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Soil fertility status and wheat nutrient content in Vertisol cropping systems of central highlands of Ethiopia

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Abstract

Background: Land degradation reduces agricultural productivity and poses a serious threat on food security status of households. In Ethiopia, farmers have been using only urea and di-ammonium phosphate for more than 15 years. Several reports that indicate lack of response to these fertilizers, which could be due to limitation of nutrients other than nitrogen and phosphorus. Therefore, the present study was initiated to evaluate the soil fertility status of ten sites in central highlands Vertisols of Ethiopia and wheat nutrient content.

Results: The physico-chemical properties of soils showed that the soils were clayey in texture, neutral to slightly alkaline (pH 7.2–7.9) and low to medium in their organic matter (1.6–3.2 %) content. Total N content was low in 100 % of the samples while 80 % of the soil samples showed P deficiency ($<10 \text{ mg kg}^{-1}$). Exchangeable K, Ca and Mg in all soil samples were high, while available sulfur was low. On the other hand, K to Mg ratio varied from 0.13:1 to 0.44:1, indicating Mg induced K deficiency. All soil samples were adequate when analyzed by ammonium bicarbonate di-ethylene tri-amine penta-acetic acid extractable Cu ($>0.5 \text{ mg kg}^{-1}$), Fe ($>5 \text{ mg kg}^{-1}$), and Mn ($>1 \text{ mg kg}^{-1}$) contents. However, 70 % of the samples were deficient in Zn ($<1.5 \text{ mg kg}^{-1}$) content. Mehlich 3 extractable B ($<0.5 \text{ mg kg}^{-1}$) and acid ammonium oxalate extractable Mo ($<0.1 \text{ mg kg}^{-1}$) were found to be low in all soil samples. The plant analysis data showed that all samples were low in N, P and K, while high in Ca and Mg concentrations. The deficiency of tissue K content was not predicted by the soil exchangeable K test. Plant micronutrient analysis showed that Cu, Fe, Mn and Cl concentrations were within the sufficiency range while Zn was deficient in all of the samples.

Conclusions: Soil and/or tissue test results are indicative of deficiency of N, P, K, S, Zn, B and Mo that could be amended by fertilizer application, although more data are needed to thoroughly support this conclusion. The highest correlation ($r > 0.90$) between soil and plant nutrient content was observed for P, K, Mg, Cu, Fe, Mn and Zn, implying that flag leaves at flowering stage can be used to calibrate soil and plant contents for the deficient nutrients.

Keywords: Soil, Plant, Nutrient, Soil fertility, Deficient, Adequate, Fertilizer

Background

In Ethiopia, agriculture is the mainstay of the majority of the population and major driver of the national economy. Agricultural production has been highly dependent on natural resources for centuries [1]. However, increased human population and other factors have degraded the natural resources in the country thus seriously

threatening sustainable agriculture and food security [2, 3]. Continuous cropping and inadequate replacement of nutrients removed in harvested materials or loss through erosion and leaching has been the major causes of soil fertility decline [4]. This is particularly evident in the intensively cultivated areas, traditionally called high-potential areas that are mainly concentrated in the highlands of Ethiopia. To tackle this problem, the country initiated community-based participatory watershed management [5], and to date, it has rehabilitated millions of hectares of degraded land.

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Soil nutrient depletion in smallholder farming systems is recognized as a causal force leading to food insecurity and rural poverty in Africa [6, 7]. The rate of annual soil macronutrient depletion in Africa was estimated at 22 kg N ha⁻¹, 2.5 kg P ha⁻¹ and 15 kg K ha⁻¹ over 30 years of no use or insufficient use of fertilizers [8]. In Ethiopia, the depletion rate of macronutrients, 122 kg N ha⁻¹ year⁻¹, 13 kg P ha⁻¹ year⁻¹ and 82 kg K ha⁻¹ year⁻¹, was estimated to be high [9]. Decline in soil fertility due to long-term cultivation with little or no fertilizer additions is the major form of land degradation in most of sub-Saharan Africa. Declining soil fertility has also been stressed to be the fundamental impediment to agricultural development and the major reason for the slow growth in food production in Ethiopia [10]. The loss of soil nutrients in Ethiopia is related to cultural practices such as low fertilizer use, removal of vegetative cover (such as straw or stubble) and burning plant residues or the annual burning of vegetation on grazing land [11]. An average quantity of di-ammonium phosphate (DAP) and urea of 57 kg ha⁻¹ was consumed over the period of 1995 to 2008 for wheat production [12].

