Ethiop. J. Agric. Sci. 30(4) 97-119 (2020)

Mineralogical and Physicochemical Properties of Nitisols In The Ethiopian Highlands

Eyasu Elias[1,2] and Getachew Agegnehu[3]

[1]College of Natural and Computational Sciences, Centre for Environmental Science, Addis Ababa University, Ethiopia; E-mail: Eyasu.elias@aau.edu.et; [2]CASCAPE Program Manager, Bilateral Ethiopia-Netherlands, Partnership for Food Income and Trade (BENEFIT); E-mail: Eyaelias@gmail.com; [3] Getachew Agegnehu, Ethiopian Institute of Agricultural Research; Addis Ababa, Ethiopia, Email: geta1565@yahoo.com

አህፅሮት

ኒቲሶልስ (Nitisols) በአብዛኛዉ ቀይ ወይም ቀይ-ቡናማ ቀለም ያላቸዉ የአፈር ዓይነቶች ሲሆኑ በኢትዮጵያ ከፍተኛ አካባቢዎች በተለይም በደቡብ ምዕራብ ኢትዮጵያ ሰፊ የእርሻ መሬት ይሸፍናሉ፡፡ ይህ የአሰሳ ጥናት በ250 ሜትር ጥራት (ሪዞልዩሺን) የተወሰኑ የኒቲሶልስ ገፀ አምደ አፈሮችን በማዘጋጀት የሥነ ቅርፀ-አፈር (ሞርፎሎጂካል)፣ ፊዚካዊና ኬሚካዊ ባህሪያትን እንደዚሁም የንጥረነገር ይዘት ያጠቃልላል፡፡ ይህ በ46 የኒቲሶል ገፀ አምደ አፈሮች ላይ የተካሄደ ጥናት የአፈር ልኬተ አሲድጨው፣ የአፈር ዘአካል ካርቦን፣ ዓቢይና ንዑስ ንጥረምግቦች፣ የማዕድንና ጠቅላለ የንጥረነገሮችን ይዘት ምርመራና ትንተና የያዘ ነዉ፡፡ የዚህ ጥናት ዉጤት እንደሚያሳየዉ በኢትዮጵያ ከፍተኛ አካባቢ የሚገኘዉ የኒቲሶል መሰረታዊ የሥነ አፈር ባህርይ ይለያል፡፡ የዚህ አፈር ልኬተ አሲድጨው በ4.8 እና በ6.7 መካከል ሲሆን በጠንከራ እና አነስተኛ የአሲዳማነት ደረጃ ይመደባል፡፡ የዚህ አፈር የካርቦን፣ የናይተሮጅንና የድኝ (ሰልፈር) ይዘት በጣም ዝቅተኛ ሲሆን መጠናቸዉም በቅደም ተከተል 2.05፣ 0.18 እና 0.94 ሚ.ግ. በኪ..ግ. መሆኑን ያሳያል፡፡ ሆኖም በአፈር ዉስጥ የሚገኙ የፎስፎረስ (ከ2.40 እስከ 26.40 ሚ.ግ. በኪ..ግ) እና የፖታሲየም (ከ0.07 እስከ 2.77 ሴንቲሞል በኪ.ግ) መጠን ሰፊ የሆነ ልዩነት የታየባቸዉ ሲሆን ይህም በአፈር-ሰር ቁሶችና በመሬት አጠቃቀም ልዩነት ምክንያት የተፈጠረ ሊሆን ይችላል፡፡ የንዑስ ንጥረምግቦችን በተመለከተ ደግሞ ይህ አፈር በብረት (Fe)፣ ማንጋኒዝ (Mn) እና ነሀስ (Zn) ንጥረ ነገሮች መጠን በጣም ከፍተኛ ሲሆን በመዳብ (Cu) እና በቦሮን (B) ይዘት ግን በጣም ዝቅተኛ ነዉ፡፡ በአንጻሩ ግን ይህ የአፈር ዓይነት በመጠነ አሉታ ሙል (CEC፣ አማካይ 41.93 ወይም ከ26 እስከ 57 ሴንቲሞል በኪ..ግ) እና በጨዋማ ንጥረነገር (base saturation፣ አማካይ 73% ወይም ከ50 እስከ 95%) መጠን በጣም ከፍተኛ ሲሆን በኤፒ አድማሰ አፈር (Ap horizon) ዉስጥ አማካይ የሲልት እና ሸክላ አፈር ስብርባሪ (ፍራክሽን) ንፃሬ (ሬሺዮ) 0.38 በመሆኑ ከፍተኛ ነዉ፡፡ ከሌሎች መሰል ኒቲሶል የአፈር ዓይነቶች አንጻር በቀዳሚ ማዕድናት ይዘት በዋናነት ፊልድስፓር እና 2፡1 ፋይሎሲሊኬት (phyllosilicates) በዋናነት ማይካ በሸክላ አፈር ስብርባሪ ዉስጥ የሚገኙ ሲሆን ይህ አፈር በመካከለኛ ዕድሜ ክልል የሚገኝ ገና ያላረጀ መሆኑን ያሳያል፡፡ በዚህ አፈር ላይ ዘላቂ እርሻ ለማካሄድ በአፈር ዉስጥ ቅሬተ ዘአካል ማሳደግና እንደዚሁም የተመጣጠነ እና ትክክለኛ የአፈር ማዳበሪያ መጨመር ያስፈልጋል፡፡ በተጨማሪም በአለም አቀፍ የአፈር ሀብት (World Resource Base) ምደባ ዘዴ መሰረት የኒቶሶል ልዩ ገፀ አምደ አፈር ለንዑስ ኒቲሶል ልየታ የሚረዱ ተጨማሪ መመዘኛዎችን አካቷል፡፡

