogen in annually cropped agricultural lands in Ethiopia. Therefore, the fertilizer nitrogen management should be among the top priority agendas of the plant nutrient management strategies for sustaining crop production.

The available phosphorus (Av. P) content extracted by Olsen *et al*. (1954) for the E/Shewa zone ranged from 9.02 mg/kg to 12.01 mg/kg, which falls within the range considered to be low to marginal based on the criterion developed by Thiagalingam (2000) and Horneck *et al*. (2011). Similarly, for the soils sampled from Arsi and O/Liyuu zones, the Bray-1 P values ranged from 0.50 to 3.01 mg/kg, which were very low based on the criteria developed by Horneck *et al*. (2011). According to Landon (1991), in such low P soils, fertilizer responses are most likely expected.

Table 4.2: Some physico-chemical properties of the soils in the study areas (W/Gora, G/Silingo, Keteba, Bekejo, N/Suba and B/Tokofa) cultivated for wheat

Study Area (Zone)	District	Farmer Field	Soil Type	pH (1:2.5), Soil:H_2O	EC (mS/cm)	Exchangeable Bases (Cmol(+)/kg) Ca^{2+}	Mg^{2+}	Na^{+}	K^{+}	CEC (Cmol(+)/kg)	PBS (%)	TN (%)	OC (%)	Av.P (mg/kg)	SO_4-S (mg/kg)	Soil Textural Class
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

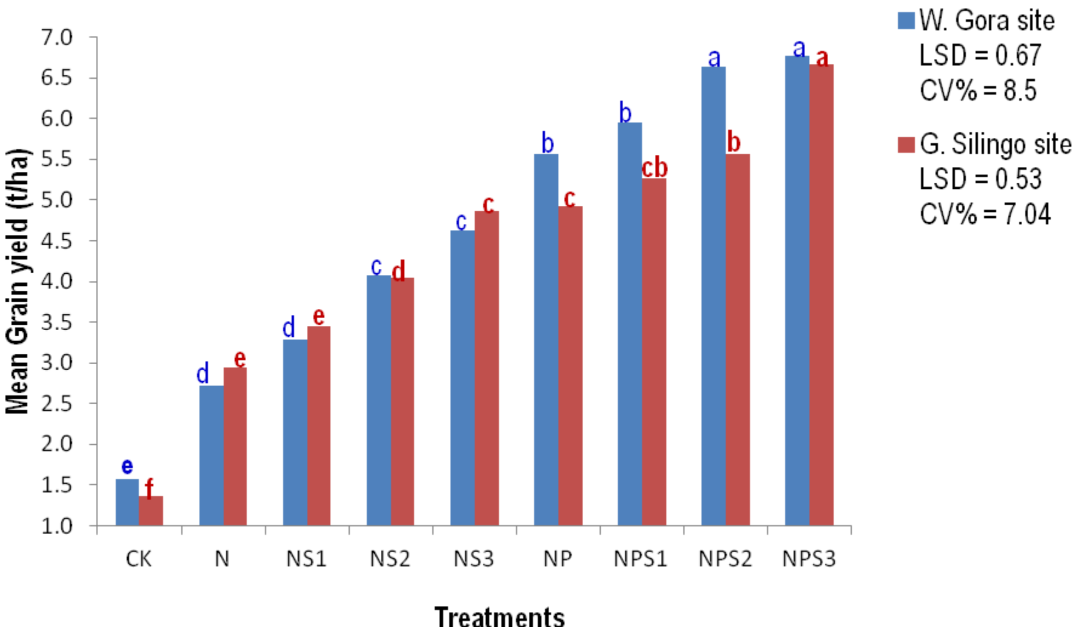
Key: Study Areas (Ar = Arsi, ES = East Shewa, OL = Oromia Liyuu); Districts (Ti = Tiyo, Ad = Ada'a, and We = Welmera); Farmer fields (WG = Wonji Gora, GS = Gora Silingo, Ke = Keteba, Bk = Bekejo, NS = Nano Suba, BT = Befeta Tokofa,); Soil Types (CV = Chromic Vertisol, Ni = Nitisol, PV = Pellic Vertisol); and Soil Texture (C = Clay, SC = Sandy clay, and CL = Clay loam). Av P (for pH > 7.0, by Olsen; and for pH < 7.0, by Bray-1 method used). The soils are classified as vertisols (E/Shewa, B/Tokofa, W/Gora) and nitosols (N/Suba) and (for G/Silingo) (Can also be referred to chapter 2, Menna *et al*., 2015).

The organic carbon (OC) contents of soils ranged from 0.96 % to 2.71 % (Table 4.2), which falls in the range considered to be very low to low/marginal based on the criteria developed by Thiagalingam (2000). Most importantly, the OC contents of most studied soils were far below the critical threshold of 2 %, suggested by various workers (Horneck *et al*., 2011; Patrick *et al*., 2013) for sustaining soil health/quality, below which soil structural stability will suffer a significant decline.

It is well recognized that OC/OM is key to sustainable agriculture, contributes significantly to C, S, N, P and K and other essential plant nutrients and to other soil functions. The OC content of the soils in equilibrium with vegetation is a function of annual additions and decomposition of OM. As a result, under low external input farming systems, the nutrient status of soils will decrease, and any agronomic practice that has impact on OM can bring changes in soil fertility, particularly OC, N, P, K and S. According to Bloem (1998), up to 98 % of the total soil sulphur may be present as organic S compounds, and is associated with a heterogeneous mixture of plant residues, animals and soil microorganisms. Also, the profile of organic S concentration generally reported to follow the pattern of OM concentration in soils with depth (Probert, 1980). Based on this, therefore, it is not surprising that the studied soils can be deficient in N, S and P. In the present study, it is observed that in all the studied areas, even during crop growing periods, there is continuous removal of plant biomass in the form of weeds 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 are especially common in Ethiopia and in the fields of cereals such as maize, teff, wheat, sorghum and finger millet. Soil fertility is a major concern in Ethiopia and hence, high and sustainable crop yields can be obtained with judicious and balanced use of inorganic fertilizer combined with organic resources.