Soil degradation is common also in Ethiopian Vertisols, which cover about 13 Mha of land. Ethiopia ranks third in Vertisols abundance in Africa after Sudan and Chad [13]. More than half (8.6 Mha) of the Vertisols are found in the central highlands with altitude of more than 1500 meters above sea level (masl) [13, 14]. About 25 % (1.9 Mha) of the Vertisols occurring in the highlands are cultivated [15]. The crops that are commonly grown on Vertisols of Ethiopia are teff, bread wheat, barley, chickpea, lentil and niger seed [16]. Recently, farmers in Ethiopia are using modified plough called broad bed maker (BBM) and harvesting higher yields from multiple crops on the same plot of land per season [17].

Previously, only nitrogen (N) and phosphorus (P) were considered to be the limiting nutrients in Vertisols of Ethiopia [18]. However, many soils in the highlands of Ethiopia are poor in available plant nutrients and organic matter content [19]. Recently, the results of national soil fertility mapping initiative has also indicated that other nutrients including K, S, Fe, Zn and B are also found to be deficient in these soils [20]. In addition to the high fixing characteristics of Vertisols [21], lack of response to P application on central highland Vertisols of Ethiopia may be due to deficiency of nutrients other than P.

Soil tests are commonly used to assess the sufficiency or deficiency of essential plant nutrients. Although soil tests provide information about a soil's ability to supply plant available nutrients, it is an indirect measurement. Plant analysis, on the other hand, reveal the nutritional status of the plant directly and when combined with the soil tests can be used to evaluate the nutritional

sufficiency of the soil–plant system and further to design corrective treatments [22]. Therefore, this study was initiated with the objectives of identifying nutrient limitations through soil analysis and wheat nutrient status. The results of the study serve in making suggestions on improving fertilization and soil management to achieve sustainable crop production on Vertisols of the central highlands of Ethiopia.

Methods

Description of sampling locations

Surface soil (0–15 cm) and wheat leaf samples were taken from ten sites of central highland Vertisols listed in Table 1. Global Positioning System (GPS) was used to identify the geographical locations (Additional file 1: Figure S1).

Traditional farming practices of wheat growers

Information regarding farming practices of farmers at the sampling sites is presented in Table 2. Farmers have been using only two types of fertilizers for more than 15 years, urea (46 % N) and DAP (18 % N, 46 % P₂O₅). They usually apply one-third and two-thirds of the nitrogen dose at sowing and tillering stage, respectively. They use broad bed maker (BBM), which is an oxen-drawn traditional wooden plough, modified for the construction of raised beds and furrows to facilitate surface drainage through the furrows between the beds so as to grow crops on the beds [23]. The improved bread wheat variety Digalu (*HAR-3116*) was the most common cultivar cultivated in the study sites.

Soil and plant sampling

Twelve composite surface soil (0–15 cm) samples were collected from each wheat fields at the sampling locations. Each composite soil sample comprised of 15 sub

Table 1 Sampling locations and site characteristics

Location (District)	Latitude (N)	Longitude (E)	Altitude (m)
Akaki (Mereno)	8°52'1"	38°47'1"	2400
Ambo (Kisole Odoliva)	8°59'2"	37°51'30"	2104
Chefe Donsa (Haberu Sefetu)	8°57'60"	39°06'28"	2444
Debre Zeit (Denkaka)	8°41'36"	39° 03'17"	1880
Ginchi (Jemjem Legebatu)	9°3'37"	38° 07'11"	2200
Holeta (Guntuta)	9°3'58"	38° 29'53"	2415
Mojo (Ajere Wolkite)	8°47'41"	39°16'2"	2275
Sheno (Wentu)	9°24'16"	39° 21'23"	2911
Tullu Bolo (Awash Bune)	8°38'56"	38° 07'23"	2115
Woliso (D/Kora)	8°50'50"	38° 48'37"	2090

Table 2 Fertilizer application rates and previous year cropping history of wheat growers in central highlands of Ethiopia

Location (District)	Fertilizer used		Previous crop
	N (kg ha ⁻¹)	P (kg ha ⁻¹)	
Akaki (Mereno)	60	20	Wheat
Ambo (Kisole Odoliva)	65	20	Teff
Chefe Donsa (Haberu Sefetu)	86	25	Lentil
Debre Zeit (Denkaka)	90	25	Lentil
Ginchi (Jemjem Legebatu)	75	20	Teff
Holeta (Guntuta)	78	20	Lentil
Mojo (Ajere Wolkite)	83	30	Teff
Sheno (Wentu)	60	30	Wheat
Tullu Bolo (Awash Bune)	63	30	Teff
Woliso (D/Kora)	62	25	Teff

samples collected in a zigzag pattern within each block and mixed thoroughly following a standard procedure for soil sampling and sample preparation [24]. Six composite flag leaf samples were collected from each field of the sampling sites. Each composite leaf sample comprised 150 randomly selected flag leaves at flowering stage. A total of 120 surface soil (0–15 cm) and 60 composite leaf samples were taken from the studied sites. The area of each experimental field in all sites was about 1 ha.