Abstract

Nitisols cover an extensive area of the agricultural landscape in the Ethiopian highlands. This study outlines the morphological and physico-chemical properties, and the mineralogical and total elemental composition of some Nitisol profiles based on soil survey at 250 m resolution. Analytical data of 46 Nitisol profiles were studied for soil pH, organic carbon (OC) and some macro and micronutrients, and mineralogical and total elemental composition. Results showed that Nitisols of the Ethiopian highlands differ in some fundamental ways from the pedogenetic characteristics often referred to in the mainstream soil science literature. The soils in this study are strongly to moderately acidic with pH of 4.8-6.7, and very low in OC, TN and sulfur (S) with mean values of 2.05%, 0.18% and 0.94 mg/kg. But levels of available phosphorus (AP) and exchangeable K showed wide variation (2.40 to 26.40 mg/kg P and 0.07 to 2.77 cmol (+)/kg K), reflecting differences in parent materials and land use. Considering micronutrients, the soils are very high in iron (Fe), manganese (Mn) and zinc (Zn) but severely deficient in copper (Cu) and boron (B). Conversely, the soils are very high in CEC (mean 41.93, range 26-57 cmol (+)/kg) and base saturation (mean 73%, range of 50-95%), and mean silt/clay ratio of 0.38 in the Ap horizon is rated high. Mineralogical composition of primary minerals (chiefly feldspars) and 2:1 phyllosilicates (mainly mica) in the clay fraction, suggests that the soils are still young and cannot be qualified as "highly weathered soils" in contrast with other tropical Nitisols. At a local level, the results suggest that sustainable agricultural production on these soils depends on the replenishment of organic matter and application of fertilizers in proper balance and right amounts. Also, the distinct characteristics of Nitisol profiles described provide additional diagnostic criteria to distinguish subunits of Nitisols (i.e., third level) under the WRB system of classification.

Keywords: Ethiopian highlands, mineralogical composition, Nitisol profiles, physicochemical soil properties, quantitative mineralogy

Introduction

Assessing the characteristics and fertility status of different soil types is an important first step for sustainable agricultural production (Santra *et al.*, 2017). Detailed characterization of individual soil profiles enables a better understanding of soil resources for sustainable use and management at the local level, and at the same time provides diagnostic criteria for distinguishing soil subunits under the World Reference Base for Soil Resources system of classification (Nachtergaele *et al.*, 1994).

Given the complex geology, rugged terrain, and sub-tropical climatic conditions, the pedogenetic factors in the Ethiopian highlands can be considered unique compared to many other tropical soils. Hence, generating and documenting more information on the nature and properties of the Ethiopian highland soils in soil science literature will contribute to a more comprehensive soil reference database for soil classification, as well as technology transfer for sustainable soil management (Mishra *et al.*, 2004).

Nitisols, covering an estimated area of 150,000 km^2, are the most extensive agricultural soils in the Ethiopian highlands supporting the bulk of cereal and livestock production (Elias, 2016; FAO, 1984). In fact, more than half of all the Nitisols of tropical Africa are found in the Ethiopian highlands, followed by Kenya, Congo and Cameroon (Stocking, 1988). In Ethiopia, the soils are particularly extensive in the southwestern and north-central highlands, representing 64 and 25% of the agricultural landmass respectively (Elias, 2016).

However, in spite of the areal extent and agricultural importance, the pedogenetic characteristics and quantitative mineralogy of Nitisols are not well documented in the literature (De Wispelaere *et al.*, 2015). At local level, the lack of spatially explicit information on soil characteristics has hindered sustainable soil management, particularly soil-specific fertilizer recommendation, a pre-condition for increased agricultural production (Mateete *et al.*, 2010. Years of unsustainable soil management practices based on the blanket fertilizer application recommendation of 100 kg DAP (Di-ammonium Phosphate: 18% N, 46% P_2O_5) and 100 kg urea (46% N) has affected the productivity of agricultural soils in Ethiopia (Elias, 2016).

Continued use of N and P fertilizers alone seems to have depleted macronutrients such K, and S, and micronutrients that are not included in the fertilizer regime (Abera and Kebede, 2013). Soil degradation is currently considered one of the main environmental problems, compromising short and medium range development priorities related to food security (Agegnehu *et al.*, 2019; Elias *et al.*, 2019). The estimated macronutrient depletion rate of −122 kg N, −13 kg P and −82 kg K ha^{-1} is among the highest in Africa (Stoorvogel *et al.*, 1993). Measures for improved soil management based on reliable data are of critical importance for sustainable agricultural production in Ethiopia. Such management can only be based on a proper understanding of the nature and properties of the soils and the development of soil-specific fertilizer recommendations. Therefore, the objectives of this study were (1) to characterize the distinctive morphological, physico-chemical and mineralogical properties of the Nitisols of the Ethiopian highlands; and (2) to provide crucially important soil resource information for soil-specific fertilizer recommendations in support of sustainable agricultural production, while at the same time contributing to a soil information database with unique diagnostic features important for classification.

Materials and Methods

Description of the study area

The study was conducted in 30 districts in the Ethiopian highlands (Fig. 1), selected as part of a Dutch-supported action research project known as Capacity building for scaling agricultural best practices for increased production in Ethiopia (CASCAPE)) that supported the soil survey work. The topography is characterized by plains, hills and undulating to rolling high plateaus accompanied by basins and deep river gorges (FAO, 1984; Mohr, 1971). The Trap Series volcanics that took place during the Tertiary period that over poured huge lava flows over the peneplained land surface. These are mainly basalt in the north-central highlands but more felsic rocks (rhyolites, trachytes, pumice and unwelded tuff) are prevalent in the south and south-western highlands (Williams, 2016). The sub-tropical climatic conditions range between tepid moist to sub-moist agro-ecological zones, marked with alternating wet and dry seasons with mean annual rainfall of 1200-2000 mm. A mixed crop-livestock system is the most dominant land use type with a wide range of soil management practices across the highlands. The bulk of Nitisols are under staple cereals such as *teff* (*Eragrostis tef Zucc*), bread wheat (*Triticum aestivum*), maize (*Zea mais*) and barley (*Hordium vulgarae*), cultivated with the application of 46 kg P_2O_5 and 64 kg N ha^{-1} (Elias *et al.*, 2019). In the agroforestry-based system of the south-western highlands, Nitisols support both garden and forest coffee (*Coffea arabica*) and *ensat* (*Ensete venticosum*), along with horticultural crops and cereals. In the sorghum-*khat*[1] (*Khata edulis*) system of the southeastern highlands, irrigated cultivation of *khat* and vegetable mixture is commonly practiced.

