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Spatial and temporal variability of soil micronutrients and their relationships with wheat (*Triticum aestivum* L.) yield and some major soil variables

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Studying the spatial and temporal variability of soil micronutrients and their effects on plant growth is important for implementing precision-farming and/or economizing fertilizer management. The present investigation was done through soil sampling (0–20 cm depth) from three locations in central Ethiopia. The tools employed include, descriptive and/or classical statistics. The concentrations of available copper ranged from 1.38–3.20 mg/kg with narrower range in season-I, than season-II. Manganese ranged from 5.00 – 65.00 mg/kg, indicating its significant uneven distribution over the years and locations. The concentrations of iron ranged from 1.80 – 8.20 mg/kg. Narrower ranges were observed for zinc, boron and molybdenum. From the influencing factors analysis, soil pH was the major factor negatively influenced the availability of the evaluated micronutrients, except molybdenum. Organic carbon was the major positive contributor to sulfur, nitrogen, manganese, zinc, and boron availability. Considering the widely varied wheat yields due to the variations in soil nutrients, more positive relationship was established for the grain than total biomass yield indicating more partitioning of plant nutrients into grains. Overall, the dynamics of soil nutrients, particularly the micronutrients and their influences on wheat yield were described and the results could provide practical bases for sustaining crop production in precision-agriculture.

Key words: Soil micronutrients, spatial and temporal variability, geostatistics, regression, correlation.

INTRODUCTION

Micronutrients are metal elements that play critical role in plant growth and sustaining their metabolic processes. Though needed in small quantities, if soils are deficient in those trace elements, plant growth and development are negatively affected resulting in reduced yield and quality. However, according to Rengel and Marschner (2005), micronutrients deficiency in soils can not only be due to their inherent low levels, but can also be due to their chemical or biological fixation and spatio-temporal variations or unavailability. In such conditions, however, micronutrient-efficient varieties of crops can have greater yield advantage in comparison with the in-efficient ones,

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even when fertilizers are applied at lower rates and less frequently (Rengel and Marschner, 2005). Knowledge of the spatial variations or temporal un-availabilities of micronutrients in agricultural fields and their relationships to each other or with other major soil variables are critically important to improve soil and crop management practices. Such relationships can also be important in predicting factors affecting soil micronutrients and thus increase the efficiency of fertilizer use. Geographic information systems have been used to characterize the variability of soil micronutrients at field scale (Ramzan and Wani, 2018). In India, Arvind et al. (2016) mapped the spatial distribution of micronutrients using ordinary Kriging or Semi-virograms and suggested different management options. Such methods were also hopped to provide the basis to interpolate or extrapolate recommendations based on the relative homogeneity of soils and their related properties at different scales.

Factors influencing the spatial or temporal variability of micronutrients, such as parent material, topography, climate and vegetation are widely recognized. However, according to Li et al. (2007), Wu et al. (2014) and Jiménez-Ballesta et al. (2017), their concentrations in soils are rarely indicative of plant availability, being influenced by organic matter, pH, adsorptive surfaces and related soil physico-chemical and biological factors. Such variability of soil properties can also be caused by management practices like cultivation history (tillage type and intensity, type and rate of fertilizer-applied, and crop species grown) and variability arising from uneven field management (O¨zgo¨z, 2009; Wang et al., 2009; Zhang et al., 2011). This, indeed, will affect soil dynamics and crops performance. Therefore, characterizing and understanding spatial variability or distribution of micronutrients are essential for predicting rates of ecosystem processes and functions with respect to natural and anthropogenic factors. They are also important to locate homogenous sites that need similar treatment (Schimel et al., 2000; O¨zgo¨z, 2009). The spatial and temporal heterogeneity of soil properties and its influencing factors have been discussed, using traditional statistical methods (Schade and Hobbie, 2005; Housman et al., 2007; Abril et al., 2009) and descriptive statistics (Liu et al., 2009). In view of the above background, the objectives of this study were (1) to assess the interrelationships among micronutrients and other related soil properties (2) to examine the variability of available soil micronutrients in relation to wheat yield, other related soil variables and factors influencing them.

MATERIALS AND METHODS

Site selection, experimental treatments and design

In three locations, namely Arsi (Ar), East Shewa (ES) and West Shewa (WS) zones in Ethiopia, twenty four (24) sites were randomly selected and geo-referenced using Global Positioning System (GPS), GARMIN-model #GPS-60 assisted by Google earth (2011). The specific locations and some of the salient features of the selected sites are presented in Table 1. Twenty-four on-farms experiments (18 in Season-I; and six in Season-II, that is, in 2013/14 and 2015/16), respectively were installed for evaluating wheat response to nitrogen (N), phosphorus (P) and sulfur (S). In this paper, out of 24, 12 sites which are representative to soil sampling were considered. All the sites were year and site replicated. In Season-II, the six sites were randomly selected on areas some 0.5 – 3.0 km away from the previous year (Season-I's) sites depending on wheat response to NPS fertilizers. The experiments were conducted in a nutrient omission fashion using bread wheat knows locally as "kekeba" as a test-crop. In Season-I, four treatments were tested: absolute control (without fertilizer) tagged CK; N alone tagged N1; N and S tagged N1S1; and N, P and S tagged N1P1S1. The nutrients evaluated were: 2-levels N (0 and 69 kg N/ha); 2-levels of P (0 and 20 kg P/ha); and 2-levels of S (0 and 20 kg S/ha). But, in Season-II, five additional treatments were included: CK; N alone = N1; NS1; NS2; NS3; nitrogen and phosphorus (NP) = (N1P1); NPS1; NPS2; and NPS3. Here, the nutrient levels used were 2-levels of N (N = 0, and N = 69 kg N/ha); 2-levels of P (P = 0 and P1 = 20 kg P/ha); and 4-levels of S (S = 0, S1 = 5, S2 = 10 and S3 = 20 kg S/ha). Experiments were laid-out in randomized complete block design (RCBD) in triplicate. Each replicate was sub-divided into a 3 x 5 m = 15 m^2 plots. Plant spacing for wheat 25 cm by 5 cm (between rows and plants) respectively was used. In doing so, utmost care was taken to maintain the recommended number of plants per row though replanting and/or tinning to compensate for the ungerminated seeds, if there were any. In total, there were 12-rows of plants per plot with two borders on each side. Another one row next to one border row was used for plant sampling, whereas the central rows, a 4 x 1.5 m = 6 m^2 were used for collecting yield/agronomic data. Urea-N was split-applied; where 1/3 was incorporated into soils before seeding and the remaining 2/3 was top-dressed at the stage of tillering. The entire sulfur and phosphorus (S and P) were incorporated into soils just before seeding. The highest levels of N and S were based on local recommendations or the experiences from other areas for wheat. The land was prepared by oxen plough and finally made uniform by using rakes. To avoid weed competition, hand weeding was done as needed. During the entire growing period, records on relevant agronomic data like total above ground biomass (TAGBY), grain yield (GY), stover yield (SY), plant height (PH), number of tiller per plant (NTPP), spike length (SL), spike weight (SW) were made. Harvesting was commenced when the average wheat grain dry moisture content reached 13.5%, which was done by taking plants from one row meant for plants sampling.

Soil sampling, preparation and analysis

Before planting, surface soil samples (0-20 cm depth) were collected during the two seasons. Soils were sampled from 10 different spots from each block and bulked into composite sample per farmer field. The samples then were air-dried, ground to pass 1-mm sieve, and analyzed for Cu, Mn, Fe, Zn, B, Mo, pH, organic carbon (OC), electrical conductivity (EC), total nitrogen (TN), available phosphorous Av. P, SO_4-S, exchangeable bases, CEC, base saturation or saturation percent (SP) and soil texture, employing the procedures outlined in Table 2. For presenting and interpreting of the results, traditional or descriptive statistics such as mean, median, range, standard deviation (Std Dev), coefficient of variation (CV), kurtosis and skewness for the micronutrients Cu, Mn, Fe, Zn, B, Mo and related soil variables in the native soils (Tables 3 and 4), were used. Furthermore, the spatial and temporal heterogeneity of soil properties and its influencing factors have been discussed using correlation and regression (Tables 5, 6 and 7).

