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Assessment of Sulfur Deficiency in Soils through Plant Analysis in Three Representative Areas of the Central Highlands of Ethiopia-IV

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Author's contribution

The sole author designed and executed the study, performed laboratory and statistical analysis, interpreted; and prepared the manuscript.

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ABSTRACT

Field survey was conducted in Arsi(Ar), East Shewa(ES) and Oromia Liuu(OL) zones in 2012-15 cropping seasons, aimed at assessing sulfur(S) status of soils through plant analysis. The general information on land-use, soil types, were collected using semi-structured questionnaire to trace past fertilizer use. For the purpose of the reliability of data, out of 350 surveyed farmers' fields or samples, randomly selected 200 wheat seed samples were considered. Based on the critical levels(CLs) estimated for TS content in wheat seed, 0.12%, about 61.8% of the fields in Arsi were found to be severely deficient in S, and 17.7% were marginal, necessitating the application of external S in about 79.5% of the studied fields. Likewise, in ES, about 51.5% fields were found severely deficient in S, and 30.3% were marginal, again necessitating the application of external S in about 81.8% of fields. In OL, about 63.6% of the fields were severely deficient in S, and 24.2% were marginal. From the study, therefore, across all 3 locations, 59.0% of studied fields were severely S deficient and 24% were marginal. This necessitates the application of external S (full dose or some supplemental amount, depending on soil-test results) in about, 83.0% of the fields in three studied areas. This extent of S deficiency is comparable when the CL for N/S-ratio in wheat

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seed is 15:1. But, when the CL is 17:1, inconsistencies observed. In summary, the study affirmed that, S deficiency is becoming wide-spread in annually-cropped agricultural lands in the country. Hence, there is a need to integrate S in balanced fertilizer formula, if soil-test and crop-response data are available. In doing so, S from known/trusted sources can be blended with DAP or TSP for applying it into soils, with recommended doses of other nutrients, especially nitrogen and phosphorus. Sulfur can come from locally available source, (gypsum), to use its integrative benefits and economize fertilizer use.

Keywords: Sulfur deficiency; plant analysis; total S; N/S-ratio; farming system; and cropping system.

1. INTRODUCTION

The decline in the fertility of agricultural soils in Ethiopia has been well documented in recent decades, with most of the attentions being focused on the so-called 'fertilizer elements', nitrogen (N), phosphorus (P) and potassium (K). Sulfur(S) is a macro-nutrient taken-up by most grain crops in amounts similar to those of P, namely 10-30 kg/ha [1,2]. However, while P has been subject to extensive investigations throughout Africa [3,4], much less is known about the S status of African soils and the responses to S applications.

Although, some early reports recognized the problem of S deficiency [5], there are several reasons why S hasn't received adequate attention by agriculturalists in Africa, including Ethiopia. First, low-yield shifting subsistence agriculture has been based on exploiting natural soil reserves, mainly mineral S released as soil organic matter (SOM) decomposes. Second, during the 1950s to 1980s, adequate S was commonly supplied to crop-lands from animal manures, or from the then popular low-analysis fertilizers such as ammonium sulfate (AS) and single super-phosphate (SSP), which were applied for NP contents, but actually supplied more S than NP, thereby obscuring the occurrence of S deficiencies and responses, especially in research field-plots.

The situation regarding S fertility has changed in recent decades. First, as OM has been depleted by continuous cropping, and as high-yielding varieties and hybrids have found wider use, the supply of S from OM mineralization has become inadequate in many instances. Secondly, there has been a rapid shift in African agriculture away from the use of low-analysis fertilizers (e.g., AS and SSP) toward high-analysis fertilizers, urea and di-ammonium phosphate (DAP), which contain little or no S. Where such high-analysis fertilizers are used with high-yielding varieties/hybrids, failure to supplement S in balanced fertilizer formula can be expected to rapidly deplete available S supplies in soils. From 24 explorative field experiments conducted in 2012-15 in Ar, ES and OL administrative zones, about 72% overlapping sites showed responses to applied S in wheat as directly related to soil-test values [6,7]. For augmenting the results, therefore, the objectives of this work were: (i) to assess the extent of S deficiency in major annual crop growing soils, (ii) to assess some of the causes of S deficiency in the studied areas.

The possible questions intended by this set of study are a) Is S deficiency wide-spread in the annual crop-lands in the central highlands (CHLs) of Ethiopia? b) What are some root causes of S deficiency?

2. MATERIALS AND METHODS

Survey was conducted in Ar, ES and OL administrative zones in farmers' fields in 2012-15. Each field was geo-referenced using Global Positioning System (GPS) and/or Google earth (2011) assisted by road maps. Farmer's fields were classified by elevation, size and soil type when known and mapped. During surveys, land-use history, type and amount of fertilizer used, and soil type etc. were collected using semi-structured questionnaire.

Three hundred and fifty farmers' fields divided among three study areas were visited. In doing so, 230 (wheat) and 120 (faba bean) plant tissues were sampled during wheat booting and faba bean early flowering stages, from land/plot areas of 10 m x 100 m. From each plot, 500 g representative disease-free shoots were randomly collected with clean hands and scissors to avoid contaminations. For wheat, 54 plants per plot were collected, cutting at soil level. Faba bean samples were collected from 30-45 plants per plot, picking only one complete leaf petiole plus three leaflets from recently matured leaves. After sampling the materials were rinsed quickly in distilled water in fields' immediately and shaken to dry and placed in paper bags (air-dried in dust-free rooms). Then, in laboratories (Labs), samples were oven-dried at 65–70°C for 48 hrs to a constant weight. On dry-weight basis, relative yield and S up-take were calculated. From 54 oven-dried wheat shoots, 27 were randomly selected and cut at upper 1/3 part of plants and ground finely (<1mm size) using a Tecator-CYCLOTEC-1093, sample mill and saved for total nitrogen(TN), total sulfur(TS) and critical levels(CLs) determination. Finally, N/S ratios and S up-take were calculated.