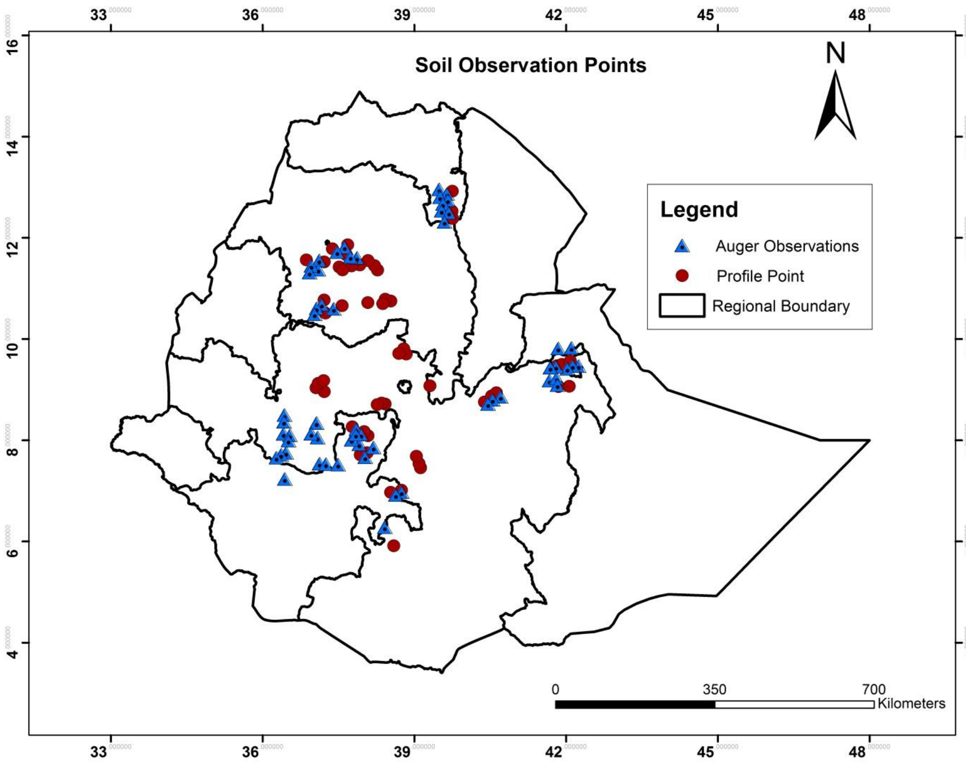

Figure 1. Location map of soil survey sites in the Ethiopian highlands

Soil profile database

This study was extracted from the soil profile and analytical database generated by a soil land-landscape survey conducted at 250 m resolution in the Ethiopian highlands, the profile data of which was compiled in an Africa soil profile database (Elias, 2016; Leenaars *et al.*, 2016). Out of 204 geo-referenced profile pit observation points, 46 were classified as Nitisols, further classified into soil units by means of prefix and suffix qualifiers (Annex 1). The analytical data of the Nitisol profiles were organized for two standard depth intervals by means of weighted averages for surface soil horizon (0-30 cm) and subsurface horizon (30-100 cm). The soil parameters studied include soil physical characteristics (particle size distribution and bulk density). Selected chemical properties studied include soil pH, electrical conductivity (EC), OC, TN, AP, CEC, exchangeable bases and some micronutrients (Fe, Mn, Zn, Cu, and B). These parameters were originally measured at the soil fertility laboratory of the Waterworks Construction, Design and Supervision Enterprise in Addis Ababa, Ethiopia. Standard laboratory procedures were applied for the measurement of soil properties (van Reeuwijk, 2006).

Analysis of quantitative mineralogy

A representative sample profile was selected for quantitative mineralogical analysis at the laboratory for mineralogy and petrology of the University of Ghent in Belgium. Coarse samples were pulverized (using pestle and mortar) until passing through a 500 µm sieve. About five grams of the pulverized sample was spiked with 5% zincite and further micronized by wet grinding using a McCrone Micronizing mill to obtain a grain size of 10 µm or less. The obtained slurries were then spray-dried (Hillier, 1999). Clay fractions (<2 µm) separated using successive sedimentation were Ca^{2+} and K^{+} saturated, and for each saturation an oriented slide was prepared by pipetting a suspension onto a glass slide. The Ca^{2+} saturated slides were recorded in air-dry condition and after 24 hours of ethylene-glycol solvation. The K^{+} saturated slides were recorded in air-dry condition and after heating to 350° and 520°C as outlined by Hillier (1999).

Both the bulk powders and oriented slides were recorded using a Bruker D8 ECO Advance X-ray diffractometer, equipped with a Cu-anode (40 kV, 25 mA) and an energy-dispersive position-sensitive LynxEye XE detector. The incoming bundle was automatically collimated to an irradiated beam length of 15 mm (oriented slides) or 17 mm (powders). The acquired powder spectra were modeled quantitatively using the BGMN Rietveld model (Bergmann *et al.*, 1998). Next, the oriented patterns were modeled using PyXRD following standard procedure outlined (Dumon *et al.*, 2014). According to ISO 14869-2 the total elemental composition of bulk samples was determined after fusion with lithium meta/tetraborate at 950°C and dissolution in 4% HNO_3 to provide compositional constraints for the mineralogy. Loss on ignition (LOI) was determined after heating the samples at 105 °C and 850 °C. Elemental concentrations were measured using inductively coupled plasma optical emission spectrometry (ICP-OES).

Data analysis

The analytical data of the entire 46 Nitisol profiles were subject to descriptive statistics (mean, range, variance and coefficient of variation-CV) for major physicochemical soil properties at two depth intervals – surface horizon (0-30 cm) and subsurface horizon (30-100 cm). The same procedure was applied for total elemental composition of the clay fraction. According to the (IUSS Working Group WRB, 2006), the morphological and analytical data for the entire master horizon is provided for five representative sample profiles to depict the properties of soils by depth, and to elaborate the various soil classification units. The ratings proposed by Landon (1991) were used to interpret the analytical data for most parameters except for exchangeable bases and CEC, for which the ratings of Hazelton and Murphy (2007) were adopted, while Benton (2003) was used for rating micronutrients. The quantitative mineralogical results were plotted on XRD-graphs with the corresponding attributes of 2 Theta values, d-spacing values and Peak Height values.