Table 1. Geographical locations of the selected study sites.

Location/Zone	Site/farmer field	Latitude (N)		Longitude (E)		Altitude (m)	Soil type
		Xo	Y'.Z"	Xo	Y'.Z"		
Arsi (Ar)	Wonji Gora1/Dosha1(WG1/Do1)	7	53.813	39	6.176	2418.32	Nitosol
	Gora Silingo1 (GS1)	8	0.792	39	8.436	2151.10	Light Vertisol
	Wonji Gora2/Dosha2 (WG2/Do2)	7	59.944	39	8.876	2123.74	Pellic Vertisol
	Gora Silingo2 (GS2)	8	0.833	39	8.444	2229.54	Nitisol
East Shewa (ES)	Keteba1 (Ke1)	8	53.553	39	1.913	2224.37	Pellic Vertisol
	Bekejo1 (Bk1)	8	38.376	38	55.322	1874.16	Pellic Vertisol
	Keteba2 (Ke2)	8	52.814	39	2.344	2224.37	Pellic Vertisol
	Bekejo2 (Bk2)	8	37.378	38	55.796	1874.16	Chromic Vertisol
West Shewa (WS)	Nano Suba1 (NS1)	8	57.287	38	29.756	2229.54	Nitosol
	Berfeta Tokofa1 (BT1)	8	59.605	38	30.98	2252.64	Nitosol
	Nano Suba2 (NS2)	8	57.249	38	29.989	2229.54	Nitisol
	Berfeta Tokofa2 (BT2)	9	0.227	38	30.826	2252.64	Pellic Vertisol

Numbers (1) and (2) are used to indicate the information which was generated in Season-I and Season-II respectively.

Table 2. The laboratory procedures followed for the determination of the selected soil in the soils studied.

Parameters	Unit	Extraction/Analytical method by	References
pH	-	Potentiometrically,1:2.5;Soil:Water	Van Reeuwijk (1993)
EC	mS/cm	1:5 soil:water suspension	Klute (1986)
Exch.bases (Na^1, K^1)	$cmol_c$/kg	1*M.*NH4OAc-solution, pH=7.00	Rowell (1994)
Exch.bases (Ca^{2+}, Mg^{2+})	$cmol_c$/kg	1*M.*NH4OAc-solution, pH=7.00	Van Reeuwijk (1993)
CEC	$cmol_c$/kg	1*M.*NH4OAc-solution, pH=7.00	Van Reeuwijk (1993)
Saturation percent (SP)	%	Lab results from Exch. bases	Van Reeuwijk (1993)
TN	%	Kjeldahl Digestion	Okalebo et al. (2002)
OC	%	Walkley-Black as described in	Nelson and Sommers (1996)
Av. P	mg/kg	Bray-I,(pH<7.00), acidic soils	Bray and Kurtz (1945)
Av. P	mg/kg	Olsen,(pH>7.00), alkaline soils	Olsen et al. (1954)
SO_4-S (SO_4^{2-})	mg/kg	Calcium Ortho-Phosphate, Turbidi-metric	Rowell (1994)
Soil-texture	%	Hydrometer	Bouyoucos (1962)
Copper	mg/kg	(DTPA/-AAS)	Lindsay and Norvell (1978)
Manganese	mg/kg	(DTPA/-AAS)	Lindsay and Norvell (1978)
Iron	mg/kg	(DTPA/-AAS)	Lindsay and Norvell (1978)
Zinc	mg/kg	(DTPA/-AAS)	Lindsay and Norvell (1978)
Boron	mg/kg	Hot-water-soluble	Berger KC and Truog E (1939)
Molybdenum	mg/kg	Acid-NH_4-Oxalate, pH3.3 extractable	Grigg (1953) and Lombin (1985)

DTPA = Diethylene-tetramine-penta-acetic; AAS = atomic-absorption-spectrometry; SP = saturation percent (base saturation).

Statistical analysis

Data on yield and yield components of wheat were analyzed using SAS-version 2002 (SAS, 2002). Analysis of variance (ANOVA) was done using PROC-MIXED of generalized linear model for SAS to evaluate the differences between variables. When the differences between treatments were significant, least significant difference (LSD) was used to separate means at 0.1, 1 and 5% probability levels. Correlation and regression analysis were done using the PROC-REG (SAS, 2002).

RESULTS AND DISCUSSION

Physico-chemical properties of soils

Comparing the seasons, the respective mean values of Cu, Mn, Fe, Zn, B and Mo were varied from 1.78 to 2.53 mg/kg, 37.45 to 39.26 mg/kg, 4.82 to 4.68 mg/kg, 0.73 to 0.81 mg/kg, 0.35 to 0.56 mg/kg and 0.22 to 0.22 mg/kg respectively (Table 3). Though there was no significant

Table 3. Contents of micronutrients and related soil variables under native soil conditions: Arsi, East Shewa and West Shewa zones before planting.