4.3.2 Wheat yield and yield components as affected by nitrogen, sulphur and phosphorus

Table 4.3 and Fig.4.1 present the response of wheat grain, total above ground biomass (TAGB) dry matter yield, and number of tillers per plant (NTsPP) of wheat at Arsi zone (W/Gora and G/Silingo sites) as affected by N, S and P nutrition. The grain yield, TAGB yield and NTsPP responded highly significantly to N, S and P ($P < 0.001$) application both individually or in combinations.



Key: CK = absolute control or without any fertilizer; N = nitrogen only; NS_1= nitrogen and sulphur; NS_2 = nitrogen and sulphur; NS_3 = nitrogen and sulphur; NP = nitrogen and phosphorus; NPS_1 = nitrogen, phosphorus and sulphur; NPS_2 = nitrogen, phosphorus and sulphur; and NPS_3 = nitrogen, phosphorus and sulphur. Where N was applied at 69 kg/ha; phosphorus at 20 kg/ha; S_1 (sulphur applied at 5 kg/ha), S_2 (sulphur applied at 10 kg/ha) and S_3 (sulphur applied at 20 kg/ha).

Figure 4.1: Wheat grain yield at Arsi zone (W/Gora and G/Silingo sites) in response to applied N, S and P nutrients.

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

There is a progressive increase in yield advantage due to the applied fertilizers at all treatment levels in both fields in the parameter considered. At the W/Gora site with heavy black clays, vertisols, there was significant N and P response. Moreover, there was response to S at the intermediate rate (i.e., 10 kg S/ha), though the initial soils tested adequate for the SO_4-S in this site. Regardless of the adequate S before planting, the yield response at this site might be due to the fact that the plant available S might have been lost, probably through leaching before it could be absorbed by the growing plants, and/or affected by factors other than plant uptake. Therefore, despite its initial soil test values, the (W/Gora) site may need the application of some supplemental amount of S at 5-10 kg/ha.

But, at G/Silingo site, there was yield response due to applied N and S at all treatment levels, except for the S that might be expected to come from TSP, which can be seen by looking at the wheat yield levels between treatments (NPS_3-NS_3) (Fig. 4.1 and Table 4.3). There is wheat yield response between these two treatments. But, the grain yield response at this stage can also be attributable to the applied P, because there was P response at this site, which can be seen by looking at the wheat grain yield response between the treatments (N and NP). Also, these sites were tested low in available P (Table 4.2), and the suggested amount of S, 2-6 % (Weil and Mughogho, 2000) from TSP might not be adequate to bring a yield change. This third reason can be noticeable from the lower level treatments between N and NS_1, as there was no yield response due to applied S at 5 kg/ha. But, the higher level S treatments above 5 kg/ha, showed significant yield response throughout, particularly for G/Silingo site, which suggests the better positive synergy between the applied fertilizers.

In G/Silingo site, in general, it is observed that there is better correlation of wheat yield with the soil test values (particularly for N and S), than at the W/Gora. But, the overall wheat yield at W/Gora site was much higher than that of G/Silingo closer to the maximum yield potential. Moreover, there was better positive synergy between applied N, S and P at this site as compared with the W/Gora. In general, at G/Silingo, since the highest rate of S resulted in a significant increase in yield over the previous rate, it implies that the yield plateau has not been reached, as the applied nutrients response curve was not reached. However, because the initial soil tests value at this site was marginal, applying S at a rate of 20 kg/ha is reasonable for increasing wheat yield and to reduce quality loss.

Table 4.3: The TAGB yield and NTsPP of wheat at Arsi zone (W/Gora and G/Silingo) sites in response to applied N, S and P nutrients

Fertilizes Used (code)	W. Gora		G. Silingo	
	TAGB yield (t/ha)	NTsPP	TAGB yield (t/ha)	NTsPP
CK	5.22g	1.33g	4.08g	1.67e
N	7.46f	2.67f	7.54f	3.00d
NS_1	8.55f	3.67e	8.49fe	3.67d
NS_2	10.00e	4.00ed	9.43e	4.00cd
NS_3	11.77d	4.67cd	11.30d	5.00cb
NP	13.89c	5.33cb	11.61cd	5.67b
NPS_1	14.70bc	5.67b	12.63cb	5.67b
NPS_2	15.66ba	7.00a	13.05b	5.67b
NPS_3	16.07a	6.00b	15.51a	7.00a
LSD	1.22	0.93	1.05	1.25
Alpha	***	***	***	***
CV %	6.14	11.96	5.85	15.75

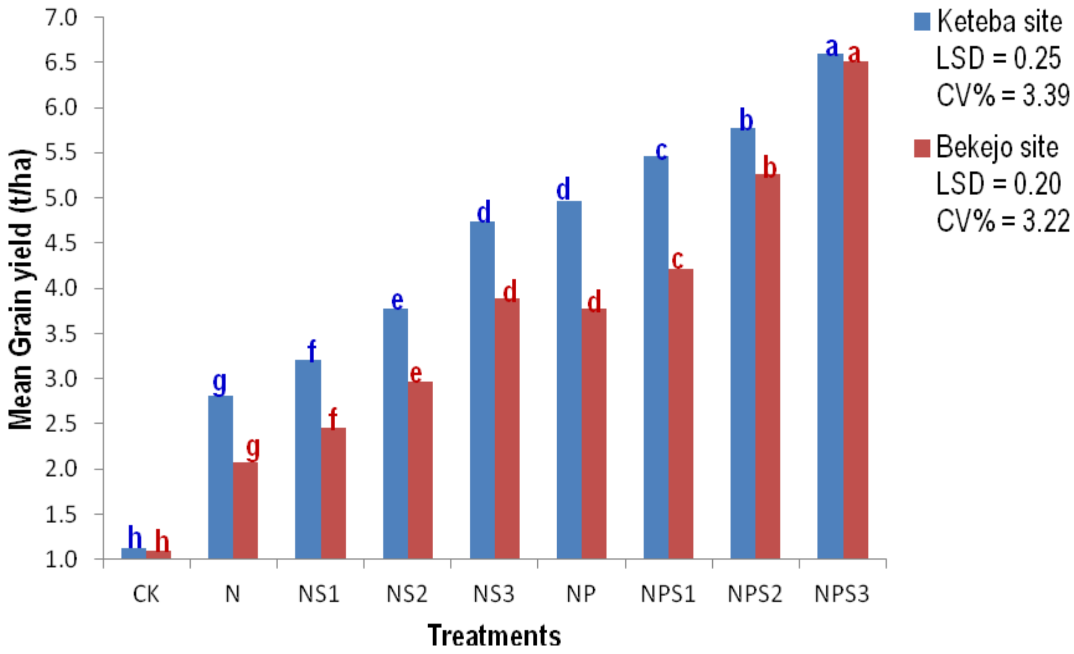
Key: TAGB = total above ground biomass yield (on dry matter basis); and NTsPP = number of tillers per plant.