Results

The Nitisol reference soil groups (RSG) and soil units

The soil survey found five RSGs accounting for 90% of the agricultural landscapes of the Ethiopian highlands: Nitisols (29%), Vertisols (27%), Leptosols (26%), Luvisols (11%) and Planosols (2%) (Elias, 2016). Out of the 283 profiles investigated, 46 were classified as Nitisols based on the presence of shiny nitic subsoil horizons as diagnostic criteria as outlined (IUSS Working Group WRB, 2006). At the soil unit level, the profiles were grouped as Luvic, Mollic and Haplic Nitisols based on some diagnostic properties. About 65% of the profiles were categorized as Luvic Nitisols, having high CEC (>24 cmol (+)/kg), high base status (>50%) and clay enrichment down the profile (Annex 1). Profiles grouped as Mollic Nitisols have dark surface soil with high base saturation (>50%) and moderate organic matter content, but they accounted for only about 11% of the Nitisol profiles. These are largely confined to the upland plateau of the south-western highlands where an agroforestry system is common. The suffix qualifier "Eutric" indicates that the soils had a base saturation of ≥50% and those having the opposite property are grouped as "Dystric," which accounts for only few. Soils with the "Rhodic" qualifier had ≥30 cm thick topsoil, redder hue (3.5 YR) while those with the suffix qualifier "Humic" had organic carbon in excess of 1.4% in the surface horizon (Ap).

Geomorphologic environment of occurrence of Nitisols in the Ethiopian highlands

As shown in Table 1, about 75% of the Nitisol profiles occurred on well-drained undulating to rolling plateaus with sloping to strongly sloping land-forms (5-15% gradient). Only a small proportion of the Nitisols were found on moderate to high relief hills and dissected side slopes having steep slopes (15-30% gradient). Residual landform genesis and volcanic parent (mostly basaltic in the north-central highlands and felsic in the south-western highlands) were major geomorphologic features of the Nitisol landscapes. In the uplands of pyroclastic deposits, the Nitisols are found intergrading with Luvisols and Andosols, and with Vertisols and Planosols in the undulating landscapes of the basalt plateaus. The findings were in agreement with results of other East and southern African countries where Nitisols are reported to be extensive on well-drained upland positions of gently undulating plateaus (Chileshe and Ting-tiang, 1988).

Morphological characteristics of Nitisols

The majority of the profiles (70%) were very deep (150-200 cm), but some profiles occurring on the dissected side slopes and high relief hills with steep slopes were shallower (<150 cm). This is due to accelerated erosion and removal of topsoil from such elevated landscapes. Profiles typically had an Ap-AB-Bt horizon sequence with smooth boundaries between horizons. Whereas the boundary that separates the Ap horizon from the Bt1 horizon was mostly diffuse, a more gradual boundary separates Bt1 and Bt2 horizons. The thickness of the surface horizon ranged from 0 to 20 cm, showing no variability among profiles. It was marked by very dark brown (7.5YR3/2, moist) to very dark grayish brown (10YR3/2, moist) colours, a weak to moderate and coarse to medium sub-angular blocky structure that is hard when dry and friable when moist, and a slightly sticky and slightly plastic consistency when wet (Table 1). The subsoil (Btx horizon) in most profiles was dark reddish brown 2.5YR2.5/4, moist) and occasionally dusky red (2.5YR 3/2), having a moderate to strong, medium to coarse sub-angular blocky structure and similar to the Ap horizon in its consistence. Some differences in particle size distribution and wet consistence were observed among pedons. Pedons from the cereal dominated north-central highlands (pedons 3, 5, and 6) were coarser and slightly sticky in consistency, while those from the agroforestry based south-western highlands (pedons 1, 2 &4) were medium in structural size and sticky in wet consistency (Table 1). The finding was in agreement with previous reports, suggesting that land use significantly affected soil structural aggregates and particle size distribution with coarser structures in the intensive cereal system (Elias, 2017; Gebreselassie *et al*., 2015).

Physicochemical properties of Nitisol profiles

Particle size distribution, silt to clay ratio and bulk density

Table 2 presents selected physicochemical properties of all 46 profiles by means of weighted averages at two depth intervals. The physical and chemical properties of the entire horizons for each of the five sample profiles are summarized in Annex 1. Regarding particle size distribution, the soils are generally clayey with mean sand, silt and clay fractions of 21, 21 and 58% for the Ap and Btx horizons (Table 3). The clay-rich illuvial layers (Btx) had prominent nutty structures with many shiny ped faces that qualify as a strongly developed nitic horizon (IUSS Working Group WRB, 2006). The rather higher sand content in the surface horizon may indicate the effects of land use and erosion-deposition processes in the plough layer (Elias, 2017). There was substantial difference among pedons in the particle size distribution, generally with a coarser and more sandy-clay texture in the intensive cereal livestock system, perhaps due to intensive tillage and cattle grazing. The result suggests that although texture is an inherent property of the soil, it can be altered by land use practices over a longer period.

The silt to clay ratio ranged from 0.17 to 1.06 and showed a slight decrease with depth. The generally high Si/Cl ratio suggests the presence of large reserves of weatherable minerals. This indicates that the soils still have high potential fertility as result of rejuvenation through geologically recent volcanic ash falls (Williams, 2016). The bulk density (BD) ranged from 0.57 to 1.50 g/cm^3 in the surface horizon and between 1.06-1.36 g/cm^3 in the subsurface horizon (Table 2).

According to Hillel (2004) these figures were below the critical values for agricultural use of soil (1.4 g/cm^3), indicating the absence of excessive compaction or restrictions for root development. The low bulk density, along with the generally friable consistency, indicate that the soils had good physical conditions for agricultural crops (Fageria *et al.*, 2011). However, bulk density as high as 1.50 g/cm^3 was recorded in some profiles from the intensive cereal-livestock system, indicating the development of soil compaction due to repeated tillage in these profile sites.

Selected soil chemical properties

The mean soil pH-H_2O ranged from 4.8 to 6.7, which is rated as very strongly to slightly acidic in the Ap horizon, showing a steady increase in pH with profile depth (Table 3). But there is marked variation among profiles with very strongly acidic profiles, largely being confined in the south-western highlands where soils have developed on silica rich parent materials (e.g., rhyolites, trachyte) that produce acidic clays (Buol *et al.*, 2011). This is consistent with the relatively low exchangeable bases (Ca, Mg) in the soils of these profile sites. The mean electrical conductivity is 0.05 dS/m and its highest value was 0.22 dS/m, which was rated as non-saline, suggesting that the soils are free of salt accumulation.