Location/Zone	Site	Alt (m)	Soil Type	pH (1:2.5, soil:H$_2$O)	OC (%)	TN (%)	Av. P (mg/kg)	SO$_4$-S (mg/kg)	Exch. Ca^{2+} (cmol$_c$/kg)	SP (%)	Cu (mg/kg)	Mn (mg/kg)	Fe (mg/kg)	Zn (mg/kg)	B (mg/kg)	Mo (mg/kg)	GY (t/ha)	TAGBY (t/ha)	Soil Tex.
2013/14																			
Arsi	Do1	2418.32	Nit	5.30	2.04	0.25	1.84	10.44	7.55	42.48	1.38	59.67	6.40	1.01	0.44	0.04	1.84	8.96	C
Arsi	GS1	2151.10	CV	6.12	1.17	0.14	3.73	7.77	12.52	68.24	1.65	43.33	3.50	0.63	0.43	0.03	1.39	4.75	SC
East Shewa	Ke1	2224.37	PV	8.14	1.06	0.06	7.55	5.78	29.65	96.47	1.47	6.70	1.80	0.33	0.23	1.08	1.29	4.88	C
East Shewa	Bk1	1874.16	PV	7.33	1.31	0.07	10.82	1.30	23.97	93.39	2.11	5.00	1.90	0.26	0.35	0.04	1.38	5.23	SC
West Shewa	N/S1	2229.54	Nit	5.65	1.47	0.13	0.39	5.64	3.48	45.73	2.29	50.00	7.10	0.91	0.41	0.07	1.32	5.52	C
West Shewa	BT1	2252.64	Nit	5.07	1.69	0.12	1.89	3.82	3.65	41.60	1.75	60.00	8.20	1.25	0.25	0.06	1.16	3.90	CL
Sum-I	na	na	na	37.61	8.74	0.77	26.22	34.75	80.82	37.61	10.65	224.7	28.9	4.39	2.11	1.32	8.38	33.24	na
Mean-I	na	na	na	10.75	2.50	0.22	7.49	9.93	23.09	10.75	1.78	37.45	4.82	0.73	0.35	0.22	1.40	5.54	na
2015/16																			
Arsi	Do2	2418.32	PV	5.36	2.71	0.21	2.01	31.98	5.11	31.9	2.56	61.67	4.10	0.87	1.60	0.06	1.58	5.22	C
Arsi	GS2	2151.10	Nit	6.24	2.18	0.17	3.01	12.11	6.11	65.24	2.47	41.67	4.60	0.93	0.38	0.05	1.36	4.08	CL
East Shewa	Ke2	2224.37	PV	8.00	1.15	0.05	9.02	6.77	30.35	93.31	1.47	6.70	2.10	0.36	0.34	1.06	1.13	3.03	C
East Shewa	Bk2	1874.16	CV	7.15	1.17	0.08	12.01	4.03	19.72	83.2	3.20	5.50	2.20	0.49	0.21	0.05	1.10	2.95	SC
West Shewa	N/S2	2229.54	Nit	5.85	0.96	0.14	0.89	4.58	4.01	53.16	2.38	55.00	6.90	0.98	0.44	0.05	1.08	2.91	C
West Shewa	BT2	2252.64	PV	4.85	2.03	0.15	0.50	35.83	5.10	26.0	3.11	65.00	8.20	1.21	0.41	0.04	1.50	5.46	C
Sum-II	-	na	na	37.45	10.20	0.80	27.44	95.30	70.40	352.81	15.19	235.54	28.10	4.84	3.38	1.31	7.75	23.65	na
Mean-II	-	na	na	10.70	2.91	0.23	7.84	27.23	20.11	100.80	2.53	39.26	4.68	0.81	0.56	0.22	1.29	3.94	na
Range (Do1-Do2)	-	-	-	±0.06	±0.67	0.04	±0.17	±21.54	2.44	10.58	±1.18	±2.00	2.30	0.14	±1.16	±0.02	0.26	3.74	
Range (GS1-GS2)	-	-	-	±0.12	±1.01	±0.03	0.72	±4.34	6.41	3.00	±0.82	1.66	±1.1	±0.3	0.05	±0.02	0.03	0.67	
Range (Ke1-Ke2)	-	-	-	0.14	±0.09	0.01	±1.47	±0.99	±0.7	3.16	0.00	0.00	±0.3	±0.03	±0.11	0.02	0.16	1.85	
Range (Bk1-Bk2)	-	-	-	0.18	0.14	±0.01	±1.19	±2.73	4.25	10.19	±1.09	±0.5	±0.3	±0.23	0.14	±0.01	0.28	2.28	
Range (N/S1-N/S2)	-	-	-	±0.2	0.51	±0.01	±0.5	1.06	±0.53	±7.43	±0.09	±5.00	0.2	±0.07	±0.03	0.02	0.24	2.61	
Range (BT1-BT2)	-	-	-	0.22	±0.34	±0.03	1.39	±32.01	±1.45	15.6	±1.36	±5.00	0.0	0.04	±0.16	0.02	±0.34	±1.56	
Sum-All	na	na	na	75.06	18.94	1.57	53.66	130.05	151.22	740.72	25.84	460.24	57.00	9.23	5.49	2.63	16.13	56.89	na
Mean-All	na	na	na	6.255	1.5783	0.1308	4.4717	10.838	12.602	61.727	2.1533	38.353	4.75	0.7692	0.4575	0.2192	1.3442	4.7408	na
Std Dev-All	na	na	na	1.136	0.5497	0.0607	4.2092	11.191	10.457	25.215	0.625	24.901	2.5051	0.3439	0.3691	0.3976	0.222	1.6527	na
CV(%)-All	na	na	na	-	-	-	-	-	-	-	29.025	64.926	52.739	44.709	80.678	181.387	na	na	na
Max-All	na	na	na	8.14	2.71	0.25	12.01	35.83	30.35	96.47	3.20	65.000	8.20	1.25	1.6	1.08	1.84	8.96	na
Min-all	na	na	na	4.85	0.96	0.05	0.39	1.3	3.48	26	1.38	5.000	1.80	0.26	0.21	0.03	1.08	2.91	na
Range-all	na	na	na	3.29	1.75	0.2	11.62	34.53	26.87	70.47	1.82	60.000	6.40	0.99	1.39	1.05	0.76	6.05	na
CL	na	na	na	-	2.0	0.2	20.0	10-13	5.0	20.0	0.20	1.00	4.50	1.0	0.5-0.52	0.10	≥8.50	-	-

Soil Types (CV = Chromic Vertisol, RNi = Red Nitisol, PV = Pellic Vertisol); and Soil Texture (SCL = Sandy clay loam, C = Clay, SC = Sandy clay, and CL = Clay loam); and Av. P (for pH > 7.0, Olsen; and for pH < 7.0, Bray-1 method). CL = critical levels/or threshold values. Three soil pH conditions: medium (Ar); high (ES) and low (WS).Soils from ES are calcareous with nodules of CaCO$_3$; na = not applicable. Range here indicates the differences between the values of soil variables of season-I and season-II.

change in the mean values over years in some variables, significant variations were observed on individual values over sites. These variations were

Table 4. The mean, standard deviation, sum, range and coefficient of variations of soil variables.

Variable	N	Mean	(Std Dev)	Sum	(Min)	(Max)	Range	CV (%)
Site	12	6.50000	3.60555	78.00000	1.00000	12.00000	11	na
pH	12	6.25500	1.13597	75.06000	4.85000	8.14000	3.29	18.16
OC	12	1.57833	0.54971	18.94000	0.96000	2.71000	1.75	34.83
TN	12	0.13083	0.06067	1.57000	0.05000	0.25000	0.2	46.37
Av. P	12	4.47167	4.20920	53.66000	0.39000	12.01000	11.62	94.13
SO_4-S	12	10.83750	11.19116	130.05000	1.30000	35.83000	34.53	103.26
Ca^{2+}	12	12.60167	10.45675	151.22000	3.48000	30.35000	26.87	82.98
SP	12	61.72667	25.21520	740.72000	26.00000	96.47000	70.47	40.85
Cu	12	2.15333	0.62496	25.84000	1.38000	3.20000	1.82	29.02
Mn	12	38.35333	24.90138	460.24000	5.00000	65.00000	60	64.93
Fe	12	4.75000	2.50509	57.00000	1.80000	8.20000	6.4	52.74
Zn	12	0.76917	0.34387	9.23000	0.26000	1.25000	0.99	44.71
B	12	0.45750	0.36911	5.49000	0.21000	1.60000	1.39	80.68
Mo	12	0.21917	0.39759	2.63000	0.03000	1.08000	1.05	181.41
GY	12	1.34417	0.22199	16.13000	1.08000	1.84000	0.76	16.52
TAGB	12	4.74083	1.65265	56.89000	2.91000	8.96000	6.05	34.86

important, because micronutrients are needed in small quantities by plants. However, there exist significant difference in the mean TAGB dry matter (DM) yield, with tremendous decline from 5.54 t/ha in Season-I to 3.94 t/ha in Season-II. Accordingly, mean GY was reduced from 1.40 to 1.29 t/ha. These indeed were the manifestations of the variations in contents of soils nutrients. So, it is necessary to account for such differences in precision agricultural practices. Looking at some results, available Mo and P in Season-II; and SO_4-S in both seasons were not normally distributed, owing to the relative larger differences across sites and hence may need certain type of transformation. The other parameters were however, normally distributed based on the criterion developed by Nielsen and Bouma (1985). Individually, Fe showed slight decrease, whereas the rest of the micronutrients, except Mo showed significant increase. The coefficient of variation (CV) of the soil variables ranged from 18.66% for pH in Season-II; to 191.62% for Mo in Season-I (Table 4). When characterizing such CV values for the micronutrients, Nielsen and Bouma (1985) identified three categories: <10% as low; 10–100% as medium and >100% as high. However, Dahiya et al. (1984) described the CV values between (15–75%) as medium. Based on the second criteria, variables like Ca^{2+}, Mo and Av. P in Season-I; and SO_4-S (90.04%) and B (91.27%) in Season-II were classified as high, but they could be regarded as medium based on the first criteria. The CV values of the variables like TN, Fe, Zn and Mo were declined in Season-II compared with Season-I, which could be associated with the mobility of nutrients in the soil and/or plant system. The pH did not show significant change (19.42 and 18.66) which might be due to the inherent chemistry of calcareous and strongly acidic soils.