Means bearing the same letter(s) within a column are not significantly different at $P < 0.01$ % probability level analyzed by T-test.

Table 4.4 and Fig. 4.2 present the mean grain yield, TAGB yield, and NTsPP of wheat at E/Shewa zone (Keteba and Bekejo) fields as affected by N, S and P fertilization. In this study area also the grain yield, NTsPP and TAGB dry matter showed highly significant response ($P < 0.001$) among treatments due to applied N, S and P fertilizers individually or in combinations.

As indicated in the Fig. 4.2, the yield increased progressively in response to applied fertilizers at all treatment levels at both sites in the three variables considered in this study. This means that wheat yield of almost all succeeding treatments was higher than that of the preceding treatment by a certain percent, especially for the grain yields, except that between NP and NS_3 at Bekejo site. For instance, the grain yield sequence was CK (absolute control or a treatment without fertilizer) < N (only nitrogen treatment) < NS_1 < NS_2 < NS_3 $\leq$ NP < NPS_1 < NPS_2 < NPS_3. But, at Bekejo site the grain yield of NS_3 treatment was (3.89 t/ha) slightly > that of NP treatment (3.77 t/ha), which may indicate the better positive synergy between N and S in a highly S limiting soil conditions, than between the N and P.

In general, in this study area, (i.e., East Shewa zone), it is observed that there was better consistency of yield response to applied nitrogen, sulphur and phosphorus as compared with Arsi zone. When looking at yield trend within the study area, still much higher wheat yield was recorded at Keteba (Calcareous vertisols) than in Bekejo site. The overall low yield at Bekejo as compared with Keteba may be due to, the slightly lower initial soil-test sulphate sulphur value at Bekejo than the latter site. Similarly, the sandy clay texture of soils at the Bekejo (Table 4.2) might have also caused loss of plant available S below root zone before it could be absorbed by the wheat plants. It is widely reported that, S deficient soils are often low in OM, coarse-textured, well-drained and subject to leaching (Mchunu and Chaplot, 2012). Also, sandy soils are reported to adsorb much less (SO_4^{2-}), than both clay and silt size separates (Ayuke, *et al*., 2012; Van Pham and Smith, 2014).



Key: CK = absolute control or without any fertilizer; N = nitrogen only; NS_1= nitrogen and sulphur; NS_2 = nitrogen and sulphur; NS_3 = nitrogen and sulphur; NP = nitrogen and phosphorus; NPS_1 = nitrogen, phosphorus and sulphur; NPS_2 = nitrogen, phosphorus and sulphur; and NPS_3 = nitrogen, phosphorus and sulphur. Where N was applied at 69 kg/ha; phosphorus at 20 kg/ha; S_1 (sulphur applied at 5 kg/ha), S_2 (sulphur applied at 10 kg/ha) and S_3 (sulphur applied at 20 kg/ha).

Figure 4.2: Wheat grain yield at E/Shewa zone (Keteba and Bekejo) sites in response to applied N, S and P nutrients.

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

In general, in both sites of this study area, there is yield response to applied N, S and P at all treatment levels, and there is better correlation of wheat yield with the soil-test values. Moreover, as it was noticeable from (Fig. 4.2), there is better positive synergy between N, S and P, as the wheat yields increases with any type and level of nutrient elements added, though the interaction effect of S with N is more pronounced than S with P.

However, in both fields, yield increase due to applied fertilizers at higher treatment levels may indicate that this was not the final dose of nutrients that should be supplied to the test crop as the maximum nutrient response curve or plateau yield was not reached. But, for the moment, farmers in such sites (in the East Shewa zone) can be advised to apply S at a rate of 20 kg/ha for increasing wheat grain yield and/or to maintain its quality.

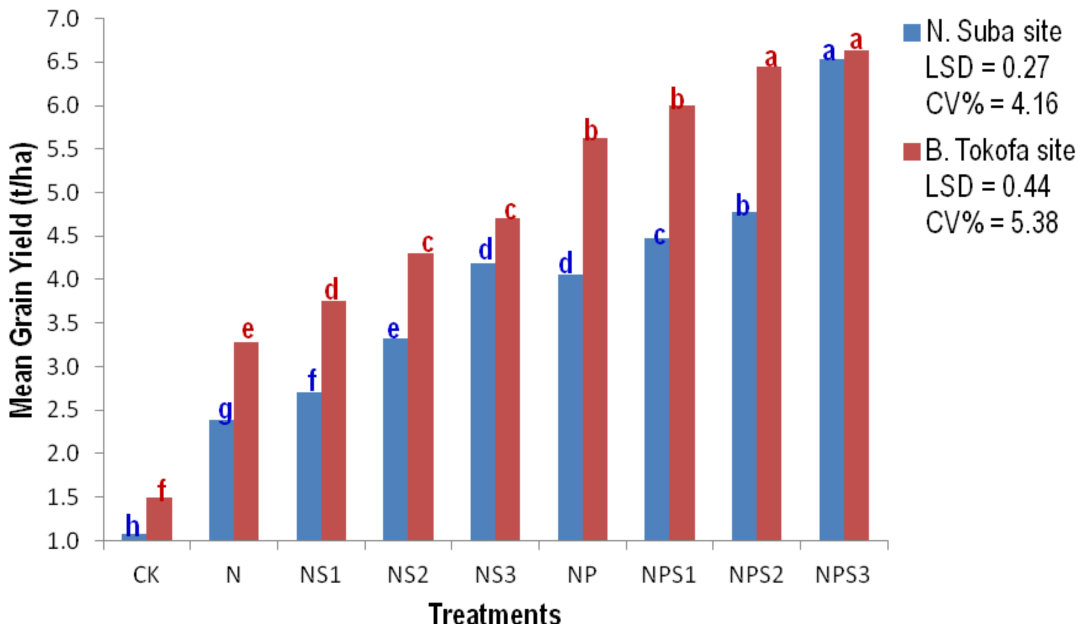
Table 4.4: The TAGB and NTsPP of at E/Shewa zone (Keteba and Bekejo) sites in response to applied N, S and P nutrients