At maturity, both kinds of seed and tissue samples were collected from 350 plots from the same farmers' fields. Moisture content was found to be 13.5%. Then, 100 g representative samples from both kinds of seeds were washed using distilled water and oven-dried at 65-70℃ for 48 hrs to constant weight. The less reliability of TS content and N/S-ratio as S availability index in wheat during its early stages of growth was reported by [8]. Therefore, only 200 randomly selected wheat seed samples were ground (<1mm size). In Labs, finely ground material were wet-digested using 68%HNO_3-30%H_2O_2 for TS determination, and read using spectro-photometer, whereas, TN was extracted by Kjeldahl wet-digestion using (conc.H_2SO_4) as described by [9] and back-titrated against 0.05N H_2SO_4.

2.1 Statistical Data Analysis

Survey data collected on the farming systems, cropping systems history, and the crop; and their farmers' responses were analyzed using Statistical Package for Social Sciences (SPSS) Version-20 and Micro Soft office Excel 2007. The data on yield and yield components for soil-test and/or crop-response experiments were analyzed using SAS statistical package Version-9 as presented in [6].

3. RESULTS AND DISCUSSION

To diagnose S deficiency methods based on soil and plant analysis have been used [10,11]). However, the critical values determined for various indices vary depending on the growth stages and parts of plant analyzed; experimental conditions; and method of analysis. In line with this, [12] made reviews on a wide range of indices and concluded that, plant analysis was better than soil-testing for predicting the need for S application. In accordance, [13], evaluated organic carbon (OC), SO_4-S in native soil; and TS and N/S-ratio in wheat grain, and indicated that, plant variables showed better correlation with S-uptake than soil. The authors concluded that, TS in wheat seed followed by its N/S-ratio were found to be a better index of S supply than others. In the following sub-sections discuss the extent of S deficiency in terms of TS and N/S ratio. Soil types in the Tables are presented as characterized by [14,15,16,17], but need further detailed/specific classifications.

3.1 Total Sulfur Content in Wheat Grain

Fig. 1 depicts the sulfur status of soils in the studied three locations in the CHLs of Ethiopia, namely Ar, ES and OL or West Shewa zones, based on plant analysis (in it the TS contents in wheat grain are presented). Regarding the total sulfur (TS) in wheat grain as an index of S supply, wide range of critical levels(CLs) have been reported in literatures [12]. In line with this, [13] estimated a CL for the TS in wheat grain to be 0.118%, and this was in accordance with, that reported by other workers [18,19,20]. Their study recommended this CL, 0.118% =0.12% to be used as a provisional recommendation for wheat production in Ethiopia. The authors further noted that, as CLs determined by [21] procedure divide only low and high values, the marginal/medium levels can stretch up to 0.125% or even higher.

Based on this CL determined by [13,18], 0.12%, therefore, within Arsi zone about 61.8% of the fields were found to be severely S deficient (highlighted-red), and 17.7% of fields (highlighted-yellow) were found to be marginal (Fig.1). This necessitates the application of external S in some 79.5% of the studied fields/sites in this area. The remaining, 20.6% of fields were either adequate or close to adequate for plant available S. Likewise, in E/Shewa, 51.5% of fields were found to be severely deficient in S and 30.3% were marginal. In O/Liuu zone, 63.6% of the studied fields were found to be severely deficient in S, and 24.2% were marginal, making the total number of fields that need the application of external S in this zone to be about 87.9%.

The overall, severely S deficient fields in the three studied locations were 59.0% (aggregate), and the overall fields marginal for plant available S were about 24%. This affirms that, the S deficiency is becoming wide-spread in annually cropped agricultural lands in Ethiopia. This necessitates the application of external S in about, 83.0% of the fields. It is worth mentioning that, those fields marginal for plant available S (Fig.1), will soon fall to S deficient side, if mineralizable soil organic matter(SOM) was not sufficient enough to balance the different losses including plant up-take, SOM being the major source of plant available S in the Ethiopian crop production systems. For example, [6] reported that OC contents of about 78% of the studied areas soils was either very low or low/marginal. Hence, need the application of some supplemental amount of S at lower concentrations. In such fields, plants will suffer from S deficiency, particularly in their early stages of growth (a stage where plants are in greater S demand), if the mineralization process is also slow acting). In harmony, [6,7] reported that, over 72% of studied soils in the CHLs of Ethiopia to be either very low or marginal in the plant available SO_4-S.

3.2 Nitrogen to Sulfur Ratio in Wheat Grain

It is widely recognized that, CLs for sulfur depend on plant species, sampled part of plants, stages of development and yield level [22,23]. Assefa Menna et al. [13], reported that, N/S-ratio in wheat grain to be a satisfactory index of S supply based on the criterion set in literatures for field experiments. In accordance, [18] reported, the N/S-ratio to be a satisfactory index of S supply in wheat grain based on the threshold they determined, 17:1.

But, [13] in Ethiopia, reported the CL for N/S-ratio in wheat grain to be 15:1, and suggested that this can be used to separate S responsive sites or treatments from non-responsive ones. However, this was slightly lower than that determined by [18], but is comparable to that reported by [24], 14.8:1. The authors further noted that, as CLs separate low and high values only, the marginal levels can go slightly above 15:1. Hence, the most reasonable CLs for N/S-ratio could still be 17:1 as suggested by [18,1].

When considering this 17:1 as a CL (Tables 1 through 3), inconsistencies for S deficiency as compared to when considering TS as an index were observed. Based on this criterion, therefore, 66.2% of the fields in Ar, 47% of fields in ES and 56.1% in OL zone were found to be severely S deficient. This makes the overall severely S deficient fields/sites in the three locations to be only 56.5%. In harmony, the less reliability of N/S-ratio as an index of S supply is crops; especially wheat was reported and discussed earlier in [13].