The micronutrients and other soil properties showed significant variations across locations, far above the critical levels (Table 3); though the values within sites over years were narrow enough to receive similar management and/or recommendations. And while the micronutrients are essential for completing the life cycle of plants, their concentrations far above critical levels (CLs) would result in antagonistic effects to plants and potential environmental risk factors. Therefore, such high concentrations of elements like Cu and Mn on plants or their interaction with other macro- or micronutrients need to be explored further. In general, the mean value of pH, Fe, Zn, Av. P and Mo was nearly constant over years, whereas OC, TN, Cu, Mn and B showed an increase in season-II, compared with season-I, while Ca^{2+}, saturation percent (SP) decreased in season-II. However, in the long run such differences can be large enough depending on the prevailing random or inherent factors. Zhang et al. (2013) reported the effects of such random and/or inherent factors on the spatial and temporal variations of soil micronutrients. Likewise, the mean value of SO_4-S showed tremendous increase in Season-II (5.79 to 15.88 mg/kg) falling beyond the suggested threshold range of 10.00–11.30 mg/kg (Patrick et al., 2013; Menna et al., 2015).

Influencing factors' analysis

Correlation analysis

Coefficients of correlation (r) between the micronutrients and other soil variables are presented in Tables 4 and 5.

Table 5. Pearson correlation coefficients of the considered soil variables, N = 12 Prob > |r| under H0: Rho=0.

Variable	Site	pH	OC	TN	Av. P	SO_4-S	Ca^{2+}	SP	Cu	Mn	Fe	Zn	B	Mo	GY	TAGBY
Site	1.00000	-0.09877 0.7601	0.02569 0.9368	-0.17662 0.5829	-0.03025 0.9256	0.35288 0.2606	-0.15890 0.6218	-0.18072 0.5741	0.72338 0.0078	0.07110 0.8262	0.21438 0.5034	0.24380 0.4451	0.02835 0.9303	-0.06310 0.8455	-0.48668 0.1086	-0.62987 0.0282
pH	-0.09877 0.7601	1.00000	-0.61683 0.0326	-0.77724 0.0029	0.85003 0.0005	-0.51662 0.0855	0.94504 <.0001	0.96863 <.0001	-0.28085 0.3766	-0.96088 <.0001	-0.88114 0.0002	-0.93153 <.0001	-0.35199 0.2618	0.74205 0.0057	-0.44195 0.1503	-0.38707 0.2138
OC	0.02569 0.9368	-0.61683 0.0326	1.00000	0.74881 0.0051	-0.48436 0.1105	0.74479 0.0055	-0.55616 0.0604	-0.67777 0.0154	0.25469 0.4244	0.60714 0.0363	0.34830 0.2672	0.54806 0.0651	0.68056 0.0149	-0.39703 0.2013	0.67962 0.0150	0.46312 0.1295
TN	-0.17662 0.5829	-0.77724 0.0029	0.74881 0.0051	1.00000	-0.71381 0.0091	0.50388 0.0949	-0.75425 0.0046	-0.77376 0.0031	0.06130 0.8499	0.81116 0.0014	0.53862 0.0708	0.68023 0.0149	0.53189 0.0751	-0.58373 0.0463	0.76108 0.0040	0.64381 0.0239
Av. P	-0.03025 0.9256	0.85003 0.0005	-0.48436 0.1105	-0.71381 0.0091	1.00000	-0.45166 0.1405	0.87002 0.0002	0.87146 0.0002	-0.02695 0.9337	-0.94688 <.0001	-0.86170 0.0003	-0.87214 0.0002	-0.31801 0.3138	0.41555 0.1791	-0.36923 0.2375	-0.34475 0.2725
SO_4-S	0.35288 0.2606	-0.51662 0.0855	0.74479 0.0055	0.50388 0.0949	-0.45166 0.1405	1.00000	-0.39090 0.2090	-0.64616 0.0232	0.45477 0.1374	0.53937 0.0703	0.31075 0.3256	0.44652 0.1456	0.64070 0.0248	-0.19143 0.5512	0.51594 0.0860	0.25877 0.4167
Ca^{2+}	-0.15890 0.6218	0.94504 <.0001	-0.55616 0.0604	-0.75425 0.0046	0.87002 0.0002	-0.39090 0.2090	1.00000	0.90703 <.0001	-0.34408 0.2734	-0.92928 <.0001	-0.85699 0.0004	-0.91615 <.0001	-0.33248 0.2910	0.76864 0.0035	-0.29230 0.3566	-0.23693 0.4584
SP	-0.18072 0.5741	0.96863 <.0001	-0.67777 0.0154	-0.77376 0.0031	0.87146 0.0002	-0.64616 0.0232	0.90703 <.0001	1.00000	-0.31048 0.3260	-0.96126 <.0001	-0.86486 0.0003	-0.92021 <.0001	-0.46633 0.1265	0.60726 0.0362	-0.45780 0.1345	-0.38281 0.2194
Cu	0.72338 0.0078	-0.28085 0.3766	0.25469 0.4244	0.06130 0.8499	-0.02695 0.9337	0.45477 0.1374	-0.34408 0.2734	-0.31048 0.3260	1.00000	0.14012 0.6640	0.17653 0.5831	0.24541 0.4420	0.18783 0.5588	-0.50583 0.0934	-0.14361 0.6561	-0.29793 0.3469
Mn	0.07110 0.8262	-0.96088 <.0001	0.60714 0.0363	0.81116 0.0014	-0.94688 <.0001	0.53937 0.0703	-0.92928 <.0001	-0.96126 <.0001	0.14012 0.6640	1.00000	0.87318 0.0002	0.93043 <.0001	0.41450 0.1803	-0.58890 0.0439	0.44659 0.1456	0.37729 0.2267
Fe	0.21438 0.5034	-0.88114 0.0002	0.34830 0.2672	0.53862 0.0708	-0.86170 0.0003	0.31075 0.3256	-0.85699 0.0004	-0.86486 0.0003	0.17653 0.5831	0.87318 0.0002	1.00000	0.94860 <.0001	0.01627 0.9600	-0.51455 0.0870	0.18481 0.5653	0.25271 0.4281
Zn	0.24380 0.4451	-0.93153 <.0001	0.54806 0.0651	0.68023 0.0149	-0.87214 0.0002	0.44652 0.1456	-0.91615 <.0001	-0.92021 <.0001	0.24541 0.4420	0.93043 <.0001	0.94860 <.0001	1.00000	0.17410 0.5884	-0.56912 0.0534	0.26407 0.4069	0.23725 0.4578
B	0.02835 0.9303	-0.35199 0.2618	0.68056 0.0149	0.53189 0.0751	-0.31801 0.3138	0.64070 0.0248	-0.33248 0.2910	-0.46633 0.1265	0.18783 0.5588	0.41450 0.1803	0.01627 0.9600	0.17410 0.5884	1.00000	-0.21206 0.5082	0.43150 0.1613	0.18181 0.5717
Mo	-0.06310 0.8455	0.74205 0.0057	-0.39703 0.2013	-0.58373 0.0463	0.41555 0.1791	-0.19143 0.5512	0.76864 0.0035	0.60726 0.0362	-0.50583 0.0934	-0.58890 0.0439	-0.51455 0.0870	-0.56912 0.0534	-0.21206 0.5082	1.00000	-0.28825 0.3636	-0.22511 0.4818
GY	-0.48668 0.1086	-0.44195 0.1503	0.67962 0.0150	0.76108 0.0040	-0.36923 0.2375	0.51594 0.0860	-0.29230 0.3566	-0.45780 0.1345	-0.14361 0.6561	0.44659 0.1456	0.18481 0.5653	0.26407 0.4069	0.43150 0.1613	-0.28825 0.3636	1.00000	0.92683 <.0001
TAGBY	-0.62987 0.0282	-0.38707 0.2138	0.46312 0.1295	0.64381 0.0239	-0.34475 0.2725	0.25877 0.4167	-0.23693 0.4584	-0.38281 0.2194	-0.29793 0.3469	0.37729 0.2267	0.25271 0.4281	0.23725 0.4578	0.18181 0.5717	-0.22511 0.4818	0.92683 <.0001	1.00000

*, **, ***, significant at $p < 0.05$, $p < 0.01$ and $p < 0.001$ levels, respectively (N = number of observations).

Soil pH had negative correlations with all the available micronutrients, except Mo. Particularly, the relationship of Ph with Mn, Fe and Zn was

Table 6. Stepwise regression analysis of the considered soil variables.