Fertilizes Used (code)	Keteba site		Bekejo site	
	TAGB yield (t/ha)	NTsPP	TAGB yield (t/ha)	NTsPP
CK	3.03h	1.00e	2.95h	1.00g
N	7.20g	2.33d	5.33g	3.00f
NS_1	7.90f	3.33c	6.05f	3.67fe
NS_2	8.83e	4.00c	6.93e	4.33de
NS_3	11.02d	5.33b	9.06d	5.00dc
NP	12.06c	6.00ba	9.17d	6.00ba
NPS_1	13.08b	5.33b	10.09c	5.33bc
NPS_2	13.50b	6.33a	12.28b	6.67a
NPS_3	15.33a	6.67a	15.14a	6.67a
LSD	0.60	0.70	0.51	0.78
Alpha	***	***	***	***
CV %	3.41	9.00	3.43	9.75

Key: TAGB = total above ground biomass yield (on dry matter basis); and NTsPP = number of tillers per plant.

Means bearing the same letter(s) within a column are not significantly different at P < 0.01 % probability level analyzed by T-test.

Table 4.5 and Fig. 4.3 present the response of wheat grain yield, TAGB yield and NTsPP of wheat at O/Liyuu zone (N/Suba and B/Tokofa) sites as affected by N, S and P nutrition. The NTsPP, TAGB dry matter yield and economic yield (grain) showed highly significant response (P < 0.001) among treatments with applied fertilizers individually or in combinations. The yield response at this study zone/area follows a much similar trends as that of Arsi zone.



Key: CK = absolute control or without any fertilizer; N = nitrogen only; NS_1= nitrogen and sulphur; NS_2 = nitrogen and sulphur; NS_3 = nitrogen and sulphur; NP = nitrogen and phosphorus; NPS_1 = nitrogen, phosphorus and sulphur; NPS_2 = nitrogen, phosphorus and sulphur; and NPS_3 = nitrogen, phosphorus and sulphur. Where N was applied at 69 kg/ha; phosphorus at 20 kg/ha; S_1 (S applied at 5 kg/ha), S_2 (S applied at 10 kg/ha) and S_3 (S applied at 20 kg/ha).

Figure 4.3: Wheat grain yield at O/Liuu zone (N/Suba and B/Tokofa sites) in response to applied N, S and P nutrients.

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

In this study area, there is an increasing yield advantage due to applied kind and level of fertilizers at each treatment, which starts from the CK in both sites in the three parameters considered, especially for the grain yield except that between NP and NS_3 at the Nano Suba site. For instance, the grain yield sequence was CK (absolute control or a treatment without fertilizer) < N (only nitrogen treatment) < NS_1 < NS_2 < NS_3 ≤ NP < NPS_1 < NPS_2 < NPS_3. But, at the N/Suba the grain yield of NS_3 treatment was (4.18 t/ha) slightly > that of NP treatment (4.06 t/ha), which may indicate the better positive synergy between N and S in highly S limiting soil conditions, than between the N and P. This yield trend of N/Suba site is similar as that of the Bekejo site in the E/Shewa zone.

Singh *et al*. (2014) reported a similar trend of a progressive yield increase of wheat in India. The authors used four levels of S (0, 15, 30 and 45 kg/ha), applied to wheat along with recommended dose of N, P and potassium (K) in wheat-soybean cropping sequence. It was further reported that the direct effect of S at highest S level showed 27 % increase in grain yield over control and the increase was significant at each treatment of S level (Saeed *et al*., 2012).

At B/Tokofa site (heavy black clays, vertisols) there was significant response to N and P. Moreover, there was response to S at about 10 kg S/ha, though the initial soil-tested adequate for the SO_4-S. Regardless of the adequate soil-test value of SO_4-S before planting, wheat yield response at this site again might be due to the fact that the plant available native soil sulphur might have been lost through different factors, possibly leaching before it could be absorbed by the growing wheat roots, vis-à-vis the physico-chemical behaviour of vertisols. Chilimba and Chirwa (2004) reported yield response of maize in Malawi, despite the adequate levels of soil SO_4-S, in eight extension planning areas (EPAs) out of 30 sampled, in which case the authors indicated that the SO_4 was strongly adsorbed in highly weathered soils. Therefore, regardless of its initially seemingly adequate soil SO_4-S, B/Tokofa site may also need some supplemental amount of S between 5 and 10 kg/ha.

At N/Suba site, there was yield response of wheat due to the applied N, S and P at all treatment levels. Moreover, in this site there is better correlation of wheat yield with the soil-test values than at B/Tokofa. However, the overall wheat yield at the B/Tokofa site was much higher than that of N/Suba, and appeared to have reached maximum yield potential. There was also better positive synergy between N, S and P at this site than B/Tokofa. However, at N/Suba, the yield increase follows a similar trend as that of Keteba and Bekejo sites of E/Shewa zone with all applied types of fertilizers. However, the attainment of the highest wheat yield at the highest S level at the N/Suba suggests that this may not be the highest level of nutrients, especially S that should be applied for wheat production, since the maximum nutrient response curve or plateau yield was not reached. But, in a much similar ways as for Keteba and Bekejo sites, the N/Suba site may also need application of S at 20 kg/ha.