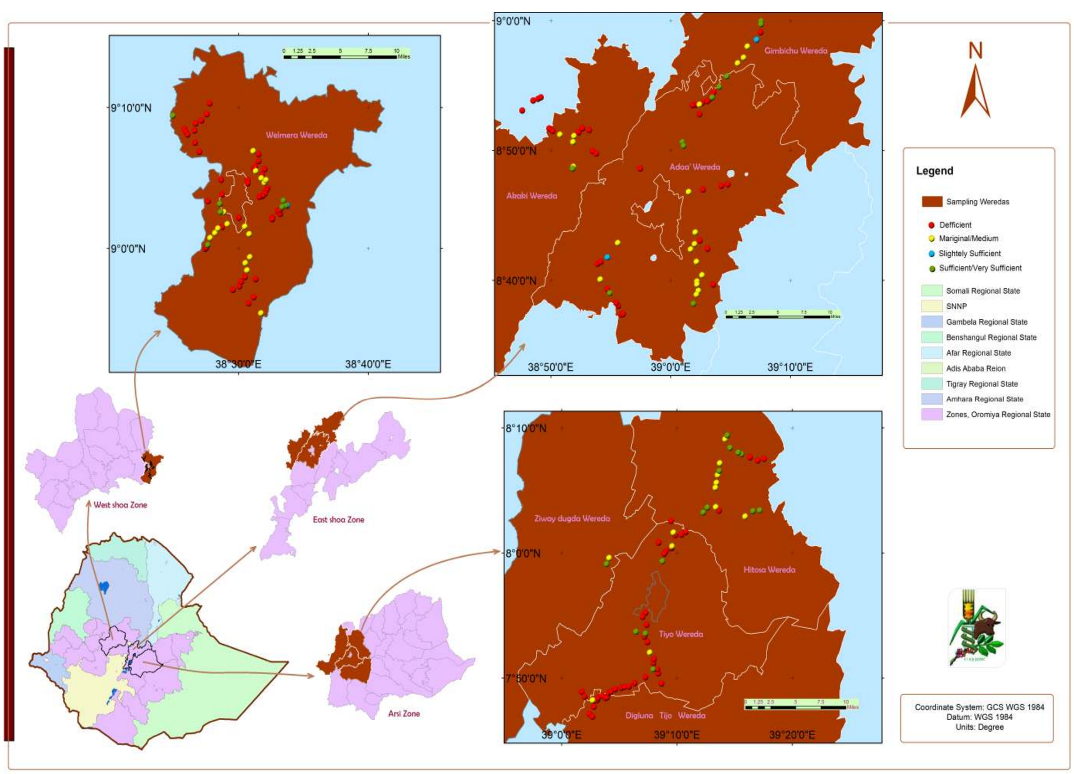

Fig. 1. Locations map showing sulfur status of soils based on wheat seed/grain analysis in Arsi, East Shewa and Oromia Liuu/West Shewa zones in central highlands of Ethiopia

Table 1. Total sulfur content, N/S-ratio, cropping and farming systems history at Arsi zone

Soil type	Last season's crop, & fertilizer used			Investigated crop (wheat) & fertilizer used		TS(%), CL=0.12, and S rating	N/S(Ratio), CL=17, and S rating	Longitude		Latitude	
	Crop	Urea (kg/ha)	DAP (kg/ha)	Urea (kg/ha)	DAP (kg/ha)			X^o.Y'	(")	(X^o.Y'	(")
mollisol	potato	50	100	100	100	0.105$^{(L)}$	18.019$^{(L)}$	39.1	47	7.48	54.8
mollisol	Rapeseed			50	100	0.114$^{(L)}$	11.997$^{(H)}$	39.2	1.9	7.48	29.8
mollisol	maize	100	100	150	100	0.121$^{(M)}$	17.082$^{(L)}$	39.2	44	7.48	13.1
mollisol	Barly	100	100	100	100	0.101$^{(L)}$	17.270$^{(L)}$	39.2	50	7.48	9.5
nitosol(red)	potato	50	100	50	75	0.094$^{(L)}$	20.059$^{(L)}$	39.2	50	7.47	42.0
nitosol(red)	Lentil		100	100	100	0.100$^{(L)}$	18.984$^{(L)}$	39.2	28	7.47	8.2
nitosol(red)	potato	50	100	100	100	0.094$^{(L)}$	21.173$^{(L)}$	39.2	43	7.46	54.3
mollisol	FB		100	100	100	0.110$^{(L)}$	22.228$^{(L)}$	39.3	7.7	7.48	12.6
nitosol(red)	fallow			75	100	0.100$^{(L)}$	22.148$^{(L)}$	39.3	12	7.48	23.8
nitosol(red)	field pea			100	100	0.096$^{(L)}$	20.781$^{(L)}$	39.3	34	7.48	34.7
nitosol(red)	barley	50	100			0.094$^{(L)}$	21.916$^{(L)}$	39.3	52	7.48	23.3
mollisol	field pea		100	100	100	0.089$^{(L)}$	21.656$^{(L)}$	39.3	59	7.48	27.3
vertisol*	FB		100	50	100	0.080$^{(L)}$	27.563$^{(L)}$	39.4	8	7.48	47.9
vertisol*	field pea	50	50	125	100	0.101$^{(L)}$	17.270$^{(L)}$	39.4	20	7.48	54.1
vertisol*	barley	50	100	100	100	0.080$^{(L)}$	24.938$^{(L)}$	39.4	41	7.49	6.5
vertisol*	chickpea	50	100			0.087$^{(L)}$	24.509$^{(L)}$	39.5	13	7.49	12.5
vertisol*	Wheat	50	100	100	100	0.094$^{(L)}$	19.316$^{(L)}$	39.5	28	7.49	16.9
vertisol*	G.abyssinica	50	50	75	100	0.092$^{(L)}$	17.794$^{(L)}$	39.5	52	7.49	18.7
vertisol*	field pea		100	100	100	0.084$^{(L)}$	19.688$^{(L)}$	39.6	22	7.49	34.9
vertisol*	barley		100	50	100	0.105$^{(L)}$	17.352$^{(L)}$	39.7	19	750	4.3
nitosol(red)	Teff	100	100	150	100	0.158$^{(H)}$	11.060$^{(H)}$	39.7	59	7.50	41.5
nitosol(red)	barley		100	100	100	0.092$^{(L)}$	21.202$^{(L)}$	39.8	43	7.49	33.2
nitosol(red)	fallow			100	100	0.096$^{(L)}$	18.229$^{(L)}$	39.8	25	7.50	21.6
nitosol(red)	wheat	150	100		100	0.098$^{(L)}$	18.614$^{(L)}$	39.8	21	7.50	41.9
nitosol(red)	FB		100	100	100	0.105$^{(L)}$	17.352$^{(L)}$	39.7	60	7.51	12.1
nitosol(red)	FB	Compost	75	100	100	0.089$^{(L)}$	18.506$^{(L)}$	39.8	2.8	7.51	31.1
Keyate(red)	field pea		100	125	100	0.126$^{(M)}$	13.033$^{(H)}$	39.7	41	7.52	1.9
nitosol(red)	FB		100	100	100	0.117$^{(L)}$	17.301$^{(L)}$	39.7	29	7.52	52.4
nitosol(red)	FB				100	0.112$^{(L)}$	17.500$^{(L)}$	39.7	14	7.53	17.9
nitosol(red)	fallow			100	100	0.160$^{(H)}$	12.250$^{(H)}$	39.7	18	7.53	33.7
nitosol(red)	maize		100	100	100	0.112$^{(L)}$	17.188$^{(L)}$	39.7	25	7.54	15.3
nitosol(red)	barley	50	100	150	100	0.117$^{(L)}$	17.003$^{(L)}$	39.7	20	7.55	13.2
nitosol(red)	field pea		100	100	100	0.110$^{(L)}$	19.052$^{(L)}$	39.7	4.3	7.54	53.2
nitosol(red)	Teff	50	100	100	100	0.144$^{(H)}$	13.125$^{(H)}$	39.6	29	7.53	42.9