Soil and plant analysis

Laboratory analyses were conducted at Debre Ziet Agricultural Research Center, Ethiopia and at Natural Resources Institute Finland (former MTT Agri food Research Finland) using the following standard methods. Soil particle size distribution was determined by hydrometer method [25]. Soil pH and electrical conductivity (EC) were measured in soil:water extract (1:2.5) according to Rhoades [26]. CaCO₃ content was determined using the calcimeter method according to Black [27]. Soil organic carbon (C) and total nitrogen (N) content were determined by dry combustion methods based on ISO 10694 [28] and ISO 13878 [29] protocols, respectively. Soil organic matter was calculated by multiplying soil organic carbon by 1.724 assuming average C concentration of organic matter of 58 %. Available phosphorus was extracted by 0.5 N sodium bicarbonate solution as described by Olsen et al. [30], and thereafter measured using Perkin Elmer Optima 8300 Inductively Coupled Plasma–Optical Emission Spectrometer (ICP-OES). Sulfate was determined in the soil extract by the turbidity method using spectrophotometer on transmittance at a wave length of 420 nm according to Williams and Steinbergs [31].

One molar neutral ammonium acetate (pH = 7) was used to extract the exchangeable cations (Ca, Mg, K and Na) [32]. Cations were then determined using ICP-OES. Available micronutrients (Cu, Fe, Mn and Zn) were extracted with ammonium bicarbonate di-ethylene tri-amine penta-acetic acid (AB-DTPA) as described by Soltanpour and Schwab [33] and were measured by ICP-OES. Mehlich 3 extraction was accomplished by mixing 2.5 g of soil and 25 ml of Mehlich 3 solution [0.2 M acetic acid (CH₃COOH), 0.25 M ammonium nitrate (NH₄NO₃), 0.015 M ammonium fluoride (NH₄F), 0.013 M nitric acid (HNO₃), and 0.001 M ethylene diamine tetra-acetic acid (EDTA)], shaking for 5 min, and filtering through a blue ribbon filter paper [34]. The filtrate was analyzed for available boron using ICP-OES. Molybdenum was extracted with acid ammonium oxalate (pH = 3) solution [35] and then analyzed using ICP-OES.

Leaves were first washed with distilled water, oven dried at 60–70 °C to a constant weight, ground, passed through 2-mm sieve and placed in paper bags. Total nitrogen in plants was determined using Kjeldahl digestion procedure as described by Bremner and Mulvaney [36]. Plant digests (using concentrated HNO₃ and 30 % H₂O₂) were prepared and analyzed for Ca, Mg, Cu, Fe, Mn and Zn using Atomic Absorption Spectrophotometer while P concentration of the digests was measured with a spectrophotometer and the K concentration with a flame photometer using required standard solutions. Plant chloride was determined by TRAACS 800 Analyzer using deionized water as an extractant [37].

Statistical analysis

Descriptive statistics was applied for calculation of means and standard errors. Correlation analysis was performed to assess relationships among soil and plant nutrient contents.

Results and discussion

Soil characteristics

Particle size distribution

The results of soil texture, as presented in Table 3 revealed that the particle size distribution of the surface soil (0–15 cm) of all the experimental sites was dominated by clay (above 53 %) except at Sheno (47 %). The relatively high clay contents observed in this study agree with the findings of Kamara et al. [38] and Lemma and Smit [39], who also reported clay level of above 50 % in Ginichi, central highlands Vertisols of Ethiopia. This is further supported by Debele [14] and Tesgaye [40], who reported that Vertisols in Ethiopian generally contain more than 40 % clay in the surface horizon.

Table 3 Particle (sand, silt and clay) size analysis and textural classes of the study sites (n = 12)

Location (District)	% Sand	% Silt	% Clay	Textural class
Akaki (Akaki)	15 ^a (0.43) ^b	19 (0.73)	67 (0.2)	Heavy clay
Ambo (Kisole Odoliva)	18 (0.35)	16 (0.7)	66 (0.88)	Heavy clay
Chefe Donsa (Haberu Sefetu)	22 (0.57)	25 (0.47)	54 (0.6)	Clay
Debre Zeit (Denkaka)	16 (0.3)	18 (0.2)	66 (0.4)	Heavy clay
Ginichi (Jemjem Legebatu)	22 (0.47)	20 (0.77)	57 (1.1)	Clay
Holeta (Guntuta)	21 (0.38)	20 (0.48)	59 (0.47)	Clay
Mojo (Ajere Wolkite)	19 (1.3)	18 (1.2)	63 (0.5)	Heavy clay
Sheno (Wentu)	23 (0.37)	30 (0.89)	47 (0.91)	Clay
Tullu Bolo (Awash Bune)	17 (0.4)	24 (0.4)	59 (0.37)	Clay
Woliso (D/Kora)	25 (0.73)	22 (0.49)	53 (0.91)	Clay

^a Indicate mean^b Indicate standard error in parentheses

Soil pH and EC

As per the ratings for Ethiopian soils by Murphy [41] and Taddese [42], the soil pH was found to range from neutral to slightly alkaline with pH ranging from 7.2 to 7.9 (Table 4). Similar results were obtained by Debele [14] and Kebede and Charles [43]. This pH range is favorable for most crops [42, 44]. The electrical conductivity ranged from 0.1 to 0.22 dSm⁻¹ in surface soil samples indicating that these soils have a low content of soluble salts and that there is no danger of salinity (Table 4).