Table 4.5: The TAGB and NTsPP at the O/Liyuu zone (N/Suba and B/Tokoffa) sites in response to applied N, S and P nutrients

Fertilizes Used (code)	N. Suba		B. Tokofa	
	TAGB yield (t/ha)	NTsPP	TAGB yield (t/ha)	NTsPP
CK	2.91f	1.00e	5.46g	1.33d
N	6.14e	3.00d	8.47f	3.00c
NS_1	6.68e	3.33d	9.26fe	4.00b
NS_2	7.76d	3.67d	10.05e	4.33b
NS_3	9.72c	4.67c	11.26d	4.33b
NP	9.87c	5.33bc	13.63c	6.33a
NPS_1	10.72b	5.67ba	14.37bc	4.33b
NPS_2	11.17b	6.00ba	14.99ba	7.00a
NPS_3	15.19a	6.33a	15.99a	7.00a
LSD	0.66	1.00	1.12	0.88
Alpha	***	***	***	***
CV %	4.28	13.32	5.64	11.00

Key: TAGB = total above ground biomass yield (on dry matter basis); NTsPP = number of tillers per plant.

Means bearing the same letter(s) within a column are not significantly different at P < 0.01 % probability level analyzed by T-test.

It was observed that the overall response of wheat to applied nutrients, particularly S depends on specific site and soil conditions. The critical soil SO_4-S level was 11.3 mg/kg (Menna *et al*., 2015), and this is in close conformity and/or within the range of, 10-13 mg/kg SO_4-S, for cereals (e.g., wheat, maize, oil rapeseed etc) reported by Tandon, (1991).

Therefore, based on this criterion, in areas like Keteba, Bekejo and N/Suba, that tested very low in plant available SO_4-S and showed highly significant yield response at the highest level of added S, suggests that these sites may need S rate higher than 20 kg/ha. But, for the moment in these sites, applying S at a rate of 20 kg/ha with the recommended dose of N and P is necessary. This is important because, in applying S at higher rates also no deleterious effects on crops were reported, rather beneficial effects were reported. For instance, in line with this, Haneklaus *et al*. (1995) reported further increases in loaf volume (quality improvement), when S rate was increased up to 100 kg S/ha, while yield responses of wheat were limited to the application of 20kg S/ha. Sakal *et al*. (1999) conducted field experiment under rice-wheat system in a highly calcareous soil in India and reported that optimum level of S for wheat at 60 kg S/ha with significant grain yield increments. Girma *et al*. (2005) also reported significant wheat grain and forage yield response revealing that the biological optimum S rate was between 56 and 112 kg S/ha.

In the present study, at the sites like G/Silingo, though wheat crop continued to respond to applied S at the highest rate tested, and since its initial soil-test value was marginal, it is more reasonable to apply S at a rate of 20 kg/ka for the moment. This can also be augmented with better OM management and better tillage practices. Whereas, in the sites like W/Gora and B/Tokofa, since the initial soil test values showed adequate SO_4-S, but, still wheat showed response to applied S at lower levels, it is reasonable to apply some supplemental amount of S of 5-10 kg S/ha.

In general, in comparing the overall wheat yield gaps at each study area, G/Silingo (Arsi), Bekejo (E/Shewa) and N/Suba (O/Liyuu zone) gave lower yields than their respective neighbours, namely W/Gora, Keteba and B/Tokofa. But, if one considers the overall wheat yield at each site, Keteba at (E/Shewa), Bekejo at (E/Shewa) and N/Suba at the (O/Liyuu) zone were found to be lagging behind the rest of the sites, and their results were directly related to soil-test values. Most importantly, when comparing wheat yield in the current study with the maximum attainable wheat grain yield cited in literature, still there exist 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 with better management practices including adequate supply of nutrients like S (Abedi *et al*., 2011).

In summary, the S rate which is being recommended for wheat in the present study, 5 to over 20 kg S/ha is in close agreement with that reported by several workers (Sakal *et al*., 1999; Saeed *et al*., 2012; Singh *et al*., 2014). But, though S is such a critically important nutrient for wheat, it is reported that wheat has a relatively low S requirement for optimum yield, amounting to about 20 kg S/ha (Oates and Kamprath, 1985). Zörb *et al*. (2013) also share similar idea, but suggested a modest amount of sulphur, 15-35 kg S/ha for better quality and optimum yield.

When considering specific nutrient element, it is noticeable that with the applied N, there was a sharp rise in wheat yield curves, in all three study zones, including the non-S and non-P responsive ones in all the parameters considered in this paper (Figs. 4.1, 4.2, and 4.3). For instance, 72.15 % to 148.67 % grain yield advantages over control were recorded with applied N, in six studied sites in the season. Indeed, this sharp rise in the yield curves with the applied N is indicative of the fact that N is still found to be the most limiting element followed by P and S for wheat production. This may primarily due to the fact that the Ethiopian soils are severely low in available N, which is in turn due to the low levels of OM content of the studied soils vis-à-vis the dynamics of N in the tropical climate and soil conditions. This indicates that N management followed by S and P is critically important in sustaining wheat production in Ethiopia. Of course, there was wheat yield advantage at any given level and kind of fertilizer added, indicating a relative positive synergy between the applied N, S and P, weather the increases were significant or not.

Tables 4.6a, 4.6b and 4.6c show pair-wise orthogonal comparisons between treatment means of wheat grain at 95 % confidence limits at the G/Silingo, Bekejo and N/Suba sites. Such data for (W/Gora, Keteba and B/Tokofa sites were not shown). It is reported that, responses to S are easily overlooked when a basal dressing of P is applied as TSP, a high-analysis fertilizer, which contain agronomically significant amount of S impurity of 2-6 % by weight (Weil and Mughogho, 2000) in addition to P and Ca (15 %). The S impurity is usually added to TSP, probably during manufacturing from rock phosphate and sulphuric acid. This effect of S from TSP can be seen from wheat yield differences between NPS_3 and NS_3. The differences between NPS_3 and NS_3 were shown in pair-wise comparisons between treatment means in the grain yield at 95 % confidence limits, which were highly significant to applied sulphur from gypsum Tables 4.6a, 4.6b and 4.6c.

Despite the wheat cultivar's highly significant response to the applied S from gypsum in over 67 % of the studied sites in this set of experiments (e.g., in the sites like G/Silingo, Table 4.6a) the response to the applied S from TSP, did not show this case. This might also be due to the inherent low levels of plant available P in the tested soils, which can be seen by looking the yield response due to P (i.e., NP-N) (Tables 4.6a, 4.6b and 4.6c).

Due to this reason, the chance of response of wheat to S from TSP might have been obscured due to the inherent low levels of plant available P in the tested soils.