Soil type	Last season's crop, & fertilizer used			Investigated crop (wheat) & fertilizer used		TS(%), CL=0.12, and S rating	N/S(Ratio), CL=17, and S rating	Longitude		Latitude	
	Crop	Urea (kg/ha)	DAP (kg/ha)	Urea (kg/ha)	DAP (kg/ha)			X^o.Y'	(")	(X^o.Y'	(")
mollisol	Sorghum	50	100	50	100	$0.174^{(H)}$	$10.045^{(H)}$	39.3	56	7.59	7.2
mollisol	maize	50	100	100		$0.126^{(M)}$	$20.242^{(L)}$	39.4	9.5	7.59	35.7
mollisol	barley	50	100	100	100	$0.096^{(L)}$	$23.698^{(L)}$	39.9	33	8.2	33.1
vertisol	FB		100	50	100	$0.132^{(M)}$	$16.229^{(H)}$	39.9	44	8.1	37.6
vertisol	Field pea	100	100	100	100	$0.096^{(L)}$	$18.229^{(L)}$	39.9	54	8.1	25.4
vertisol	Sunflower		100	125	100	$0.087^{(L)}$	$20.893^{(L)}$	39.17	36	8.7	31.0
vertisol	Potato	50	100	100	100	$0.100^{(L)}$	$18.633^{(L)}$	39.17	2.8	8.7	23.3
vertisol	Maize	100	100		100	$0.101^{(L)}$	$17.615^{(L)}$	39.16	23	8.7	38.4
vertisol	Teff	50	100		100	$0.135^{(H)}$	$16.320^{(H)}$	39.15	38	8.7	53.6
vertisol	Wheat	125	75	100	100	$0.158^{(H)}$	$9.291^{(H)}$	39.15	21	8.8	2.1
vertisol	Maize	50	75	100	100	$0.151^{(H)}$	$10.191^{(H)}$	39.14	38	8.8	24.3
vertisol	Wheat	100	100		100	$0.142^{(H)}$	$11.320^{(H)}$	39.14	24	8.9	24.4
vertisol	Maize	100	100	100	100	$0.126^{(M)}$	$13.033^{(H)}$	39.14	13	8.9	5.7
vertisol	Wheat	50	100	50	100	$0.121^{(M)}$	$17.661^{(L)}$	39.13	45	8.7	10.5
vertisol	Maize	50	100	100	100	$0.148^{(H)}$	$10.911^{(H)}$	39.13	42	8.6	34.1
vertisol	Maize	50	100	100	100	$0.123^{(M)}$	$16.834^{(H)}$	39.13	34	8.6	13.3
vertisol	Wheat	100	100	100		$0.121^{(M)}$	$17.371^{(L)}$	39.13	28	8.5	36.1
vertisol	Wheat	150	100	100	100	$0.124^{(M)}$	$13.219^{(H)}$	39.13	22	8.5	12.8
vertisol	Wheat		100	25	100	$0.142^{(H)}$	$13.043^{(H)}$	39.17	13	8.3	24.6
vertisol	Maize		100	100	100	$0.158^{(H)}$	$11.060^{(H)}$	39.16	37	8.3	20.7
mollisol	potato		100	25	100	$0.130^{(M)}$	$12.136^{(H)}$	39.15	57	8.2	55.0
vertisol	Rapeseed		75	100	100	$0.119^{(L)}$	$17.337^{(L)}$	39.13	41	8.3	22.3
vertisol	wheat	100	75	100	100	$0.128^{(M)}$	$16.406^{(H)}$	39.13	24	8.3	40.2
vertisol	Teff		75	50	100	$0.140^{(H)}$	$11.713^{(H)}$	39.12	40	8.3	38.1
vertisol	wheat		75	100	100	$0.140^{(H)}$	$13.208^{(H)}$	39.12	20	8.3	14.5
vertisol	Garllic		75	125	100	$0.117^{(L)}$	$18.494^{(L)}$	39.10	48	8.1	39.5
vertisol	FB		75	100	100	$0.100^{(L)}$	$20.039^{(L)}$	39.10	26	8.1	28.1
vertisol	barley	100	100	150		$0.103^{(L)}$	$17.990^{(L)}$	39.8	27	8.2	49.2
vertisol	wheat	50	100	100		$0.128^{(M)}$	$13.125^{(H)}$	39.9	37	8.3	32.4
vertisol	Rapeseed		0	100	100	$0.103^{(L)}$	$17.311^{(L)}$	39.9	35	8.4	23.5
vertisol	Field pea		100	75	100	$0.110^{(L)}$	$19.052^{(L)}$	39.9	29	8.5	22.8
vertisol	FB	50	100	100	100	$0.092^{(L)}$	$24.609^{(L)}$	39.9	3.1	8.6	4.6
vertisol	FB	50	100	100	100	$0.117^{(L)}$	$17.003^{(L)}$	39.8	56	7.59	56.2
vertisol	wheat	100	100			$0.146^{(H)}$	$10.564^{(H)}$	39.8	47	7.59	20.2

***Key**: (H)=high S; (M)=marginal S and (L)=low S; vertisols* =are known soils; X^o=degree, Y'=minute; and "=second; FB=faba bean. Altitude range, 1782.64-2647.34m.a.s.l.* ***N.B**: The soils as classified by [14,15,16,17]; and some are the imperial data acquired through field experience, but, need further characterization/classifications*