Soil organic matter and C to N ratio

The organic matter contents were in the range of 1.6–3.2 % on the surface soils (Table 4). These values fall under low to moderate range based on the ratings of soil

test values established by Taddese [42]. The values are similar to most cultivated soils of Ethiopia [38, 45] which is attributed to land use history such as complete removal of biomass from the field and rapid rate of mineralization [46]. The C to N ratio of the surface soil samples varied from 10 to 15 (Table 4), which is within the normal range for arable soil [47].

Total N

Data on total nitrogen of the surface soils are presented in Table 4. Total nitrogen levels between 0.1 and 0.2 % are taken as low while those below 0.1 % are very low for tropical soils [48]. It, therefore, follows that soils of the study areas are low to very low in their total nitrogen status. Total nitrogen closely followed the trend of organic matter. Generally, a site low in organic matter was also low in total nitrogen. This supports earlier studies in the area by Debele [14] and Beyene [49]. One of the characteristic features of tropical environment is its high temperature which leads to rapid loss of soil organic matter due to volatilization. Soil erosion due to steep slopes and heavy rainfall as well as leaching, may have contributed to nitrogen loss. Certainly, it is one of the most deficient elements in the tropics for crop production [11, 50, 51]. Under local conditions, in addition to the above factors, continuous crop removal also contributes the low organic matter content in the study areas.

Available P

Available P (Olsen extractable) in the studied sites varied between 3.8 and 14.6 mg kg⁻¹ (Additional file 2: Figure S2). It was found to be deficient (<10 mg kg⁻¹) and medium (between 10 and 17 mg kg⁻¹) in 80 and 20 % of the samples, respectively, when compared with the values

Table 4 Soil pH, electrical conductivity (EC), soil organic matter (SOM), total carbon (TC), total nitrogen (TN), carbon to nitrogen ratio (C:N) and sulfate-S content of the study sites (n = 12)

Location (District)	pH (1:2.5)	EC (1:2.5) dS/m	SOM (%)	TC (%)	TN (%)	C:N	SO ₄ -S (mg kg ⁻¹)
Akaki (Akaki)	7.4 ^a (0.01) ^b	0.149 (0.014)	1.9 (0.005)	1.2 (0.003)	0.1 (0.0003)	12.3 (0.06)	1.8 (0.06)
Ambo (Kisole Odoliva)	7.9 (0.02)	0.104 (0.004)	2.7 (0.01)	1.6 (0.003)	0.12 (0.0009)	13 (0.07)	1.5 (0.13)
Chefe Donsa (Haberu Sefetu)	7.8 (0.05)	0.197 (0.01)	1.9 (0.01)	1.1 (0.004)	0.1 (0.001)	11.6 (0.1)	1.2 (0.09)
Debre Zeit (Denkaka)	7.9 (0.02)	0.173 (0.005)	2.7 (0.01)	1.69 (0.01)	0.11 (0.001)	14.8 (0.08)	1.4 (0.04)
Ginichi (Jemjem Legebatu)	7.8 (0.04)	0.224 (0.003)	2.3 (0.01)	1.34 (0.004)	0.11 (0.0007)	12.7 (0.05)	1.4 (0.13)
Holeta (Guntuta)	7.8 (0.02)	0.11 (0.002)	2.3 (0.005)	1.32 (0.003)	0.11 (0.001)	12.5 (0.1)	1.9 (0.13)
Mojo (Ajere Wolkite)	7.2 (0.04)	0.125 (0.002)	2.8 (0.003)	1.65 (0.002)	0.12 (0.001)	14.3 (0.1)	1.7 (0.11)
Sheno (Wentu)	7.3 (0.07)	0.144 (0.01)	3.2 (0.003)	1.87 (0.002)	0.19 (0.001)	9.9 (0.05)	1.7 (0.05)
Tullu Bolo (Awash Bune)	7.2 (0.03)	0.12 (0.005)	1.6 (0.01)	0.94 (0.004)	0.08 (0.0003)	12 (0.09)	1.4 (0.13)
Woliso (D/Kora)	7.8 (0.02)	0.201 (0.01)	2.1 (0.01)	1.21 (0.003)	0.11 (0.001)	10.7 (0.04)	2.1 (0.21)

^a Indicates mean^b Indicates standard error in parentheses

reported by Cottenie [32]. This result is in agreement with the findings of Debele [14]; Mamo et al. [18]; Mamo et al. [20]; Tesgaye [40]; Mamo and Haque [52]; Gebrelassie [53] and Negassa and Gebrekidan [54]. The modest level of annual P application (20–30 kg ha⁻¹) in the form of DAP fertilizer over 15 years was insufficient to raise the soil P levels and satisfy crop requirement.