Table 4.6a: Pair wise orthogonal comparisons among treatments for wheat gain yield, at the Gora Silingo site in the Arsi zone (2013-14)

Treatment Comparisons	G/Silingo site DBM	95 % CL		
NPS_3 - NPS_2	1.0933	0.5639	1.6228	***
NPS_3 - NPS_1	1.3933	0.8639	1.9228	***
NPS_3 – NP	1.7433	1.2139	2.2728	***
NPS_3 - NS_3	1.8100	1.2806	2.3394	***
NPS_3 - NS_2	2.6267	2.0972	3.1561	***
NPS_3 - NS_1	3.2200	2.6906	3.7494	***
NPS_3 – N	3.7233	3.1939	4.2528	***
NPS_3 – CK	5.3033	4.7739	5.8328	***
NPS_2 - NPS_1	0.3000	-0.2294	0.8294	ns
NPS_2 – NP	0.6500	0.1206	1.1794	***
NPS_2 - NS_3	0.7167	0.1872	1.2461	***
NPS_2 - NS_2	1.5333	1.0039	2.0628	***
NPS_2 - NS_1	2.1267	1.5972	2.6561	***
NPS_2 – N	2.6300	2.1006	3.1594	***
NPS_2 – CK	4.2100	3.6806	4.7394	***
NPS_1 – NP	0.3500	-0.1794	0.8794	ns
NPS_1 - NS_3	0.4167	-0.1128	0.9461	ns
NPS_1 - NS_2	1.2333	0.7039	1.7628	***
NPS_1 - NS_1	1.8267	1.2972	2.3561	***
NPS_1 – N	2.3300	1.8006	2.8594	***
NPS_1 – CK	3.9100	3.3806	4.4394	***
NP - NS_3	0.0667	-0.4628	0.5961	ns
NP - NS_2	0.8833	0.3539	1.4128	***
NP - NS_1	1.4767	0.9472	2.0061	***
NP – N	1.9800	1.4506	2.5094	***
NP – CK	3.5600	3.0306	4.0894	***
NS_3 – NP	-0.0667	-0.5961	0.4628	ns
NS_3 - NS_2	0.8167	0.2872	1.3461	***
NS_3 - NS_1	1.4100	0.8806	1.9394	***
NS_3 – N	1.9133	1.3839	2.4428	***
NS_3 – CK	3.4933	2.9639	4.0228	***
NS_2 - NS_1	0.5933	0.0639	1.1228	***
NS_2 – N	1.0967	0.5672	1.6261	***
NS_2 – CK	2.6767	2.1472	3.2061	***
NS_1 – N	0.5033	-0.0261	1.0328	ns
NS_1 – CK	2.0833	1.5539	2.6128	***
N – CK	1.5800	1.0506	2.1094	***

Key: Trt = treatment; DBM = difference between means; CL = confidence Limits; N = nitrogen; P = phosphorus; S = Sulphur and; CK = Check; ns = not significant. The treatments used were four levels of S (S_0 = 0 = CK, S_1 = 5, S_2 = 10 and S_3 = 20 kg S/ha); two levels of N (N_0 = 0 = CK, N = 69 kg N/ha); and two levels of P (P_0 = 0 = CK and P = 20 kg P/ha; CK means check/control, treatment without any fertilizer).

Comparisons significant at the 0.001 level are indicated by ***.

The suggested amount of S from TSP (2-6 kg/ha) may also not be adequate enough to bring yield change, as it was seen from other lower level treatment, for example (at 5 kg S/ha) (Fig. 4.1, 4.2, and 4.3). Menna *et al*. (2015), chapter 2, made a similar report.

Table 4.6b: Pair wise orthogonal comparisons among treatments for wheat gain yield, at the Bekejo site in the East Shewa zone (2013-14)

		Bekejo site		
Treatment comparisons	**DBM**	**95 % CL**		
NPS_3 - NPS_2	1.25000	1.04998	1.45002	***
NPS_3 - NPS_1	2.29333	2.09331	2.49336	***
NPS_3 - NS_3	2.61667	2.41664	2.81669	***
NPS_3 – NP	2.73667	2.53664	2.93669	***
NPS_3 - NS_2	3.53667	3.33664	3.73669	***
NPS_3 - NS_1	4.05667	3.85664	4.25669	***
NPS_3 – N	4.43333	4.23331	4.63336	***
NPS_3 – CK	5.40667	5.20664	5.60669	***
NPS_2 - NPS_1	1.04333	0.84331	1.24336	***
NPS_2 - NS_3	1.36667	1.16664	1.56669	***
NPS_2 – NP	1.48667	1.28664	1.68669	***
NPS_2 - NS_2	2.28667	2.08664	2.48669	***
NPS_2 - NS_1	2.80667	2.60664	3.00669	***
NPS_2 – N	3.18333	2.98331	3.38336	***
NPS_2 – CK	4.15667	3.95664	4.35669	***
NPS_1 - NS_3	0.32333	0.12331	0.52336	***
NPS_1 – NP	0.44333	0.24331	0.64336	***
NPS_1 - NS_2	1.24333	1.04331	1.44336	***
NPS_1 - NS_1	1.76333	1.56331	1.96336	***
NPS_1 – N	2.14000	1.93998	2.34002	***
NPS_1 – CK	3.11333	2.91331	3.31336	***
NS_3 – NP	0.12000	-0.08002	0.32002	ns
NS_3 - NS_2	0.92000	0.71998	1.12002	***
NS_3 - NS_1	1.44000	1.23998	1.64002	***
NS_3 – N	1.81667	1.61664	2.01669	***
NS_3 – CK	2.79000	2.58998	2.99002	***
NP - NS_3	-0.12000	-0.32002	0.08002	ns
NP - NS_2	0.80000	0.59998	1.00002	***
NP - NS_1	1.32000	1.11998	1.52002	***
NP – N	1.69667	1.49664	1.89669	***
NP – CK	2.67000	2.46998	2.87002	***
NS_2 - NS_1	0.52000	0.31998	0.72002	***
NS_2 – N	0.89667	0.69664	1.09669	***
NS_2 – CK	1.87000	1.66998	2.07002	***
NS_1 – N	0.37667	0.17664	0.57669	***
NS_1 – CK	1.35000	1.14998	1.55002	***
N – CK	0.97333	0.77331	1.17336	***

Key: Trt = treatment; DBM = difference between means; CL = confidence Limits; N = Nitrogen; P = phosphorus; S = Sulphur and; CK = Check; ns = not significant. The treatments used were four levels of S (S_0 = 0 = CK, S_1 = 5, S_2 = 10 and S_3 = 20 kg S/ha); two levels of N (N_0 = 0 = CK, N = 69 kg N/ha); and two levels of P (P_0 = 0 = CK and P = 20 kg P/ha; CK means check/control, treatment without any fertilizer).