Table 2. Total sulfur content, N/S-ratio, cropping and farming systems history at E/Shewa zone

Soil type	Last season's crop, & fertilizer used			Investigated crop (wheat) & fertilizer used		TS(%), CL=0.12, and S rating	N/S(Ratio), CL=17, and S rating	Longitude		Latitude	
	Crop	Urea (kg/ha)	DAP (kg/ha)	Urea (kg/ha)	DAP (kg/ha)			X°.Y'	(")	X°.Y'	(")
vertisol	Teff	50	100	150	100	0.142(H)	9.598(H)	39.7	35	8.59	58.0
sandy/gray	teff	50	75	125	100	0.142(H)	12.551(H)	39.7	34	8.59	42.9
sandy/gray	lentil			100	100	0.112(L)	18.750(L)	39.7	32	8.59	5.6
vertisol	Teff	50	50	100	100	0.139(H)	13.125(H)	39.7	12	8.58	32.1
vertisol	wheat	125	100	75	100	0.128(M)	16.680(H)	39.6	26	8.58	0.0
vertisol	maize	100	100	100	100	0.121(M)	17.082(L)	39.6	7.7	8.57	9.1
vertisol	maize	50	100	50	100	0.135(M)	10.362(H)	39.5	38	8.56	43.0
vertisol	Finger millet	50	100	100	100	0.156(H)	9.396(H)	39.4	43	8.55	42.5
vertisol	Teff	50	100	75	75	0.144(H)	11.424(H)	39.4	5.3	8.54	54.1
vertisol	chickpea	50	50	75	75	0.114(L)	18.765(L)	39.3	39	8.54	30.6
vertisol	lentil		100	100	100	0.112(L)	17.188(L)	39.3	30	8.54	18.4
vertisol	Finger Millet	50	100	50	100	0.151(H)	11.118(H)	39.3	30	8.54	5.5
vertisol	lentil		100	100	100	0.098(L)	18.972(L)	39.3	17	8.53	56.3
vertisol	Garlic	100	100	100	100	0.112(L)	19.063(L)	39.3	5.6	8.53	47.9
vertisol	lentil	0	100	75	75	0.103(L)	20.706(L)	39.2	39	8.53	39.3
vertisol	Teff	100	100	100	100	0.128(M)	11.758(H)	39.2	26	8.53	32.3
vertisol	lentil		100	100	100	0.114(L)	11.382(H)	39.2	8.7	8.53	30.7
vertisol	FB		100	75	100	0.112(L)	11.875(H)	39.1	52	8.53	28.5
vertisol	chickpea	50	100	100	100	0.107(L)	17.391(L)	39.2	26	8.52	47.3
vertisol	Finger millet	50	100	50	100	0.172(H)	11.163(H)	39.1	0	8.50	39.0
vertisol	Maize	100	100	100	100	0.148(H)	11.386(H)	39.1	6.1	8.50	21.9
vertisol	Teff	75	75	125	100	0.124(M)	17.438(L)	39.1	32	8.46	48.2
vertisol	Sunflower	75	75	150	100	0.119(L)	14.692(H)	39.2	43	8.46	59.0
vertisol	FB	75	100	100	100	0.117(L)	18.793(L)	39.4	15	8.47	16.8
vertisol	Field pea	75	100			0.107(L)	20.016(L)	39.4	48	8.47	23.8
vertisol	chickpea					0.108(L)	17.106(L)	38.55	56	8.37	22.0
vertisol	Lentil		100	100	100	0.116(L)	17.870(L)	38.56	3.8	8.37	23.7
vertisol	FB		100	100	100	0.117(L)	17.003(L)	38.55	40	8.38	2.0
vertisol	Lentil		100	100		0.114(L)	19.995(L)	38.55	29	8.38	15.0
vertisol	maize	100	100	100	100	0.144(H)	12.153(H)	38.54	57	8.39	1.2
nitosol(red)	Maize	100	100	100	100	0.116(L)	17.264(L)	38.54	45	8.39	19.6
nitosol(red)	Teff	100	100	75	100	0.133(M)	16.013(H)	38.54	9.3	8.40	3.5
nitosol(red)	FB	50	50	100	100	0.106(L)	17.153(L)	38.53	56	8.41	16.5
nitosol(red)	FB	50	50	100	100	0.109(L)	17.264(L)	38.54	12	8.41	25.9