The soils are very low to medium in organic OC and TN with mean values of 2.05% and 0.18% for the surface horizon, and 1.03 and 0.1% for the subsurface horizons. The C/N ratios are optimum (10-11) throughout the profile depth suggesting no inhibition in organic matter decomposition and N-mineralization. The levels of available sulfur (S) are consistently low across all profiles with a mean value of 0.94 mg/kg (Table 3). Severe organic matter depletion and N and S mining in the Ethiopian highlands is attributed to the practice of complete removal of crop residues as cattle feed and dung burning for household energy, as well as low levels of N fertilizer application (46 kg N/ha) and no application of S-fertilizer until recently. On the other hand, the mean value of available phosphorus (P-Olsen) is 8.46 mg/kg, rated as moderate, but showing a sharp decline with profile depth and wide variation among profiles (Table 2). Low to moderate levels of phosphate in spite of substantial DAP application, particularly in the intensive cereal system, suggests phosphate fixation, which is consistent with low soil pH and high levels of Fe and Mn the soil.

Conversely, the mean value of Ca (16 cmol (+)/kg) and Mg (7 cmol(+)/kg), mean base saturation (82%) and CEC (42 cmol(+)/kg) were rated as very high invariably across all profiles and depth intervals (Table 3). The generally high CEC was well correlated with the high clay content but it was above the CEC limit for Nitisol (≤ 24 cmol (+)/kg) as indicated in the literature. The high base saturation is consistent with high levels of Ca and Mg ions in the exchange complex, indicating that the soils are not intensely leached as often described in the literature. In addition, the high base saturation is not consistent with the low soil pH and above the base status limits (<50%) as indicated in the literature for tropical Nitisols (IUSS Working Group WRB, 2006; Juo and Franzluebbers, 2003). These unique features of the Nitisols of the Ethiopian highlands compared to other tropical soils are discussed at some length in section 4.1.

Exchangeable Na mostly appears in trace amounts with a mean value of 1.05 cmol (+)/kg, consistent with the low electrical conductivity values and suggesting no salt concentrations in the soil. However, in certain profiles from the south-eastern highlands, exchangeable Na levels as high as 2.02 cmol (+)/kg were recorded, which is rated as slightly sodic. This is associated with the practice of furrow-irrigated cultivation of *khat* and vegetables in the area. The exchangeable K-levels are highly variable, ranging from very low to very high (0.07-2.77 cmol (+)/kg) and with a mean value of 0.74 cmol (+)/kg. The huge variability is related to the differences in the parent materials and land use practices. Profiles developed on basaltic and calcareous limestone parent materials in the north-central and south-eastern highlands tended to have lower levels of exchangeable K. Conversely, profiles developed on felsic parent materials (e.g., rhyolites, trachytes) in the south-western highlands contain K-feldspar and are rich in K, as shown in the clay mineralogical analysis (see below). In terms of land use, the practice of maize-potato rotation in the north-central highlands with no potassic fertilizer application and removal of crop residues from fields is reported to have causing depletion of the K-stock of the soil (Elias, 2017).

Considering the micronutrient levels, the mean values of Fe (56.64 mg/kg), Mn (57.68 mg/kg) and Zn (7.29 mg/kg) are rated as very high for both depth intervals and across all profiles. This is consistent with the low pH and low phosphate status of the soils that are known to induce increase in micronutrient contents. Conversely, the contents of Cu and B are consistently low with mean values of 1.59 and 0.5 mg/kg for the surface horizon and 0.45 and 0.41 mg/kg for the subsurface horizon (Table 3). This finding is in agreement with previous reports that Cu and B deficiency is widespread in the Ethiopian highland soils, while Fe and Mn levels are exceptionally high, which may eventually lead to root toxicity (Abera and Kebede, 2013; Haque *et al*., 2000).

Table 1. Some morphological characteristics Nitisol profiles

Pedon No & code	Hori	Depth (cm)	Munsel colour (moist) Notation	Munsel colour (moist) Description	Structure Grade	Structure Size	Structure Type	Consistence Dry	Consistence Moist	Consistence Wet
1	Ap	0-20	10YR3/2	Very dark grayish brown	MO	ME	SAB	HA	FR	ST/SPL
	AB	20-42	2.5YR2.5/4	Dark reddish brown	WE	ME	SAB	HA	FR	ST/SPL
ET-AJJI-P001	Bt1	42-90	2.5YR2.5/4	Dark reddish brown	ST	ME	SAB	HA	FR	ST/SPL
	Bt2	90-200	2.5YR2.5/4	Dark reddish brown	ST	ME	SAB	HA	FR	ST/SPL
	Ap	0-12	7.5YR 3/4	Dark brown	WE	ME	GR	SO	FR	SST/SPL
2	AB	12-30	5YR 3/3	Dark reddish brown	MO	ME	SAB	SO	FR	SST/SPL
	Bt1	30-90	2.5YR2.5/4	Dark reddish brown	MO	ME	SAB	HA	FR	ST/PL
	Bt2	90-145	2.5YR 2.5/4	Dark reddish brown	MO	ME	SAB	HA	FR	ST/PL
ETJIMLS-SP2	Bt3	145-200	2.5YR 3/4	Dark reddish brown	ST	ME	AB	HA	FR	ST/PL
3	Ap	0-20	10YR3/2	Very dark grayish brown	WE	ME	SAB	HA	FR	SST/SPL
	AB	20-40	2.5YR2.5/4	Dark reddish brown	MO	CO	SAB	HA	FR	SST/PL
ETASAA-P002	Bt1	40-80	2.5YR3/4	Dark reddish brown	MO	CO	SAB	HA	FR	SST/PL
	Bt2	80-200	2.5YR3/4	Dark reddish brown	MO	CO	SAB	HA	FR	SST/PL
	Ah	0-22	10YR3/2	Very dark grayish brown	WE	FI	GR	HA	FR	SST/SPL
4	AB	22-48	2.5YR3/4	Dark reddish brown	MO	CO	SAB	HA	FR	SST/SPL
	Bt1	48-71	2.5YR3/4	Dark reddish brown	MO	CO	SAB	HA	FR	SST/SPL
	Bt2	71-120	2.5YR 3/2	Dusky red	MO	ME	SAB	HA	FR	SST/SPL
[illegible]	Bt3	120-200	2.5YR3/4	Dark reddish brown	ST	ME	SAB	HA	FR	SST/SPL
	Ah	0-12	7.5YR3/4	Dark brown	ST	CO	SAB	HA	FR	SST/SPL
5	AB	12-40	7.5YR3/4	Dark brown	ST	CO	SAB	HA	FR	SST/SPL
	Bt1	40-95	2.5YR3/4	Dark reddish brown	MO	CO	SAB	HA	FR	SST/PL
ETASAAK-P001	Bt2	95-110	2.5YR3/4	Dark reddish brown	WE	CO	SAB	HA	FR	SST/PL
	Bt3	110-190	2.5YR3/4	Dark reddish brown	WE	CO	SAB	HA	FR	SST/PL