Comparisons significant at the 0.001 level are indicated by ***.

However, whether it could be due to applied N, S and P or not, in all the studied sites, there is always yield advantage with any kind and level of fertilizer added individually or in combination. This observed yield advantage by certain amount with every level of treatments, except NS_3-NP at Bekejo and N/Suba indicates a positive synergy between the applied nutrients.

Table 4.6c: Pair wise orthogonal comparisons among treatments for wheat gain yield, at the Nano Suba site in the O/Liyuu zone (2013-14)

Treatment comparisons	DBM	N/Suba site 95 % CL		
NPS_3 - NPS_2	1.7433	1.4751	2.0116	***
NPS_3 - NPS_1	2.0533	1.7851	2.3216	***
NPS_3 - NS_3	2.3500	2.0817	2.6183	***
NPS_3 – NP	2.4667	2.1984	2.7349	***
NPS_3 - NS_2	3.2033	2.9351	3.4716	***
NPS_3 - NS_1	3.8133	3.5451	4.0816	***
NPS_3 – N	4.1333	3.8651	4.4016	***
NPS_3 – CK	5.4433	5.1751	5.7116	***
NPS_2 - NPS_1	0.3100	0.0417	0.5783	***
NPS_2 - NS_3	0.6067	0.3384	0.8749	***
NPS_2 – NP	0.7233	0.4551	0.9916	***
NPS_2 - NS_2	1.4600	1.1917	1.7283	***
NPS_2 - NS_1	2.0700	1.8017	2.3383	***
NPS_2 – N	2.3900	2.1217	2.6583	***
NPS_2 – CK	3.7000	3.4317	3.9683	***
NPS_1 - NS_3	0.2967	0.0284	0.5649	***
NPS_1 – NP	0.4133	0.1451	0.6816	***
NPS_1 - NS_2	1.1500	0.8817	1.4183	***
NPS_1 - NS_1	1.7600	1.4917	2.0283	***
NPS_1 – N	2.0800	1.8117	2.3483	***
NPS_1 – CK	3.3900	3.1217	3.6583	***
NS_3 – NP	0.1167	-0.1516	0.3849	Ns
NS_3 - NS_2	0.8533	0.5851	1.1216	***
NS_3 - NS_1	1.4633	1.1951	1.7316	***
NS_3 – N	1.7833	1.5151	2.0516	***
NS_3 – CK	3.0933	2.8251	3.3616	***
NP - NS_3	-0.1167	-0.3849	0.1516	Ns
NP - NS_2	0.7367	0.4684	1.0049	***
NP - NS_1	1.3467	1.0784	1.6149	***
NP – N	1.6667	1.3984	1.9349	***
NP – CK	2.9767	2.7084	3.2449	***
NS_2 - NS_1	0.6100	0.3417	0.8783	***
NS_2 – N	0.9300	0.6617	1.1983	***
NS_2 – CK	2.2400	1.9717	2.5083	***
NS_1 – N	0.3200	0.0517	0.5883	***
NS_1 – CK	1.6300	1.3617	1.8983	***
N – CK	1.3100	1.0417	1.5783	***

Key: Trt = treatment; DBM = difference between means; CL = confidence Limits; N = nitrogen; P = phosphorus; S = Sulphur and; CK = Check; ns = not significant. The treatments used were four levels of S (S_0 = 0 = CK, S_1 = 5, S_2 = 10 and S_3 = 20 kg S/ha); two levels of N (N_0 = 0 = CK, N = 69 kg N/ha); and two levels of P (P_0 = 0 = CK and P = 20 kg P/ha; CK means check/control, treatment without any fertilizer).

Comparisons significant at the 0.001 level are indicated by ***.

In two neighbouring sites Bekejo and N/Suba (Tables 4.6b and 4.6c) which are found in different study zones, but geographically closer, it is observed that treatment NS_3 slightly outweighed the next treatment NP in grain yield, though statistically not significant. Therefore, from the results, it can be affirmed that in extremely S limiting condition, the wheat crop shows, the tendency of absorbing more of the applied S than P, in trying to achieve higher yield potential. The soils from these two sites tested very low in the plant available SO_4-S as compared with other sites (Table 4.2), which may show a better interaction of N and S in impacting wheat yield under severely S limiting conditions. In line with this, strong interaction between S and N in impacting wheat yield and its quality attributes (particularly, proteins synthesis) has been reported by many workers (Habtegebrial and Singh, 2009; Reussi *et al*., 2012; Saeed *et al*., 2013). In accordance with this, it is reported that S is an essential macro-nutrient that is taken-up by grain crops in amounts similar to and sometimes exceeding those of P, 10-30 kg/ha (Scherer, 2001; Jamal *et al*., 2012; Weil, 2011), and the S content of plants is approximately the same as the P content (Mengel and Kirkby, 1987).

It is well known that crops' nutrient uptake is the function of the intended yield and its nutrients concentration. Moreover, it is reported that higher plants generally accumulate S and N in amounts proportional to that incorporated into protein (Friedrich and Schrader, 1978). Therefore, the increased wheat yield due to applied S, in preference to P in the present study, may be attributed to more S interaction to N in plant growth than with P. It is also reported that responses to S application are usually greater when sufficient or abundant amounts of N are applied (Zhao *et al*., 1999b). In general, the present study demonstrated a strong positive synergy between N with S fertilization on grain yield. Wheat response to S fertilization is often reported to depend on the amount of N fertilizer supplied, and the N use efficiency in turn is enhanced by adequate S (Zhao *et al*., 1999a).