IV	DV	R^2 (%)	CV (%)	Y-intercept (I)	Slope (S)	Probability p (I)	Probability p (S)
pH	OC	38.05	28.75124	3.44540	-0.29849	0.0011	0.0326
	TN	60.41	30.60260	0.39049	-0.04151	0.0002	0.0029
	Av. P	72.25	52.00203	-15.22955	3.14968	0.0030	0.0005
	SO_4-S	26.69	92.73103	42.67260	-5.08954	0.0304	0.0855
	Ca^{2+}	89.31	28.45539	-41.81177	8.69919	<.0001	<.0001
	SP	93.83	10.64632	-72.76101	21.50083	<.0001	<.0001
	Cu	7.89	29.21418	3.11978	-0.15451	0.0147	0.3766
	Mn	92.33	18.86094	170.10356	-21.06319	<.0001	<.0001
	Fe	77.64	26.15519	16.90421	-1.94312	<.0001	0.0002
	Zn	86.78	17.05157	2.53296	-0.28198	<.0001	<.0001
	B	12.39	79.20145	1.17289	-0.11437	0.0837	0.2618
	Mo	55.06	127.5442	-1.40538	0.25972	0.0137	0.0057
OC	TN	56.07	32.23548	0.00038844	0.08265	0.9921	0.0051
	Av. P	23.46	86.37107	10.32546	-3.70884	0.0151	0.1105
	SO_4-S	55.47	72.27038	-13.09441	15.16277	0.0969	0.0055
	Ca^{2+}	30.93	72.32775	29.29967	-10.57952	0.0055	0.0604
	SP	45.94	31.50168	110.79631	-31.08953	<.0001	0.0154
	Cu	6.49	29.43548	1.69632	0.28955	0.0150	0.4244
	Mn	36.86	54.10814	-5.05557	27.50300	0.7949	0.0363
	Fe	12.13	51.84918	2.24477	1.58726	0.3415	0.2672
	Zn	30.04	39.21931	0.22805	0.34284	0.4268	0.0651
	B	46.32	61.99763	-0.26375	0.45697	0.3322	0.0149
	Mo	15.76	174.6278	0.67240	-0.28716	0.0831	0.2013
TN	Av. P	50.95	69.14082	10.95076	-49.52171	0.0006	0.0091
	SO_4-S	25.39	93.54949	-1.32257	92.94320	0.8582	0.0949
	Ca^{2+}	56.89	57.14209	29.60935	-129.9951	0.0002	0.0046
	SP	59.87	27.14031	103.79959	-321.5765	<.0001	0.0031
	Cu	00.38	30.38204	2.07072	0.63141	0.0012	0.8499
	Mn	65.80	39.82392	-5.20396	332.92200	0.6423	0.0014
	Fe	29.01	46.60372	1.84038	22.23914	0.2696	0.0708
	Zn	46.27	34.36922	0.26476	3.85532	0.1895	0.0149
	B	28.29	71.65425	0.03414	3.23585	0.8865	0.0751
	Mo	34.07	154.4868	0.71964	-3.82527	0.0136	0.0463
	GY	57.92	11.23570	0.97983	2.78473	<.0001	0.0040
	TAGBY	41.45	27.97632	2.44644	17.53674	0.0268	0.0239
Av. P	SO_4-S	20.40	96.62697	16.20734	-1.20086	0.0049	0.1405
	Ca^{2+}	75.69	42.90643	2.93676	2.16136	0.2364	0.0002
	SP	75.94	21.01329	38.38239	5.22049	<.0001	0.0002
	Cu	00.07	30.42822	2.17123	-0.00400	<.0001	0.9337
	Mn	89.66	21.89838	63.40225	-5.60170	<.0001	<.0001
	Fe	74.25	28.06686	7.04323	-0.51284	<.0001	0.0003
	Zn	76.06	22.94029	1.08777	-0.07125	<.0001	0.0002
	B	10.11	80.22396	0.58220	-0.02789	0.0043	0.3138
	Mo	17.27	173.0609	0.04365	0.03925	0.7950	0.1791
	GY	13.63	16.09742	1.43125	-0.01947	<.0001	0.2375
	TAGBY	11.88	34.31997	5.34610	-0.13536	<.0001	0.2725
SO_4-S	Ca^{2+}	15.28	80.10464	16.56003	-0.36525	0.0025	0.2090

Table 6. Contd.

	SP	41.75	32.69820	77.50491	-1.45589	<.0001	0.0232
	Cu	20.68	27.10953	1.87810	0.02540	<.0001	0.1374
	Mn	29.09	57.34075	25.34665	1.20016	0.0186	0.0703

Independent Variable (IV), Dependent Variable (DV), R^2 in the reverse direction is similar; and the slope in the reverse direction is of similar sign.

Table 7. Stepwise regression analysis of the considered soil variables.

IV	DV	R^2 (%)	CV (%)	Y-intercept (I)	Slope (S)	Probability p (I)	Probability p (S)
SO$_4$-S	Fe	09.66	52.57429	3.99614	0.06956	0.0030	0.3256
	Zn	19.94	41.95461	0.62047	0.01372	0.0009	0.1456
	B	41.05	64.96787	0.22849	0.02113	0.0907	0.0248
	Mo	03.66	186.7477	0.29287	-0.00680	0.1120	0.5512
	GY	26.62	14.83790	1.23325	0.01023	<.0001	0.0860
	TAGBY	06.70	35.31598	4.32669	0.03821	<.0001	0.4167
Ca^{2+}	SP	82.27	18.03989	34.16436	2.18720	<.0001	<.0001
	Cu	11.84	28.58061	2.41248	-0.02056	<.0001	0.2734
	Mn	86.36	25.15330	66.24020	-2.21295	<.0001	<.0001
	Fe	73.44	28.50416	7.33721	-0.20531	<.0001	<.0004
	Zn	83.93	18.79426	1.14882	-0.03013	<.0001	<.0001
	B	11.05	79.80271	0.60539	-0.01174	0.0051	0.2910
	Mo	59.08	121.7097	-0.14913	0.02923	0.2561	0.0035
	GY	08.54	16.56494	1.42236	-0.00621	<.0001	0.3566
	TAGBY	05.61	35.52034	5.21271	-0.03745	<.0001	0.4584
SP	Cu	09.64	28.93493	2.62834	-0.00770	0.0003	0.3260
	Mn	92.40	18.76980	96.95031	-0.94930	<.0001	<.0001
	Fe	74.80	27.76778	10.05370	-0.08592	<.0001	0.0003
	Zn	84.68	18.35286	1.54379	-0.01255	<.0001	<.0001
	B	21.75	74.85259	0.87886	-0.00683	0.0089	0.1265
	Mo	36.88	151.1674	-0.37188	0.00958	0.1871	0.0362
	GY	20.96	15.39965	1.59296	-0.00403	<.0001	0.1345
	TAGBY	14.65	33.77641	6.28954	-0.02509	0.0006	0.2194
Cu	Mn	01.96	67.42340	26.33077	5.58324	0.3672	0.6640
	Fe	03.12	54.44413	3.22632	0.70759	0.2741	0.5831
	Zn	06.02	45.45464	0.47840	0.13503	0.2332	0.4420
	B	03.53	83.11054	0.21862	0.11093	0.6055	0.5588
	Mo	25.59	164.1300	0.91212	-0.32181	0.0405	0.0934
	GY	02.06	17.14186	1.45402	-0.05101	0.0002	0.6561
	TAGBY	08.88	34.90099	6.43735	-0.78785	0.0048	0.3469
Mn	Fe	76.24	26.95897	1.38095	0.08784	0.0769	0.0002
	Zn	76.24	26.95897	1.38095	0.08784	0.0769	0.0002
	B	17.18	77.00521	0.22186	0.00614	0.2762	0.1803
	Mo	34.68	153.7747	0.57980	-0.00940	0.0104	0.0439
	GY	19.94	15.49813	1.19147	0.00398	<.0001	0.1456
	TAGBY	14.23	33.85930	3.78048	0.02504	0.0015	0.2267

Table 7. Contd.