Table 2. Mean values of selected physico-chemical properties of Nitisol profiles - weighted average by depth interval (N=46)

	Surface horizon (0-30 cm)				Subsurface horizon (30-100 cm)			
Property	Mean	Std. Dev	Min	Max	Mean	Std. Dev	Min	Max
Sand (%)	21.57	14.13	2.00	56.00	15.86	14.47	1.00	53.00
Silt (%)	20.75	5.87	9.00	39.00	20.44	6.50	7.00	35.00
Clay (%)	57.71	12.35	28.00	84.00	63.82	13.08	39.00	89.00
Si/C	0.38	0.15	0.17	1.06	0.33	0.11	0.12	0.59
BD (g/cm^3)	1.13	0.12	0.57	1.50	1.12	0.07	1.02	1.36
pH_{H2O}	5.36	0.45	4.80	6.70	5.29	0.48	4.40	7.10
EC (dS/m)	0.05	0.03	0.03	0.22	0.05	0.05	0.01	0.37
OC (%)	2.05	0.67	0.43	3.48	1.03	0.40	0.32	2.73
TN (%)	0.18	0.06	0.04	0.29	0.10	0.03	0.03	0.24
C/N	11.59	3.35	8.05	21.64	10.00	0.00	10	10
Exchangeable bases &cation exchange capacity (Cmol(+)/kg)								
Ca	16.43	4.13	10.60	29.40	14.91	5.38	6.20	30.00
Mg	7.31	3.62	3.40	18.80	6.46	3.44	2.60	18.20
Na	1.05	0.63	0.10	2.02	1.08	0.62	0.10	1.96
K	0.74	0.59	0.07	2.77	0.67	0.69	0.06	2.67
CEC-soil	30.93	6.26	26.00	47.00	28.22	6.45	28.00	47.00
BS (%)	82.542	15.29	37.00	112.74	81.92771	17.82	36.00	112.4000
Available macro and micronutrients (mg/kg)								
P	8.46	5.67	2.40	26.40	3.07	1.27	1.11	6.05
S	0.94	0.42	0.25	1.93	NA	NA	NA	NA
Fe	56.64	39.72	6.70	192.00	156.75	41.85	95.00	185.00
Mn	57.68	26.39	11.20		17.000	8.12	10.00	25.00
Zn	7.29	5.86	0.15	23.30	4.38	0.68	2.59	8.19
Cu	1.90	1.19	0.34	6.11	1.86	0.27	1.61	2.12
B	0.51	0.07	0.44	0.67	0.41	0.05	0.34	0.50

Total elemental composition and XRD pattern

The surface (Ap) and subsoil (Btx) horizons of the profile (pedon 4) were subject to mineralogical analysis. The dominant oxides are SiO_2 (37 wt%), Al_2O_3 (27 wt%) and Fe_2O_3, (16 wt%) with considerable amounts of TiO_2 (3 wt%), which is the resistant accessory mineral, rutile or its polymorphs (Table 3). Loss in ignition (LOI) values can also be considered high (16 wt%), indicative of considerable amounts of hydrated minerals and/or the presence of 2:1 physllosilicate minerals (Table 4).

Table 3. Total elemental composition of sample Nitisol profile

Oxides	Ap-horizon (0-30 cm) (wt%)	Btx-horizon (wt%)	Mean (wt%)
SiO_2	37.07	36.68	36.88
Al_2O_3	27.04	26.33	26.69
Fe_2O_3	16.14	15.86	16.00
TiO_2	2.81	2.72	2.77
MgO	0.47	0.49	0.48
MnO	0.17	0.15	0.16
CaO	0.16	0.22	0.19
Na_2O	0.07	0.07	0.07
K_2O	0.59	0.63	0.61
P_2O_5	0.16	0.17	0.17
LOI	15.07	16.09	15.58
Total	100	99	100

The total elemental analysis showed a slightly lower concentration of the easily leachable elements (CaO, MgO, K2O and Na2O) in the surface (Ap) horizon relative to the Btx horizon (Table 3). As the top soil is considered to be the most intensely weathered part of the profile (under normal conditions), concentrations of easily leachable elements (Ca, Mg, k and Na) were expected to be lower in the topsoil, while less mobile elements such as Al, Fe and Si tended to be higher due to residual accumulation. The subtle difference in rutile (TiO2) content of the horizons indicated the absence of lithologic discontinuity in the upper part of the soil solum. The decrease in Ca and Mg oxides to Al oxides ratio towards the soil surface indicated active weathering of primary minerals, implying that these soils do not qualify as highly weathered soils. Similarly, the SiO2 to Al2O3 and SiO2 to Fe2O3 ratios decreased towards the soil surface and this indicates a decrease in Si content released from weathering of the primary minerals, which has been lost by leaching. This is in agreement with the near constant Fe2O3/Al2O3 ratio in the soils as a result of their tendency to form stable oxides as soon as released from the primary minerals.

Table 4. Quantitative mineralogy of the sample Nitisol profile.

	wt%	
Phases	Surface horizon	Subsoil horizon
Tectosilicates		
Quartz	5.4	5.7
K-feldspar	4.2	4.7
Plagioclase feldspars	1.4	1.4
Phyllosilicates		
Kaolinite	42.4	49.8
poorly crystalized	*36.9*	*44.4*
well crystalized	*5.5*	*5.4*
Mica (illite)	20.5	11.4
Hydroxy-interlayered 2:1	5.5	6.1
Oxides & hydroxides		
Hematite (Fe_2O_3)	12.4	12.6
Goethite (Fe_3OOH)	4.2	3.6
Rutile (TiO2)	2.7	2.5
Magnetite (Fe_3O_4)	1.1	1.3
Gibbsite (Al_2O_3)	< 1	< 1

Mineralogical composition and XRD pattern

The mineralogical composition of the clay fraction (<2 µm) revealed that the clay mineralogy of the surface (Ap) and subsoil (Btx) horizons of the profile are similar in terms of composition, but differ in relative proportions (Table 4 and Fig. 2). The quantitative mineralogical analysis also revealed that although phyllosilicate minerals (Kaolinite, mica/illite) are dominant, considerable amounts of tectosilicates (plagioclase and orthoclase or K-feldspars) and (hydro) oxides and hydroxides of Fe (chiefly hematite) were found (Table 4). The dominant phyllosilicate is kaolinite (60 and 75%, for surface and subsoil horizons); with a first order 00l peak at ~0.72 nm (Fig. 2). Next is illite, a 2:1 clay mineral (30 and 17% for surface and subsoil) of mica group. As is commonly observed for kaolinitic soils (Dumon *et al.*, 2014; Hubert *et al.*, 2012), two populations of kaolinite are present: a well-crystalized kaolinite (5.5 wt% and 5.4 wt% for the topsoil and subsoil horizon respectively) and a poorly-crystalized kaolinite population (36.9 wt% and 44.4 wt% for the surface and sub respectively). The origin of these two populations is unclear but could be related to differences in octahedral iron substitution (Mestdagh *et al.*, 1980).