Available sulfur

Calcium chloride extractable sulfur (sulfate-S) in the study sites ranged from 1.2 to 2.1 mg kg⁻¹ (Table 4). The available S contents of samples from all sites were found to be deficient assuming 5 mg kg⁻¹ S as critical level (Table 5).

Exchangeable bases and cation exchange capacity

In neutral Vertisols, the exchangeable sites are occupied mainly by calcium (Ca) and magnesium (Mg) and to a lesser extent by potassium and sodium [43]. Similarly in the present study, the predominant exchangeable cation, which accounts for more than 80 % of the exchange complex was Ca⁺⁺ followed by Mg⁺⁺, K⁺ and Na⁺. Exchangeable Ca and Mg content in the studied soils ranged from 27 to 49 cmol₍₊₎ kg⁻¹ and 4.7 to 10 cmol₍₊₎ kg⁻¹, respectively (Table 6). According to the rating suggested by Hazelton and Murphy [47], both Ca and Mg are in high range at all the sites (Table 5). The exchangeable K ranged between 1.3 and 2.3 cmol₍₊₎ kg⁻¹, which is in a very high range (Tables 5, 6). Generally, the fairly high level of exchangeable Ca, Mg and K is consistent with the findings of earlier studies [38, 39, 45].

It has been suggested that the proportions of the basic cations of the effective cation exchange capacity are more relevant to plant performance than the actual levels [47]. According to Abbott [60], the potassium saturation

percentage (3.2–5.4 %) of the studied soils was found to be desirable proportion for many plants (Table 6). Nevertheless, antagonistic effects could exist when disproportionate quantities of exchangeable cations are present in the soil. Potassium to magnesium ratio of the studied soils varied from 0.17:1 to 0.44:1 (Table 6), which indicated Mg-induced K deficiency using the rating of Loide [61]. This can be corrected by K application to bring the K to Mg ratio closer to 0.7:1. The low K to Mg ratios may result in K adsorption to cation exchange sites, which reduce K activity in the soil [62]. Many soils with vermiculitic or micaceous components of the clay fraction have a preferential adsorption of K⁺ over Ca²⁺ or Mg²⁺ [63, 64]. If there is a high preferential K adsorption on the exchange sites of clay minerals, the amount of K desorbing may then decline, resulting in a reduced K uptake at low soil exchangeable K to Mg ratio. Therefore, attempts should be made to supply the plants with potassium in physiologically correct ratio and in a sustainable manner.

Vertisols usually have a relatively high CEC, which ranges between 20 and 45 cmol₍₊₎ kg⁻¹ soil and even more [65]. In Ethiopia, Debele [14] reported that nearly all the Vertisols have high CEC of 35–70 cmol₍₊₎ kg⁻¹. According to the rating of Hazelton and Murphy [47], CEC of the studied soils were very high and ranged between 37 and 58 cmol₍₊₎ kg⁻¹ (Table 6). The very high value of CEC is mainly due to high clay content and predominance of 2:1 layer clay minerals.

Micronutrients

The AB-DTPA extractable Cu ranged from 2.9 to 6 mg kg⁻¹ in the surface soils (Additional file 3: Figure S3). Cu was found adequate in all the samples as compared with the values of Soltanpour [56] and Jones [57] (Table 5). The result was similar to that of Abera and Kebede [66], who reported that Cu concentration is at an adequate level in the central highlands of Ethiopia. This was further supported by EthioSIS finding. The AB-DTPA extractable Fe varied from 22 to 77 mg kg⁻¹ (Additional file 3: Figure S3). In this study, considering 5 mg kg⁻¹ AB-DTPA extractable Fe as critical, samples from all sites were found to have sufficient level of available Fe (Table 5). The result was similar to the finding of Itanna [67] who reported adequate content of soil Fe in Ethiopian Vertisols. However, deficiency of Fe was recorded by Abera and Kebede [66] in central highland Vertisols of Ethiopia. The finding of EthioSIS has also indicated that iron deficiency existed in soils of four major regions (Tigray, Amhara, Oromia and Southern), but it was more prevalent (41 %) in Tigray agricultural soils.