Soil type	Last season's crop, & fertilizer used			Investigated crop (wheat) & fertilizer used		TS(%), CL=0.12, and S rating	N/S(Ratio), CL=17, and S rating	Longitude		Latitude	
	Crop	Urea (kg/ha)	DAP (kg/ha)	Urea (kg/ha)	DAP (kg/ha)			X°.Y'	(")	X°.Y'	(")
nitosol(red)	Teff	100	100	50	100	$0.138^{(H)}$	$8.110^{(H)}$	38.54	45	8.41	47.0
nitosol(red)	wheat	150	100	100	100	$0.131^{(M)}$	$15.719^{(H)}$	38.55	37	8.42	52.8
vertisol	Teff	100	150	125	100	$0.130^{(M)}$	$12.145^{(H)}$	38.51	54	8.48	44.8
vertisol	Teff	50	100			$0.143^{(H)}$	$15.647^{(H)}$	38.51	51	8.48	35.2
vertisol	lentil		100	100	100	$0.113^{(L)}$	$19.541^{(L)}$	38.47	39	8.53	4.1
vertisol	Sunflower		100	100	100	$0.111^{(L)}$	$19.207^{(L)}$	38.48	34	8.53	50.4
vertisol	lentil		100	0	100	$0.101^{(L)}$	$17.664^{(L)}$	38.48	58	8.53	58.5
vertisol	chickpea		100	100	100	$0.103^{(L)}$	$17.715^{(L)}$	38.49	12	8.54	5.8
vertisol	Teff	100	100	100	100	$0.108^{(L)}$	$19.807^{(L)}$	38.49	54	8.51	41.8
vertisol	FB		100			$0.106^{(L)}$	$17.153^{(L)}$	38.50	12	8.51	30.5
vertisol	Teff	100	100	100	100	$0.125^{(M)}$	$15.446^{(H)}$	38.50	48	8.51	12.8
nitosol(red)	Teff	100	150	50	100	$0.131^{(M)}$	$12.522^{(H)}$	38.51	53	8.50	38.9
vertisol	potato	100	100	100	100	$0.123^{(M)}$	$12.810^{(H)}$	38.51	58	8.51	6.6
vertisol	FB		100	75	100	$0.120^{(L)}$	$10.830^{(H)}$	38.52	20	8.51	23.2
vertisol	lentil		100	100	100	$0.116^{(L)}$	$12.047^{(H)}$	38.52	40	8.51	42.0
nitosol(red)	Teff	100	100	125	100	$0.093^{(L)}$	$23.426^{(L)}$	38.53	14	8.51	34.3
vertisol	Field pea	50	100	100	100	$0.109^{(L)}$	$19.822^{(L)}$	38.53	31	8.49	57.3
vertisol	chickpea			100	100	$0.113^{(L)}$	$17.059^{(L)}$	38.53	49	8.49	46.5
vertisol	FB			100	100	$0.115^{(L)}$	$17.114^{(L)}$	38.57	30	8.48	36.4
vertisol	FB		100	150	100	$0.118^{(L)}$	$17.813^{(L)}$	39.2	28	8.43	3.3
vertisol	Teff	100	100		100	$0.123^{(M)}$	$16.511^{(H)}$	39.2	5.5	8.43	41.1
vertisol	Lentil			100	100	$0.120^{(L)}$	$17.562^{(L)}$	39.3	6.7	8.42	25.6
vertisol	Teff	100	100	50	100	$0.131^{(M)}$	$13.055^{(H)}$	39.2	2.2	8.42	47.2
vertisol	Teff			100	100	$0.121^{(M)}$	$16.740^{(H)}$	39.1	42	8.42	22.8
vertisol	Teff	100	100	50	50	$0.125^{(M)}$	$15.446^{(H)}$	39.2	11	8.41	25.9
vertisol	Teff	100	100	100	100	$0.123^{(M)}$	$14.803^{(H)}$	39.2	40	8.40	24.0
vertisol	Field pea		100	75	100	$0.118^{(L)}$	$16.328^{(H)}$	39.3	35	8.39	40.6
nitosol(red)	FB		100	100	100	$0.123^{(M)}$	$16.226^{(H)}$	39.2	14	8.39	54.9
vertisol	Teff	100	100	125	100	$0.123^{(M)}$	$15.657^{(H)}$	39.2	15	8.39	41.0
vertisol	Teff	125	100	100	100	$0.126^{(M)}$	$16.071^{(H)}$	39.2	21	8.39	11.7
vertisol	Teff	100	100	150	100	$0.126^{(M)}$	$17.733^{(L)}$	39.2	12	8.38	54.6
vertisol	Teff	100	100	100	100	$0.148^{(H)}$	$15.822^{(H)}$	39.1	57	8.38	12.2

***Key**: (H)=high S; (M)=marginal S and (L)=low S; vertisols* =are known soils; X°=degree, Y'=minute; and "=second; FB=faba bean. Altitude range, 1837.67–2453.87m.a.s.l. **N.B**: The soils as classified by [14,15,16,17]; and some are the imperial data acquired through field experience, but, need further characterization/classifications*

Table 3. Total sulfur content, N/S-ratio, cropping and farming systems history at O/Liuu (West Shewa zone)

Soil type	Last season's crop, & fertilizer used			Investigated crop (wheat) & fertilizer used		TS(%), CL=0.12, and S rating	N/S(Ratio), CL=17, and S rating	Longitude		Latitude	
	Crop	Urea (kg/ha)	DAP (kg/ha)	Urea (kg/ha)	DAP (kg/ha)			X^{o}.Y'	(")	X^{o}.Y'	(")
nitosol(red)	Maize	100	100	50	100	$0.131^{(M)}$	$14.920^{(H)}$	38.31	45	8.55	23.5
vertisol	chickpea			100	100	$0.104^{(L)}$	$20.446^{(L)}$	38.30	49	8.56	5.4
nitosol(red)	FB		100	75		$0.103^{(L)}$	$17.374^{(L)}$	38.31	12	8.56	31.4
nitosol(red)	Potato	50	100	100		$0.093^{(L)}$	$22.670^{(L)}$	38.31	22	8.57	47.9
nitosol(red)	Lentil		100	100	100	$0.106^{(L)}$	$17.813^{(L)}$	38.30	32	8.57	57.6
nitosol(red)	Field pea		100	125	100	$0.109^{(L)}$	$17.904^{(L)}$	38.30	5.8	8.57	18.2
nitosol(red)	Barley	50	100	100	100	$0.108^{(L)}$	$17.534^{(L)}$	38.29	36	8.57	3.4
nitosol(red)	FB	0	100		100	$0.081^{(L)}$	$27.275^{(L)}$	38.30	14	8.57	37.9
vertisol	Teff	100	100		100	$0.128^{(M)}$	$16.133^{(H)}$	38.30	41	8.58	26.3
vertisol	Barley	50	100	100	100	$0.133^{(M)}$	$14.731^{(H)}$	38.30	33	8.58	57.1
vertisol	Teff	100	100	150	100	$0.131^{(M)}$	$12.256^{(H)}$	38.30	54	8.59	23.0
vertisol	Barley	50	100	100	100	$0.123^{(M)}$	$14.803^{(H)}$	38.30	51	9.1	0.5
nitosol(red)	maize	100	100	100	100	$0.131^{(M)}$	$11.456^{(H)}$	38.30	31	9.1	33.1
nitosol(red)	FB		100	50	100	$0.120^{(L)}$	$12.586^{(H)}$	38.30	3.7	9.2	9.4
nitosol(red)	Lentil		100	100	100	$0.113^{(L)}$	$17.369^{(L)}$	38.27	28	8.59	57.4
nitosol(red)	Field pea		100	75	100	$0.101^{(L)}$	$17.318^{(L)}$	38.27	33	9.2	2.9
nitosol(red)	Maize	100	100	100	100	$0.152^{(H)}$	$9.698^{(H)}$	38.27	40	9.3	15.2
nitosol(red)	Teff	100	100	125	100	$0.126^{(M)}$	$10.806^{(H)}$	38.27	50	9.4	44.8
nitosol(red)	Teff	100	100	100	100	$0.121^{(M)}$	$11.834^{(H)}$	38.28	13	9.1	5.2
nitosol(red)	wheat	125	100	100	100	$0.121^{(M)}$	$16.163^{(H)}$	38.28	26	9.1	25.1
nitosol(red)	FB	75	75	50	100	$0.111^{(L)}$	$17.003^{(L)}$	38.28	46	9.1	30.2
nitosol(red)	maize	75	100	50	100	$0.126^{(M)}$	$15.794^{(H)}$	38.29	9.9	9.1	43.1
vertisol	teff	50	50	50	50	$0.158^{(H)}$	$9.948^{(H)}$	38.28	39	9.2	35.6
nitosol(red)	teff		100		100	$0.123^{(M)}$	$13.380^{(H)}$	38.28	53	9.2	34.7
nitosol(red)	Fallow			100	100	$0.163^{(H)}$	$9.212^{(H)}$	38.28	35	9.3	10.3
nitosol(red)	Potato	75	75	75	75	$0.108^{(L)}$	$17.209^{(L)}$	38.27	41	9.3	21.5
nitosol(red)	FB		100	75	75	$0.120^{(L)}$	$12.000^{(H)}$	38.28	46	9.3	49.4
nitosol(red)	Sunflower	50	100			$0.118^{(L)}$	$12.766^{(H)}$	38.27	48	9.10	17.7
nitosol(red)	G.abyssinica	50	50	100	100	$0.098^{(L)}$	$22.214^{(L)}$	38.27	35	9.9	31.3
nitosol(red)	potato		100	100	100	$0.108^{(L)}$	$17.209^{(L)}$	38.27	11	9.9	5.0
nitosol(red)	Field pea		100	125	100	$0.094^{(L)}$	$22.266^{(L)}$	38.26	43	9.8	52.4
nitosol(red)	Field pea		100	100	100	$0.089^{(L)}$	$23.134^{(L)}$	38.26	39	9.8	21.5
nitosol(red)	FB		100	75	75	$0.086^{(L)}$	$24.449^{(L)}$	38.26	41	9.7	30.5
nitosol(red)	teff	75	100			$0.113^{(L)}$	$12.097^{(H)}$	38.27	1.3	9.6	50.8