Fe	Zn	89.98	14.83979	0.15066	0.13021	0.0663	<.0001
	B	00.03	84.60536	0.44611	0.00240	0.1021	0.9600
	Mo	26.48	163.1451	0.60709	-0.08167	0.0243	0.0870
	GY	03.42	17.02305	1.26638	0.01638	<.0001	0.5653
	TAGBY	06.39	35.37462	3.94893	0.16672	0.0043	0.4281
Zn	B	03.03	83.32425	0.31376	0.18688	0.2881	0.5884
	Mo	32.39	156.4473	0.72531	-0.65804	0.0163	0.0534
	GY	06.97	16.70655	1.21304	0.17048	<.0001	0.4069
	TAGBY	05.63	35.5174	3.86379	1.14025	0.0107	0.4578
B	Mo	04.50	185.9390	0.32367	-0.22843	0.1235	0.5082
	GY	18.62	15.62585	1.22544	0.25952	<.0001	0.1613
	TAGBY	03.31	35.95201	4.36841	0.81403	0.0003	0.5717
Mo	GY	08.31	16.58622	1.37944	-0.16094	<.0001	0.3636
	TAGBY	05.07	35.62290	4.94591	-0.93571	<.0001	0.4818
GY	TAGBY	85.90	13.72807	-4.53373	6.89986	0.0037	<.0001

Independent Variable (IV), Dependent Variable (DV), R^2 in the reverse direction is similar; and the slope in the reverse direction is of similar sign.

strongly negative; and this is in accordance with that reported by Wei et al. (2006) and Zhuo et al. (2019). This indicates greater influence of soil pH on the micronutrients availability. With Av. Mo, the pH was positively correlated ($r = 0.74$ at and $p \leq 0.01$) which might be favorable depending on crop needs. Thus, pH was found to be the major factor influencing micronutrients solubility. This indeed was in accordance with that reported by Zhuo et al. (2019).

In contrast, pH had high positive significant correlation; $r = 0.96$, $r = 0.95$ and $r = 0.85$ with SP (saturation percent), Ca^{2+} and Av. P respectively. Of special interest in this analysis was the soil OC's relationship with micronutrients and other related soil variables. For example, significantly positive correlation of soil OC with TN, SO_4-S, Mn, Zn and B was worth mentioning. This relation was instrumental for the nutrients like S which are not applied regularly as inorganic fertilizers in Ethiopian soils. Therefore, supplying soils with fertilizers of organic sources would be of paramount importance for replenishing S and N (McNeill et al., 2005; Choudhary et al., 2018).

Soil OC had either negatively or weak positive correlation with the rest of soil variables such as pH, Av. P, Ca^{2+}, Cu, Fe and Mo. Also, TN was negatively related with pH, Av. P, Ca^{2+}, SP and Mo (r = -0.78, -0.71, -0.75, -0.77 and -0.58) respectively ($p \leq 0.05$). The Av. P had high positive significant ($p \leq 0.001$) correlation with pH, Ca^{2+} and SP (r = 0.85, 0.87 and 0.87) respectively and may imply the decline in P availability in acidic than alkaline soils. Av. P had a strong negative correlation with Mn, Fe, Zn and B (r = -0.95, -0.86, -0.87 and $r = -0.32$) respectively, but it had positive correlation with Mo ($r = 0.42$). This may indicate a possible antagonistic interaction of Av. P with all the micronutrients investigated, except Mo. Menna (2018) reported a similar observation. The SO_4-S had negative correlations with pH, Av. P, Ca^{2+}, SP and Mo. In contrast, it had positive relation with OC, TN, Cu, Mn, Fe, Zn and B, but with widely varied degree of associations. This is in accordance with that reported by Menna (2021). The author reported that supplying soils with S-gypsum and N fertilizers of organic and inorganic sources is essential for enhancing soil properties including the availability of micronutrients. Generally, beyond the aforementioned relations, Ca^{2+} had strong negative correlations ($p \leq 0.001$) with Mn, Fe and Zn with r values of -0.93, -0.86 and -0.93 respectively. This may also indicate limited availability of Mn, Fe and Zn in Ca-rich alkaline soils for plants up-take. The Ca^{2+} was weakly correlated with Cu ($r = -0.34$) and B ($r = -0.33$) but significantly with Mo ($r = 0.77$), which may imply that Mo mobility to plants will be limited in strongly acidic than alkaline soils.

In the final analysis, under native soil conditions, except for pH, Av. P, Ca^{2+}, Cu and Mo, the rest of soil variables investigated were positively correlated with wheat yields. Indeed, N and S were found to be the two most yield limiting factors, followed by Mn, B, Zn and Fe in the order of their importance. And for those soils variables positively correlated with yield in the present investigation; more positive relationship goes to the grain than TAGBY, indicating the more partitioning of plant nutrients into the more economic yield parameter of wheat. This is in accordance with that reported by Amanullah and Inamullah (2016). Obviously, the TN, SO_4-S and Av. P have strong positive correlation with GY and TAGBY dry-matter, necessitating the application of NPS fertilizers in sustaining wheat production.

Regression analysis

Stepwise regression analysis was employed to quantify the influences of soil properties on the spatial and temporal variability of soil micronutrients. The overall spatial and temporal variabilities of micronutrients over years and sites and related soil properties are presented in Tables 6a and b. From the results, OC, pH, TN, Av. P, SO_4-S, Ca^{2+} on the average explained 7.89, 66.68, 46.02, 57.17, 24.83 and 30.82% of the spatial and temporal variability of available Cu, Mn, Fe, Zn, B and Mo respectively over years across sites. Taking the individual contribution, the spatial variability of Av. Cu was greatly affected by SO_4-S (20.68%). The total contribution of Av. P and TN on Cu was negligible (0.45%), indicating their minor interactions effects. This may be due to the innate high concentration of Cu in soils. Furthermore, it is observed that pH, Av. P, and Ca^{2+} had negative slopes, indicating their negative influences on Cu. In the case of Mn, the greater variability was explained by pH, Av. P and Ca^{2+} than the other factors. Relative lesser influences were caused by the OC and SO_4-S. Similar to Av. Cu, the pH, Av. P and Ca^{2+} had inverse relationships with Mn, which might indicate their antagonistic effects on Mn. Particularly, the negative effect of high pH and Ca-rich calcareous soils on Mn solubility and availability is reported by Pan et al. (2014) and Zhuo et al. (2019).

Similar to Mn, the factors that are explaining greater spatial and temporal variability of Fe were pH, Av. P and Ca^{2+} accounting for 77.64, 74.25 and 73.44% of the variations respectively. Their negative slopes may indicate their respective negative effects on Fe availability. Zhuo et al. (2019) made similar observations particularly for the relationships between P, pH and Fe. However, the relative positive influences on Fe were explained by OC (12.13%) and SO_4-S (9.66%), though with low R^2 values. And while the R^2 values look smaller, the differences in their effects might be large enough as Fe is needed in a very small quantity by crop plants. Therefore, enriching soils with OM might be the easier way towards supplying Fe to plants. Zhuo et al. (2019) and Rengel (2015) had similar observations. Considering Zn, similar to Mn, greater spatial and temporal variability was explained individually by pH, Av. P and Ca^{2+}: 86.78, 76.06 and 83.93% respectively, but all were related inversely with Zn. Less significant, but positive influences on Zn were explained by OC (30.04%) and SO_4-S (19.94%). Interestingly, these variables also had similar trend of influence on Zn as observed with Mn and Fe. Particularly, the effect of pH on Zn is in accordance with that reported by Rengel (2015).