The AB-DTPA extractable Mn ranged from 22 to 100 mg kg⁻¹ (Additional file 3: Figure S3). Based on the

Table 5 Critical levels of macro and micronutrients with different soil tests as reported by different authors

Elements	Method used	Critical levels	References
P	Olsen	10–17 mg kg ⁻¹	[32]
K	NH ₄ OAc, pH = 7	0.3–0.7 cmol kg ⁻¹	[47]
Ca	NH ₄ OAc, pH = 7	5–10 cmol kg ⁻¹	[47]
Mg	NH ₄ OAc, pH = 7	1–3 cmol kg ⁻¹	[47]
Sulfate-S	CaCl ₂	5 mg kg ⁻¹	[55]
Cu	AB-DTPA	0.5 mg kg ⁻¹	[56, 57]
Fe	AB-DTPA	5 mg kg ⁻¹	[56, 57]
Mn	AB-DTPA	1 mg kg ⁻¹	[56, 57]
Zn	AB-DTPA	1.5 mg kg ⁻¹	[56, 57]
Mo	AAO	0.1–0.5 mg kg ⁻¹	[35, 58]
B	Mehlich 3	0.5–1 mg kg ⁻¹	[58, 59]

Table 6 Exchangeable bases, cation exchange capacity (CEC), K saturation percentage, K to Mg ratio, available molybdenum (Mo) and boron (B) content of the study sites (n = 12)

Location (District)	Exchangeable bases (cmol ₍₊₎ kg ⁻¹)				CEC (cmol(+) kg ⁻¹)	K/CEC (%)	K:Mg	AAO (mg kg ⁻¹) Mo	Mehlich3 (mg kg ⁻¹) B
	Ca	Mg	K	Na					
Akaki (Akaki)	38 ^a (0.17) ^b	9.4 (0.03)	1.6 (0.002)	0.16 (0.002)	49.4 (0.16)	3.2	0.17:1	0.003 (0.002)	<0.5
Ambo (Kisole Odoliva)	45.2 (0.08)	7 (0.02)	1.8 (0.008)	0.1 (0.003)	54.6 (0.09)	3.3	0.26:1	0.01 (0.01)	<0.5
Chefe Donsa (Haberu Sefetu)	32.8 (0.2)	5.2 (0.5)	1.8 (0.16)	0.27 (0.006)	42.1 (0.15)	4.3	0.35:1	0.005 (0.002)	<0.5
Debre Zeit (Denkaka)	49 (0.11)	5.2 (0.01)	2.3 (0.01)	0.07 (0.002)	56.5 (0.13)	4.1	0.44:1	0.02 (0.01)	<0.5
Ginichi (Jemjem Legebatu)	48.8 (0.04)	6.7 (0.03)	1.9 (0.008)	0.17 (0.004)	58 (0.03)	3.3	0.28:1	0.01 (0.01)	<0.5
Holeta (Guntuta)	34.1 (0.1)	8 (0.04)	1.5 (0.02)	0.18 (0.003)	44.3 (0.16)	3.4	0.19:1	0.01 (0.005)	<0.5
Mojo (Ajere Wolkite)	32.4 (0.17)	9.8 (0.12)	1.9 (0.007)	0.13 (0.003)	44.5 (0.23)	4.3	0.19:1	0.01 (0.005)	<0.5
Sheno (Wentu)	28.3 (0.11)	9.7 (0.03)	1.3 (0.008)	0.11 (0.005)	39.8 (0.15)	3.3	0.13:1	0.02 (0.008)	<0.5
Tullu Bolo (Awash Bune)	27.1 (0.2)	8.8 (0.07)	2.1 (0.02)	0.41 (0.002)	38.8 (0.3)	5.4	0.24:1	0.01 (0.003)	<0.5
Woliso (D/Kora)	30.8 (0.08)	4.7 (0.02)	1.8 (0.002)	0.08 (0.005)	37.8 (0.11)	4.8	0.38:1	0.01 (0.003)	<0.5

^a Indicates mean^b Indicates standard error in parentheses

critical value given by Soltanpour [56] and Jones [57], samples from all sites were found to have sufficient level of available Mn (Table 5). The sufficient levels of Mn in all the sites were consistent with findings of Itanna [67] who reported adequate content of soil Mn in Ethiopian Vertisols. Likewise, EthioSIS reported sufficient Mn levels in different soil types of Ethiopia including Vertisols. Nevertheless, a deficient level of Mn was recorded by Abera and Kebede [66] in central highland Vertisols of Ethiopia.