It is reported also that, in contrast P has no such a big influence as N on protein content, but rather it supports the effect of N, resulting in better assimilation and metabolisation of absorbed N forms (Crista *et al*., 2013).

4.4 Conclusions and Recommendations

4.4.1 Conclusions

- From six on-farm experiments conducted in this set of experiments, it is learnt that the wheat crop continued to respond to applied nutrients N, S and P from urea, gypsum and phosphorus fertilizers individually or in combinations. It is also learnt that the overall response of wheat to the applied nutrient elements, particularly S was found to depend on specific site and soil conditions, and hence site/soil specific fertilizer recommendations can be made. For example, the three studied sites, which were selected, based on pre-soil test and crop-response, namely G/Silingo, Keteba and N/Suba, showed highly significant response to applied fertilizers, especially S at all treatment levels. However, from the other three sites, which were selected without pre-soil test, namely W/Gora, Bekejo and B/Tokofa, only Bekejo showed highly significant response to applied S. W/Gora and B/Tokofa showed marginal response, especially for the target element S, at a certain critical level of lower concentration, 5-10 kg S/ha.

- From the 18 explorative first set of experiments conducted in the first season, the critical level of SO_4-S was estimated to be about 11.30 mg/kg. Considering this critical limit, and the10-13 mg/kg, that reported by Tandon (1991) and Srinivasarao *et al.* (2004), for most crop species (e.g., in wheat), therefore, the sites like Keteba, Bekejo and N/Suba can be categorizes as very low; G/Silingo to be medium/marginal; whereas W/Gora and B/Tokofa can be grouped under those sites adequate for plant available S.

4.4.2 Recommendations

Based on the above information and criterion, therefore the following site specific recommendations were made.

- In sites like Keteba, Bekejo and N/Suba, which tested very low for the plant available soil SO_4-S, and at the same time showed highly significant response to applied S, the S rate can be slightly higher than 20 kg/ka, as the plateau yield or nutrient response curve was not reached. But, for the time being farmers in such areas can be advised to apply 20 kg S/ha together with the recommended full dose of N and P as provisional recommendation for increasing wheat yield and to reduce the quality loss. At G/Silingo site, since the pre-soil test result showed medium/marginal and the wheat crop showed response to applied S at its highest treatment level, applying S at a rate of 20 kg/ha together with the recommended dose of N and P is advisable.

- Whereas at the W/Gora and B/Tokofa sites that tested adequate for the initial soil's SO_4-S just before planting, but, because of the observed wheat yield response at lower treatment levels of 5-10 kg S/ha, it is reasonable to apply some supplemental amount of S, between 5 to 10 kg/ha. But, in such areas, farmers can also opt for better SOM management coupled with good agronomic practices like tillage etc. In general, since in all the studied sites, the potential attainable yield ceiling of wheat grain reported in literature and that witnessed by the farmers in the study areas (about 8.2 t/ha) was not achieved, it is important to make further detailed investigations by controlling all other factors of production including other essential nutrient elements.

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CHAPTER FIVE

5.0 General Conclusions and Recommendations

5.1 General Conclusions

The findings of the study have led to the following general conclusions:

- The overall study on sulphur status of soils has revealed that, sulphur (S) was critically low in over 72 % of the studied areas for sustaining crop production. This alarmingly low level of soil S status was due to extractive farming i.e. the use of high analysis fertilizers, only urea and di-ammonium phosphate (DAP), which are free of S, with high yielding varieties and hybrids, which is negatively affect food security, through yield or quality loss.

- The findings of the explorative sulphur response study have shown that wheat responded well to the applied sulphur, nitrogen and phosphorus from urea, gypsum and triple-super phosphate fertilizers, and that wheat grain yield and yield components response was directly related to the soil-test values, especially for S and N. In all tested sites the wheat showed dramatic yield increase due to the combined effects of the three nutrients. For instance, in the 2012-14 cropping seasons wheat grain yield increased by 446.8 % in Arsi; 520.4 % in East Shewa; and 497.3 % in Oromia Liyuu zones due to the application of N, P and S.

- The research findings on the evaluation of the different indices of sulphur supply in soils and plants, namely OC and SO_4-S in soils; and TS and N/S ratio in wheat grain, plant analysis offered better sensitivity as sulphur availability index than soil indices. Still from the plant, total S in grain was found to be a better tool for predicting S supply than the N/S ratios. The soils correlated well with the S uptake value, but showed a relative weaker degree of association than the plant variables.

- Depending on the suitability of the indices thus obtained, the critical thresholds were determined to be about 0.12 % for TS; 14.7/1 for N/S ratios (in wheat grain); and 11.3 mg/kg for SO_4-S in the surface soils.

- Site specific recommendations are possible, if soil and/or plant data are available. The results have shown that, sites like Keteba, Bekejo and Nano Suba were characterized to be severely deficient in plant available sulphur, because of the very low levels of S; and sites like Gora Silingo to be medium or marginal. Whereas Wonji Gora and Berfeta Tokofa were found to be adequate for S. Hence, site/soil specific S recommendations were deduced. Overall the study signified the importance of balanced nutrition in the plant nutrient management strategies in crop production systems in Ethiopia.

5.2 General Recommendations

In view of the above general conclusions, the following recommendations were deduced:

- Based on the sulphur response study, there is a need to integrate sulphur to produce balanced fertilizer formula, for use in crop production in the Central Highlands of Ethiopia. The sulphur can come from locally available source, gypsum, as it can address sulphur deficiency and other benefits.

- Farmers and extension or extension agents can be advised to distinguish the S responsive sites/soils in which case much S response is expected for sites or soils with TS less than 0.12 %; N/S ratio above 14.7/1; and soil's SO_4-S below 11.3 mg/kg.

- Further studies focusing on standardizing the most suitable indices of S supply for wheat and/or other crops are recommended. Moreover, as the present study is the first work in cereals (only one cultivar considered); it is recommended that further research studies should be installed aimed at standardizing the extraction methods and/or solutions for soil and plant S.

- But, since in all 24 sites, the attainable potential yield of wheat grain reported in literature as well as that witnessed by the resourceful farmers in the study areas was not reached, it is recommended that a similar research of much wider scope be installed by using more S sensitive crops at both farm and greenhouse levels by optimizing all factors of production.