The greater spatial and temporal variations on B were caused by OC and SO_4-S, explaining 46.32 and 41.05% of the variations respectively, almost with similar degree of associations. This indicates the significance of supplying soils with organic matter for enhancing B availability. Menna (2018) reported a similar finding. The relative less effects on B came from pH (12.39%), Av. P (10.11%) and Ca^{2+} (11.05%), though their effects seem to be antagonistic on B. The greater individual influences on Mo were explained by pH (55.06%) and Ca^{2+} (59.08%); with the least from SO_4-S (3.66%), though the overall effects of OC, TN and SO_4-S on Mo also seem to be antagonistic. With respect to wheat yield, on the average, the TN, Av. P, SO_4-S, Ca^{2+} explained 26.68; and 16.41% of the spatial and temporal variability of grain yield (GY) and total above ground biomass yield (TAGBY) respectively. The contributions of TN, SO_4-S and Av. P on GY were higher than that of other factors, with separate effects of 57.92, 26.62 and 13.63% respectively. Corroborating, the correlation results, this also suggests N to be the most yield limiting element successively followed by S and P. This particularly applies to the calcareous soils of East Shewa zone. In fact, this is in accordance with the finding by Moosavi et al. (2015). The influences caused by TN, Av. P, SO_4-S and Ca^{2+} separately on the TAGBY were 41.45, 11.88, 6.70 and 5.61% respectively, further affirming the greater significance of N nutrition in wheat than that by P or S. But, the influences contributed by Av. P and Ca^{2+} on TAGBY were negative, indicating the likely negative effects of the elements in strongly acidic and calcareous soils. The least influence still came from Ca^{2+} (5.61%) affirming that excess concentrations of Ca^{2+} in the soils; and is thus not limiting wheat production in the studied soils in at least two of the locations, that is, Arsi and ES zones, which are characterized by having medium and high soil reactions.

On average the micronutrients Cu, Mn, Fe, Zn, B and Mo can explain 9.89 and 16.41% of the spatial and temporal variability of GY and TAGBY respectively. Taking each compounding factor, a relative greater influence on GY was explained by Mn (19.94%) and B (18.62%), with the least being by Cu (2.06%) and Fe (3.42%). Zinc (6.97%) and Mo (8.31%), however, showed intermediate effects. Likewise, the micronutrients: Cu, Mn, Fe, Zn, B and Mo on the average can explain about 7.25% of the spatial and temporal variability of TAGBY over years across the sites with greater influence caused by Mn (14.32%). However, their respective component contribution was below 10.00%. In the case of TAGBY, the contribution of Cu and Mo were negative, further affirming that Cu in all soils and Mo in most studied soils were not deficient for limiting wheat yields.

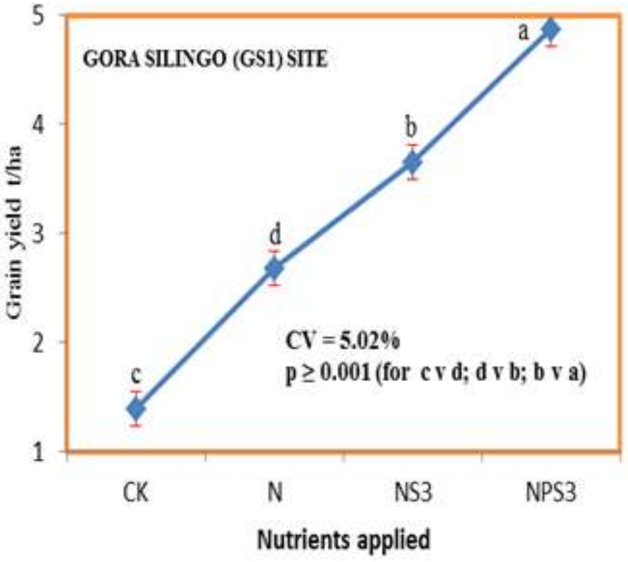

Figure 1. Mean wheat grain yield at Arsi zone.

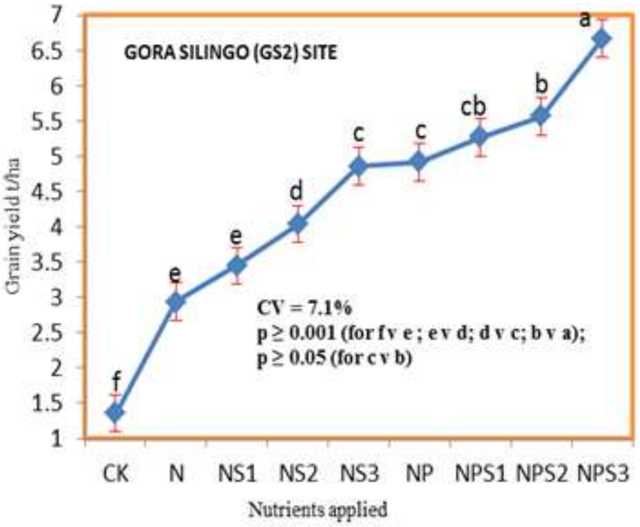

Figure 2. Mean wheat grain yield at Arsi zone. Means bearing same letter(s) within same group are not significantly different at p < 0.01% probability level by T-test. *, **, *** and NS; implies significant at p < 0.05, p < 0.01, p < 0.001 respectively; and not significant at the respective probability levels.

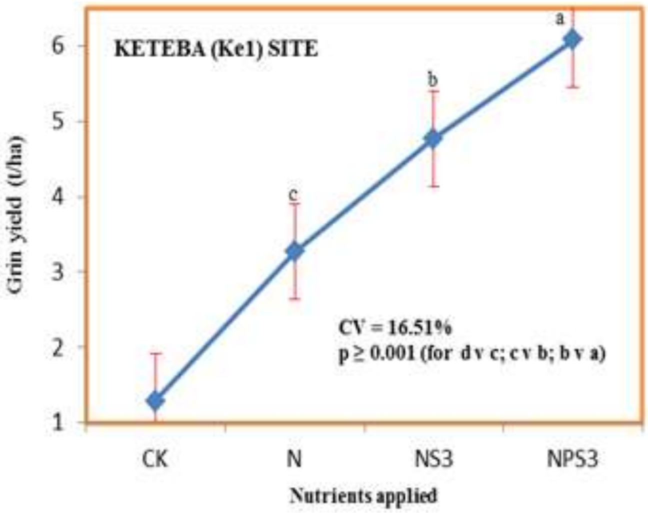

Figure 3. Mean wheat grain yield at East Shewa zone.

The total contribution of Av. P, Ca^{2+}, Cu and Mo on both the GY and TAGBY were also negative, further corroborating the idea that these elements were not deficient in most of the soils studied. In general, the negative or weakly positive slopes, in the curves indicate the less significance of the soil variables in wheat nutrition. Indeed, this supports the idea that except P and Mo in some sites, the other nutrients were far above the suggested CLs in Table 3. Phosphorus availability to wheat is also questionable in both the calcareous soils of ES; and strongly acidic soils that came from WS zones, supporting the less effect of this element on wheat nutrition. Contribution of GY to TAGBY was highly significant ($p \leq 0.001$) and positive (85.90%). This might indicate that the contribution of biomass partitioning and translocation to reproductive parts like grain is higher than that of the total biomass, and from plant nutrition points of view, GY was the most important component in cereals like wheat.