Aside from kaolinite, there is a considerable amount of dioctahedral mica present with its first order 00l peak at ~1.0 nm and a smaller amount of a hydroxy-interlayered (HI) open 2:1 phyllosilicate, with a broader first order 00l peak at ~1.45 nm when air-dry, shifting to slightly higher d-spacings upon glycolation (Fig. 2). This HI open 2:1 phyllosilicate was most likely formed by intercalation of an open 2:1 phyllosilicate (e.g. a smectite or vermiculite) with soluble aluminum, which immediately precipitates as a hydroxide in the interlayer space. The interlayer space of the open 2:1 phyllosilicate is then (partially) blocked, resulting in a more restricted swell-and-shrink behavior and a reduced cation-exchange capacity. Although the reduction in exchange capacity can be considered as detrimental to the quality of the soil, this reaction also immobilizes the soluble and toxic aluminum and prevents the formation of large amounts of gibbsite, which can help in preventing phosphate fixation.

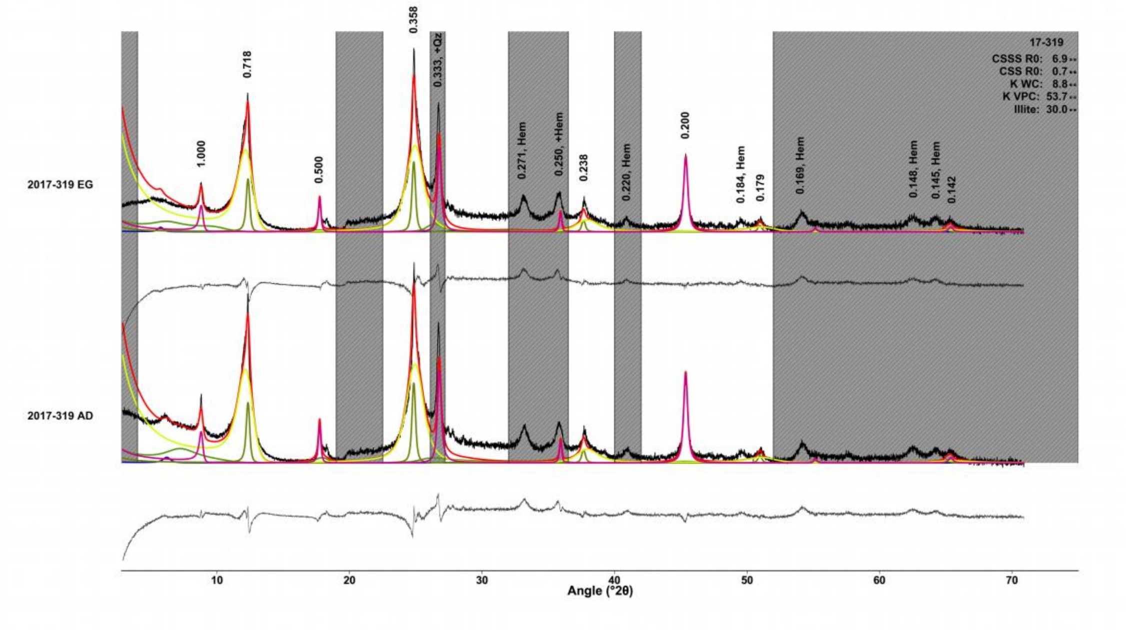

Figure 2a. X-ray differentiation pattern of surface horizon

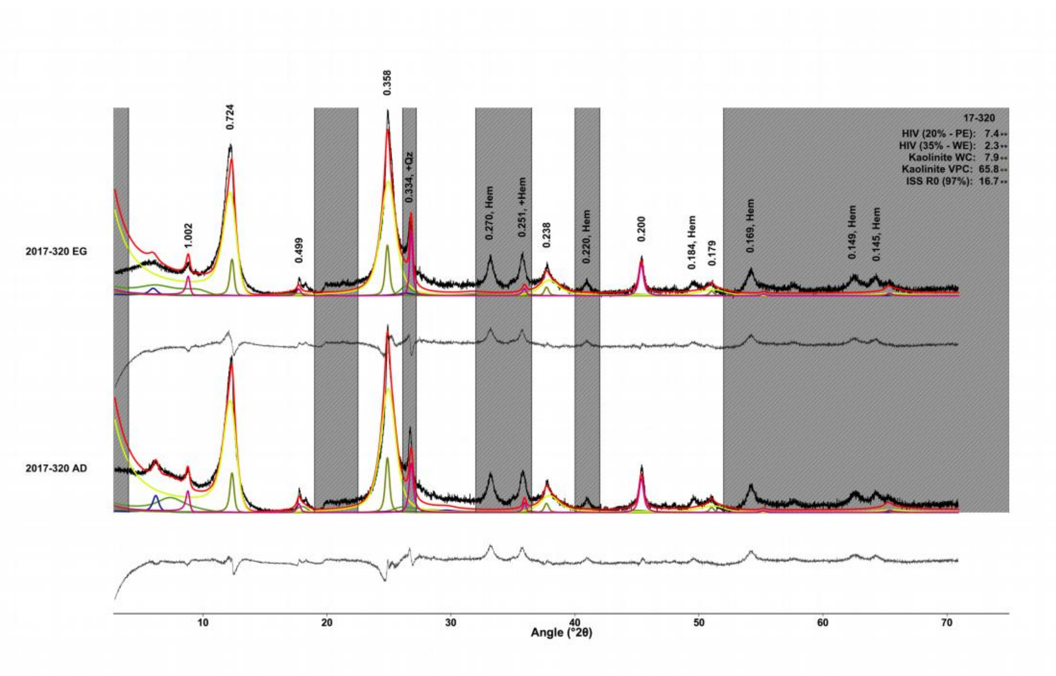

Figure 2b. X-ray differentiation pattern of subsurface horizon

Discussion

Some unique characteristics of Nitisols in the Ethiopian highlands

The morphological, physicochemical and mineralogical properties of Nitisols of the Ethiopian highlands described in this paper stand out because they differ in some fundamental ways from other tropical African Nitisols (Table 6). First, morphological differences in colour must be highlighted. As shown in Table 2, the colour of the soils studied ranges predominantly between very dark brown to very dark reddish brown, contrasting with how Nitisols are often characterised in the literature as “the red tropical soils” (Baligar *et al*., 2004; Eswaran, 1988). This “chocolate” appearance might be due to the result of historically buried dark topsoil material (Eswaran, 1988), or to eluviation processes under the alternating dry and wet seasons that prevail in the Ethiopian highlands.

Secondly, Nitisols in the Ethiopian highlands are very high in CEC (mean of~ 40 coml+/kg) and with a base saturation above 80%, which is more than double that of some other African countries (Table 5). These values are above the clay activity and base status limits that define Nitisols in the literature (IUSS Working Group WRB, 2014). Mainstream literature often defines Nitisols as low activity clays (≤24 cmol/kg) and low base status (<50%) soils (FAO, 2001; IUSS Working Group WRB, 2014). The high CEC could be due to the presence of large amounts of 2:1 clay minerals (illite), which appears to be logical with respect to the relatively less intense degree of wreathing in the predominantly subtropical climate when compared to the tropics.

Third, the total elemental analysis and quantitative mineralogy indicate that the soils do not qualify as highly weathered soils, which is contrasting with the mainstream soil science literature where Nitisols are described as “strongly weathered and heavily leached kaolinitic soils” (Juo and Franzluebbers, 2003; IUSS Working Group WRB, 2014). In fact, under the USDA soil classification system, Nitisols are classified under low base status Alfisols sub-orders (Baligar *et al*., 2004; Juo and Franzluebbers, 2003). In this study, however, the presence of appreciable amounts of primary minerals (i.e., feldspars) and 2:1 phyllosilicates (i.e., mica) in the clay fraction is indicative of active weathering still taking place even in the surface horizon, which is supposed to be intensely weathered. In addition, the silt/clay ratio (0.57 to 1.50) is rated as high. These facts lead to the conclusion that the Nitisols of the Ethiopian highlands are still young, developed over young volcanic materials, and thus cannot qualify as “highly weathered soils”. Instead, the soils can be regarded as transitional between the strongly leached and the moderately leached red clays of Africa (Chileshe and Ting-tiang, 1988).