Soil type	Last season's crop, & fertilizer used			Investigated crop (wheat) & fertilizer used		TS(%), CL=0.12, and S rating	N/S(Ratio), CL=17, and S rating	Longitude		Latitude	
	Crop	Urea (kg/ha)	DAP (kg/ha)	Urea (kg/ha)	DAP (kg/ha)			$X^o.Y'$	(")	$X^o.Y'$	(")
vertisol	lentil	50	50	75	75	$0.109^{(L)}$	$19.822^{(L)}$	38.28	42	9.4	52.3
nitosol(red)	2-years fallow					$0.160^{(H)}$	$10.500^{(H)}$	38.24	58	9.9	25.7
nitosol(red)	Barley	50	75			$0.103^{(L)}$	$17.715^{(L)}$	38.25	52	9.8	28.9
nitosol(red)	Barley	100	100			$0.081^{(L)}$	$22.513^{(L)}$	38.25	59	9.8	16.4
nitosol(red)	FB	75	75	75	100	$0.083^{(L)}$	$26.719^{(L)}$	38.26	6.5	9.8	4.7
nitosol(red)	FB	50	50	50	50	$0.108^{(L)}$	$17.209^{(L)}$	38.31	12	9.5	39.6
nitosol(red)	Field pea	50	75	50	75	$0.093^{(L)}$	$23.426^{(L)}$	38.31	18	9.5	48.3
nitosol(red)	Field pea	50	50			$0.101^{(L)}$	$18.357^{(L)}$	38.31	34	9.6	11.6
nitosol(red)	Barley	50	100	50	50	$0.118^{(L)}$	$17.219^{(L)}$	38.31	34	9.6	41.0
nitosol(red)	Teff	50	100		100	$0.135^{(M)}$	$14.547^{(H)}$	38.31	9.3	9.6	55.0
nitosol(red)	teff	150	100	50	75	$0.121^{(M)}$	$15.586^{(H)}$	38.31	22	9.5	29.4
nitosol(red)	potato	50	100	150	100	$0.121^{(M)}$	$16.452^{(H)}$	38.31	47	9.4	58.9
nitosol(red)	potato	50	50	50	50	$0.125^{(M)}$	$16.007^{(H)}$	38.32	1.8	9.4	40.0
nitosol(red)	barley		100	50	50	$0.098^{(L)}$	$24.723^{(L)}$	38.32	17	9.4	16.5
nitosol(red)	potato	FYM	FYM		75	$0.109^{(L)}$	$17.584^{(L)}$	38.32	11	9.4	7.6
nitosol(red)	teff	100	100			$0.150^{(H)}$	$9.807^{(H)}$	38.33	29	9.3	23.3
nitosol(red)	Maize	100	100			$0.173^{(H)}$	$7.869^{(H)}$	38.33	39	9.3	1.1
nitosol(red)	teff	50	75	80	80	$0.148^{(H)}$	$9.210^{(H)}$	38.33	23	9.2	56.5
nitosol(red)	potato	75	75	50	100	$0.115^{(L)}$	$12.530^{(H)}$	38.32	3.6	9.5	37.5
nitosol(red)	G.abyssinica		100	50	100	$0.118^{(L)}$	$17.516^{(L)}$	38.31	50	9.5	14.4
nitosol(red)	maize	75	75	50	100	$0.126^{(M)}$	$13.023^{(H)}$	38.32	9	9.4	50.9
nitosol(red)	teff	50	100	compost	100	$0.140^{(H)}$	$14.772^{(H)}$	38.33	47	9.3	1.7
nitosol(red)	FB	50	75	50	50	$0.089^{(L)}$	$23.918^{(L)}$	38.33	1.9	9.2	38.5
nitosol(red)	tomato	50	100	FYM	100	$0.083^{(L)}$	$23.326^{(L)}$	38.32	39	9.2	10.8
nitosol(red)	Field pea		100	50	75	$0.098^{(L)}$	$23.648^{(L)}$	38.32	38	9.2	4.1
nitosol(red)	Lentil			50	50	$0.098^{(L)}$	$21.140^{(L)}$	38.33	15	9.2	26.7
nitosol(red)	FB			150	75	$0.099^{(L)}$	$21.133^{(L)}$	38.33	13	9.2	43.2
nitosol(red)	Barley	60	60	50	75	$0.103^{(L)}$	$17.374^{(L)}$	38.32	3.1	9.3	52.8
nitosol(red)	Field Pea	50	75	150	75	$0.098^{(L)}$	$22.573^{(L)}$	38.31	52	9.3	42.8
nitosol(red)	potato	50	75	50	50	$0.089^{(L)}$	$25.486^{(L)}$	38.31	38	9.3	38.6
nitosol(red)	wheat	150	100	100	100	$0.101^{(L)}$	$17.318^{(L)}$	38.30	45	9.4	50.0
nitosol(red)	FB	50	100	50	100	$0.106^{(L)}$	$17.483^{(L)}$	38.30	44	9.4	36.4