Zinc has low mobility in soils and tendency of being adsorbed on clay particles [68]. As shown in Additional file 3: Figure S3, AB-DTPA extractable Zn in the surface soils (0–15 cm) ranged from 1.1 to 2.7 mg kg⁻¹. However, the values recorded were lower than the critical level of 1.5 mg kg⁻¹ as established by Soltanpour [56] and Jones [57] except in Ambo, Holeta and Sheno (Table 5). In confirmation with this study, Asegelil et al. [69] reported Zn deficiency in 78.4 % of the soil samples collected from Vertisols of Ethiopia. This was further supported by Abera and Kebede [66] who reported deficiency of Zn in 98 % of the soil samples collected from central highland Vertisols of Ethiopia. A recent finding by Bereket et al. [70] also supported Zn deficiency on Ethiopian Vertisols. Similarly, this was reported by the findings of EthioSIS. The inherently low content of zinc in these soils may have been further depleted by intensive cropping. The poor availability of Zn in 70 % of the sites needs immediate intervention to improve wheat production.

Results reported by different researchers [59, 71–73] indicate that Mehlich 3 extracts comparable amounts of B as the hot water-soluble method. Consequently, we have used the sufficiency range (0.5–1 mg kg⁻¹) of B extracted using hot water-soluble method and applied it

to Mehlich 3 extractable B. Samples from all sites in the study were found to be deficient (Tables 5, 6). Comparison of the acid ammonium oxalate extractable Mo with the sufficiency range of 0.1–0.3 mg kg⁻¹ [35, 58] showed that samples from all sites were also found to be deficient (Tables 5, 6).

Wheat nutrient status

Data on wheat flag leaves analysis at flowering stage showed that N content varied from 1.4 to 2 % (Additional file 2: Figure S2). Tissue N concentration of samples from all sites was below the critical value of 3.6 %, suggesting there were insufficient N levels in the plant [74] (Table 7). To increase the pool of N available for crop growing, agricultural activities should focus on proper N management via application of N fertilizers and organic amendments and cultivation of wheat after legumes.

Table 7 Sufficiency ranges for nutrient content in wheat (flag leaves at flowering stage)

Nutrients	Sufficiency range	References
N (%)	3.6–4.5	[74]
P (%)	0.2–0.5	[76]
K (%)	1.5–3	[77]
Ca (%)	0.2–1	[76]
Mg (%)	0.15–0.5	[77]
Cu (mg kg ⁻¹)	4.5–15	[76]
Fe (mg kg ⁻¹)	30–200	[76]
Mn (mg kg ⁻¹)	20–150	[76]
Zn (mg kg ⁻¹)	18–70	[76]

As a consequence, the pool of N potentially available for the crop increases, which should improve the N status and yield of crops [75]. Phosphorus concentration in wheat leaves ranged from 0.05 to 0.15 % at flowering stage (Additional file 2: Figure S2). According to Plank and Donohue [76], P was deficient in samples from all sites but the values were close to the lower limit of sufficiency range at three sites (Mojo, Sheno and Tullu Bolo) (Table 7). Similarly, K ranged from 0.8 to 1.4 % and was found to be deficient in samples from all sites (Additional file 2: Figure S2). About 70 % of the tissue K content of the flag leaves was slightly under the lower limit of the sufficiency range suggested by Jones [77]. The deficient tissue K content was not predicted by the soil exchangeable K test. Similarly, response to K has been observed on Ethiopian Vertisols with high amount of ammonium acetate extractable K [78]. This was further supported by the findings of Suba and Srivastava [79], who reported that Vertisols with high exchangeable and non-exchangeable K showed a response to applied K, though the response was different depending on the type of plant. The poor agreement between the soil K status and response to K fertilizer is due to the fact that K response is affected by other soil variables like K saturation to cation exchange capacity, the proportion of K to other basic cations and K fixation capacity of clay minerals. In this regard, the K recommendations which depend on the cation exchange capacity and/or clay content of the soil have been compiled [80, 81]. For example, in India, Suba and Srivastava [79] have quadrupled K critical level for smectite-rich swell and shrink soils. Moreover, EthioSIS has established a critical value of Mehlich 3 extractable K of 190 mg kg⁻¹ based on field crop K response and soil analysis results, suggesting the need to amend the threshold value of K to get a common and realistic recommendation for K across all Vertisols of Ethiopia for sustainable crop production. Calcium and magnesium content of the wheat leaves ranged from 0.3 to 0.5 % and 0.25 to 0.83 %, respectively (Additional file 2: Figure S2). Both Ca and Mg were found to be within the sufficiency range made in Plank and Donohue [58] and Jones et al. [74], respectively (Table 7).