Wheat yield and harvest index

The combined analysis of variance over years and sites showed that, wheat yield and yield components responded well to different nitrogen, phosphorus and sulfur (NPS) treatments with increasing GY, TAGBY and harvest index (HI). For example, the applications of NPS had highly significant ($p < 0.001$) effect on GY of wheat (Figures 1 to 6). Owing to soil variability, even in those sites already tested adequate in individual nutrient elements, maintenance levels could be needed for increasing yields. In this regard, there is huge potential to increase wheat yield by improving soil fertility or crop management practices. Soil fertility status, particularly in the Ethiopian highlands needs to be greatly improved through balancing nutrients for achieving potential yields. For example, in the present work with applied highest level of NPS, maximum wheat grain yield recorded was about 6.2 t/ha. But with all optimal conditions and management, the GY of wheat reportedly reached over 8.5 t/ha (Zhao, 1999). Similar results showed that wheat yield can be doubled by applying balanced nutrients including Cu, Mn, Fe, Zn, B and Mo (Menna, 2018). On the other hand, in the unfertilized soils, HI of wheat

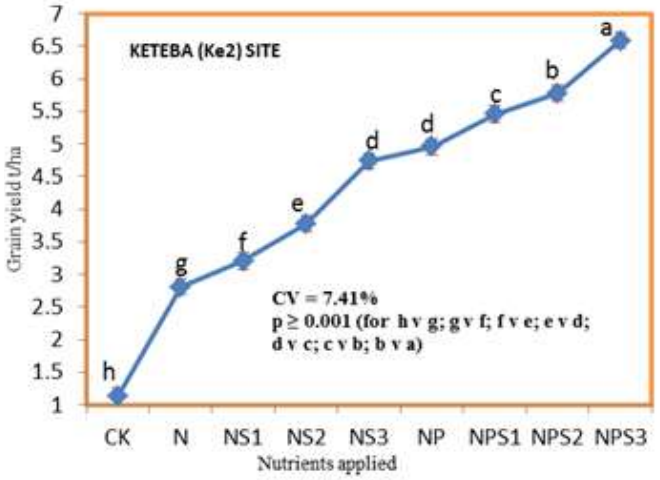

Figure 4. Mean wheat grain yield at East Shewa zone. Means bearing same letter(s) within same group are not significantly different at P < 0.01% probability level by T-test. *, **, *** and NS; implies significant at p < 0.05, p < 0.01, p < 0.001 respectively; and not significant at the respective probability levels.

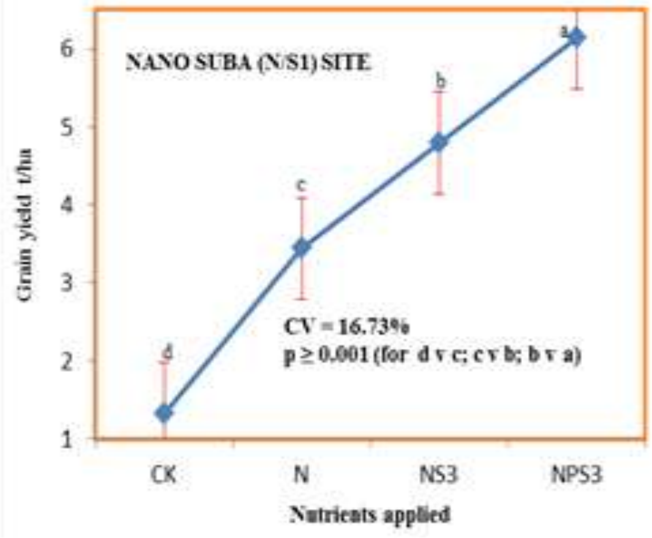

Figure 5. Mean wheat grain yield at West Shewa (WS/OL).

(which is obtained by dividing GY by TAGBY), were very low (≤ 20%) implying that the total biomass was very high compared to its grains. But, significantly higher HI was recorded with applied levels of NPS as a manifestation of improved soil fertility. Regression analysis from the unfertilized plots showed that GY correlated significantly with TAGBY (R^2 = 0.86); but less with HI (R^2 = 0.56) (Tables 6a, b and Figures 1 to 6). From this, it can be deduced that higher total biomass was not a desirable trait for cereals. For well-nourished plant, the regression line is expected to have positive slope between grain and

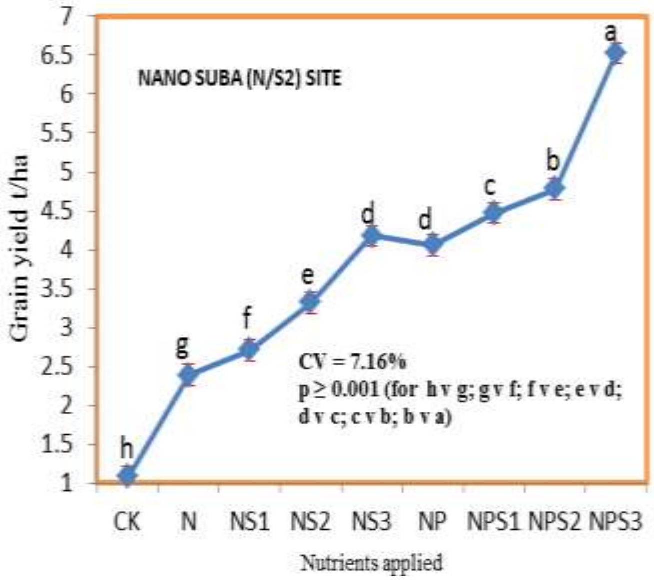

Figure 6. Mean wheat grain yield at West Shewa (WS/OL). Means bearing same letter(s) within same group are not significantly different at p < 0.01% probability level by T-test. *, **, *** and NS; implies significant at p < 0.05, p < 0.01, p < 0.001 respectively; and not significant at the respective probability levels.

HI as reported by Agegnehu et al. (2014).

Despite the significant R^2 = 56% obtained, the slope however was negative (-0.2) indicating their inverse relations under native soil conditions. This further affirmed the lack of uniformity in the studied soils. For example, TAGBY at Dosha1 site was about 9.0 t/ha (control plot) creating a remarkable yield gap with the rest of the sites (Table 3), with the values ranging from 2.91 t/ha (N/S2) to 8.96 t/ha (Do1). This indicates the need for optimizing soil fertility for boosting yields in production fields. Correlation between GY and HI from pooled mean showed strong negative relations (r = -0.75). Hence, due to the wide spatial and temporal viabilities in soils, the observed relationship between GY and HI in control plots did not reflect the real conditions, as the yield and yield components were affected by different soil fertility gradients. However, with the rate of NPS applied, progressive yield differences in GY, TAGBY and HI at ($p \le 0.001$; $p \le 0.01$; $p \le 0.05$) respectively were recorded. For example, dramatic GY increase of 197.28%, the least at Do1 site; and 504.63%, the highest at N/S2 site over control were recorded as a manifestation of improved soil fertility. Significant increases in nutrient uptake, grain and straw yields of wheat due to increased soil fertility through integrated soil fertility management (ISFM) and crop management practices were widely reported by different workers (Agegnehu et al., 2014; Agegnehu and Bekele, 2005; Matsi et al., 2003; Sharma et al., 1990; Gruhn et al. (2000). Based on these reports, wheat GY increased form 1.2 t/ha, in control plots to 9.40 t/ha, with the combined use of ISFM technologies and/or cropping-systems. This and the present results clearly elucidate that, if the application rate of NPS are increased and/or applied in integrated form, wheat GY can be doubled or tripled compared with farmers' practices.

CONCLUSION AND RECOMMENDATIONS

The results of the study revealed that there are important variations in soil micronutrients over time across sites with significant effects on wheat yield. The variations and distributions of Cu, Mn and Fe were so wide, whereas that of Zn, B and Mo were in narrow ranges. For such variations and distributions, random-factors like history of fertilizer use, cropping systems and tillage practices were observed to be more important than the non-random factors. Considering the influencing factors analysis, except for Mo, soil pH had strong inverse relation with the rest of available micronutrients, dictating pH's negative influence on their availability. Following soil pH, OC was the major factor that influenced micronutrients and other soil variables. With respect to biomass partitioning, an increasing trend of positive relation goes to soil nutrients with grain yield than the total biomass, indicating the more partitioning of plant nutrients into the more economic yield. Looking at yield limiting factors, the contribution of N, P, and S was higher than that of others in sustaining wheat yield. Overall, there exist complex network of relations between soil micronutrients and other soil properties in affecting wheat yield at a given point. Such relations have either inverse or direct effects that accordingly can have detrimental or beneficial effects on crop performances. Given such series of intra- or interrelationships between different variables, validation works should be installed using advanced geostatistical tools at farm or catchment levels taking few variables at a time. The results will have implications for inferring sites that may need similar management, especially in precision agriculture and also in predicting deficiency or toxicity levels of nutrients to plants.

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CONFLICT OF INTERESTS

The author has not declared any conflict of interest.

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