***Key**: (H)=high S; (M)=marginal S and (L)=low S; vertisols* =are known soils; X^o=degree, Y'=minute; and "=second; FB=faba bean. Altitude range, 2159.23– 2736.5m.a.s.l. **N.B**: The soils as classified by [14,15,16,17]; and some are the imperial data acquired through field experience, but, need further characterization/classifications*

But, when considering, 15:1 as a CL for N/S-ratio as reported by [13,24], most studied fields again become more severely deficient in S. Based on this criterion, therefore, about 72.1% of the fields in Arsi, 66.7% in ES and 65.1% at OL, were found to be severely S deficient, making the overall S deficient sites in the three locations to be 68.0%. This further confirms that, the S deficiency is becoming wide-spread in annual crop-lands in Ethiopia. However, the immediate application rates of S will depend on the S status of soils and/or plants at the time or point of sampling/planting, because fertilizers application rates are location specific.

3.3 Causes of S Deficiency in the Studied Locations

In general, as observed, the S status has reached to this alarmingly low level due to the cropping and farming systems (extractive farming –the use of high-analysis fertilizers lacking adventitious sulfur) with high-yielding varieties of crops and hybrids. Tables 1 through 3 simultaneously show the cropping sequence and the farming systems, particularly, the past and present inorganic fertilizer (mainly urea and DAP) use in the three locations. It is also shown that, farmers in the areas mainly rotate legumes or oil crops with cereals as indigenous soil fertility or pest management practices. Both practices, can lead to a considerable amount of S depletion from the native soil, if the corresponding amounts of S are not applied through fertilizer. Jamal et al. [25], reported that, for oil crop producers, S fertilizer is especially important, because they require more S than cereals. According to the authors, the amount of S required to produce one ton of seed is about 3-4 kg S for cereals, ranging 1-6; 8 kg S for legume crops, ranging 5-13; and 12 kg S for oil crops, ranging 5-20. In general, oil crops require about the same amount of S as, or more than P for high yield and product quality. Therefore, in Ethiopia, in such intensive crop rotations including legume and oil crops, S up-take can be very high, especially when crop residues are removed from fields along with the produce.

In addition, almost all farmers in the studied areas use significant amount of urea and DAP (fertilizers, lacking adventitious S) with high-yielding varieties and hybrids, even with legumes and oil crops (Tables 1 through 3). Weil [1], reported that the use of such high-analysis fertilizers, that contain little or no S are leading to sulfur deficiency in agricultural soils of Africa. The farmers also use free grazing after crop harvest, (i.e., cattle are left in farm-fields after crop harvest in order to browse/graze on crop residues until next season land preparation (data not shown). This will actually mine nutrients from out/mid-fields and bring them into in-fields, areas closer to homestead. This will negatively affect SOM dynamics and nutrient-recycling into the system, thereby adversely affecting next season's crop harvest. Most organic recourses also have alternative uses. Not only this, but also during the crops' growing periods, farmers in the studied areas remove, plant biomass in the form of weed and heap-up in areas outside of farm-fields or use as cattle feed, that will further negatively affect plant nutrients, notably S return into soils.

In general, as observed, some of the root causes of S deficiency in annual cropped lands in the CHLs of Ethiopia, areas with high crop production potential, may be summarized as: i) increased use of high-analysis fertilizers (urea & DAP that contain little or no S); ii) intensive cropping-systems that include legumes and oil crops, that mine more S from native soil; iii) traditional practices that leave behind little OM and/or its complete removal including farm yard manure (FYM) for various alternative uses; v) increased crop yields due to the use of improved varieties and hybrids resulting in more S removal; vi) may be due to no or less deposition of S from atmosphere due to no significant industrial sector development, and less or no use of S containing pesticides; and vii) other losses of SO_4-S (e.g., leaching/run off, because CHLs of Ethiopia are endowed with an abundant precipitation). Such reasons are more pronounced in the CHLs of Ethiopia, areas with high crop production potential, most likely to be driven by high market access for the harvested produce in big towns and city in the centre of the country.

4. CONCLUSIONS AND RECOMMENDA-TIONS

- The survey study further affirmed that, S deficiency is widespread and is becoming one of the soil health challenges in annually cropped lands in Ethiopia. This alarmingly low level of soils S was mainly due to both the cropping and farming systems, which could affect food security through yield and quality losses.
- Among others, the farming and cropping systems are found to be the root cause for

the observed S-deficiency in the studied locations.

- Therefore, there is a need to integrate sulfur from known/trusted sources into a balanced fertilizer formula, if soil-test and crop-response data are available. The sulfur can come from locally available source (e.g., gypsum), to use its integrative benefits and economize fertilizer use. Arresting soil erosion in order to reduce nutrients loss from farm fields is also important.
- Based on my field experience/observation, and farmers practice, DAP, TSP and urea are still the most effective fertilizers under Ethiopian farming conditions. So, blending sulfur with DAP or TSP to be applied into soils at planting is imperative, as both S and P limit plant growth in its early stages.
- The overall studies revealed that, crop response to S depends on specific soil conditions and/or agro-ecological zones. Given the spatial and temporal dynamics in soils environment, therefore, immediate application rates of S and other nutrients should depend on soil-tests and/or crop-responses, for soil management research is location specific, as several factors interact to define a given site.

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COMPETING INTERESTS

Author has declared that no competing interests exist.

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