Regarding wheat micronutrient tissue concentrations, Cu concentration in wheat leaves ranged from 6.1 to 9.6 mg kg⁻¹, Fe from 71 to 97 mg kg⁻¹, Zn from 7.5 to 18 mg kg⁻¹, Mn from 29 to 100 mg kg⁻¹ and Cl from 0.54 to 1.3 mg kg⁻¹ (Additional file 3: Figure S3). All the plant samples were sufficient in Cu, Fe and Mn as given in Plank and Donohue [76] and Jones et al. [77] (Table 7). Since the contents of Fe and Mn in all the samples were far above the critical levels, their deficiency may not be expected in the foreseeable future as far as wheat crop is concerned. Zinc status of bread wheat flag leaf at flowering stage was deficient according to the sufficiency range in Plank and

Donohue [76] which agreed with the low levels of Zn in the soil (Table 7). Tissue Cl concentration of all the samples was above the critical value of 0.4 % [82], suggesting there were sufficient Cl in the soils (Table 8).

Soil and wheat nutrient content relationships

Interpretation of soil test results and plant analysis data is essential for further development of nutrient management. Additional files 2 (Figure S2) and 3 (Figure S3) presented the interrelation between soil and wheat flag leaf nutrient contents at flowering stage, collected from ten Vertisols of central highlands of Ethiopia. Soil and tissue nutrient concentrations were expected to be positively correlated for most nutrients because the concentration of a particular nutrient in the plant is generally greater when the concentration in the soil is greater [51]. Soil total N and C:N ratio had no significant correlation (unrelated) with plant N content at flowering stage. However, soil P, K, Ca, Mg, Cu, Fe, Mn and Zn concentrations exhibited a significant positive correlation with tissue nutrient concentrations. This indicated that soil total N did not proportionally alter internal plant N content, and it was less affected by changes in soil total N concentration than other nutrients. The mobility of N in the soil makes it difficult to get a solid representation of the available N concentration in soils. The highest correlation ($r > 0.90$) between soil and plant nutrient content was observed for P, K, Mg, Cu, Fe, Mn and Zn (Additional file 2: Figure S2, Additional file 3: Figure S3), implying that flag leaves at flowering stage can be used to calibrate soil and plant contents for the deficient nutrients.

Conclusions

From the present study, it can be concluded that the soil analysis data of wheat fields in central highland Vertisols

Table 8 Chloride content of wheat leaf samples from ten wheat growing areas of central highland Vertisols (n = 6)

Location (District)	Cl (%)
Akaki (Akaki)	1 ^a (0.04) ^b
Ambo (Kisole Odoliva)	1.1 (0.03)
Chefe Donsa (Haberu Sefetu)	1.1 (0.05)
Debre Zeit (Denkaka)	1 (0.05)
Ginichi (Jemjem Legebatu)	1.2 (0.03)
Holeta (Guntuta)	1.2 (0.1)
Mojo (Ajere Wolkite)	1.3 (0.1)
Sheno (Wentu)	0.94 (0.06)
Tullu Bolo (Awash Bune)	0.84 (0.01)
Woliso (D/Kora)	0.54 (0.01)

^a Indicates mean

^b Standard error in parentheses

of Ethiopia showed deficiency in the levels of N, P, S, Zn, Mo and B. Moreover, the plant analysis data from the same sites indicated that wheat plants were deficient in N, P, Zn and K. The nutrient deficiencies identified in this study could be due to either inherently low availability of these nutrients in the soils or as a consequence of continuous intensive cropping without applying fertilizer or manure containing these nutrients. The results of this study show the need for further studies in the deficient areas for determining wheat response to balanced fertilization. Further research on a wide range of wheat growing Ethiopian highland Vertisols is desirable to obtain holistic view of wheat nutrition. The rallies and training programmes for the farmers should be arranged for increasing awareness regarding the benefits of inorganic fertilizers other than DAP and urea in improving soil fertility, nutrient status and crop production.

Additional files

Additional file 1: Figure S1. Geographical map of the sampling sites.

Additional file 2: Figure S2. Literature critical levels and plant vs. soil macro-nutrient contents of the study sites.

Additional file 3: Figure S3. Literature critical levels and plant vs. soil micro-nutrient contents of the study sites.

Abbreviations

NH₄OAc: ammonium acetate; AB-DTPA: ammonium bicarbonate di-ethylene tri-amine penta-acetic acid; AAO: acidic ammonium oxalate; CEC: cation exchange capacity; DAP: di-ammonium phosphate; EDTA: ethylene diamine tetra-acetic acid; EC: electrical conductivity; EthioSIS: Ethiopian soil information system; FAO: food and agriculture organization; GPS: global positioning system; ICP-OES: inductively coupled plasma-optical emission spectrometer; SOM: soil organic matter; TC: total carbon; TN: total nitrogen.

Authors' contributions

HH and TM conceived the study. All authors participated in the design and coordination. HH collected and analyzed the samples and interpreted the data, which was part of her Doctorial thesis of Soil Science at Haramaya University, Ethiopia. All the authors also helped to draft the manuscript as well as approved the final manuscript. All authors read and approved the final manuscript.

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Competing interests

The authors declare that they have no competing interests.

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