The pedogenetic conditions in the Ethiopian highlands (e.g., complex geology, rugged terrain, and largely sub-tropical climatic conditions) can be considered unique compared to many other tropical soils (Mishra *et al.*, 2004). There appears to be a fertility gradient going from the Ethiopian highlands to Kenya and down to Tanzania and Malawi with mean clay content, CEC and BS saturation falling drastically while soil pH remains consistent (Table 5). This variation has largely been seen as a systematic variation (and not random) but in fact, is a partly spatially correlated variation linked not only to landform and climate, but also to geological time horizon as soil forming factors (Smaling and Braun, 1996). Whereas, many soils in tropical Africa are derived from Precambrian materials and often intensively weathered, the soils in the Ethiopian highlands are derived from the Trap Series volcanics of the Tertiary period over poured huge lava flows over a peneplained land surface (van Wambeke and Nachtergaele, 2004; Williams, 2016). This was again rejuvenated by the huge Miocene shield volcanoes that have superimposed on the flood basalt resulting in younger and deeper soils in the Ethiopian highlands (Regassa *et al.*, 2014; Williams, 2016).

Table 5. Contrasting properties with other African countries (data are mean values of several profile data points per country.)

Property/ country	Soil depth interval Surface soil Subsoil	Soil colour (moist)	Clay (%))	pH (H_2O)	OC (%)	CEC (cmol+/kg)	BS (%)
Ethiopia	Surface soil	Very dark greyish brown (10YR3/2)	58	5.36	2.05	41.93	82.95
	Subsoil	Dark reddish brown (2.5YR2.5/4)	65	5.29	1.03	39.22	79.68
Kenya	Surface soil	Dark reddish brown (5YR 3/3)	56	4.90	2.47	22.80	31.00
	Subsoil	Dark reddish brown (2.5YR ¾)	64	5.30	2.29	20.40	31.00
Tanzania	Surface soil	Red (5YR 4/8)	41	5.20	1.30	15.50	22.00
	Subsoil	Very dusky red (2.5YR3.5)	49	5.70	0.90	18.00	28.00
Zambia	Surface soil	Dark red (2.5YR 3/6)	25	5.20	2.30	11.00	49.00
	Sub-soil	Dark red (2.5YR 3/6)	39	5.70	1.40	10.00	39.00
Malawi	Surface soil	Dusky red (10YR¾)	28	4.30	0.90	1.97	44.00
	Subsoil	Dark red (2.5YR 3/6)	36	5.00	0.70	2.73	49.00

Implications for classifying subunits within the Nitisol reference group

The paper highlights the complexities in state factors that dictate the chemical and mineralogical properties of soils even within the same pedogenetic class. It underlines the need for considering such complexities for soil classification and management. The results provide functional information for soil fertility management at the local level while at the same time having implications for better referencing and reclassification of Nitisols under the WRB. The WRB follows periodic revisions of legends of the soil map of the world and refines guidelines for distinguishing subunits within a given pedogenetic class or reference soil group (Nachtergaele *et al*., 1994). The distinct characteristics of 46 individual Nitisol profiles described in this paper may provide possible additional diagnostic criteria for distinguishing soil subunits under the Nitisol reference group for mapping at a reconnaissance level. Since its inception, the WRB has continuously redefined lower level soil units within the main reference soil groups. For this, the International Union of Soil Science Society Working Group for WRB depends on detailed new profile investigations from different countries, such as the one outlined in this paper. We argue that given the unique characteristics of the Nitisol profiles, including the dark greyish brown colour, the high CEC, high base status, high Si/Cl ratio and the presence of substantial amounts of primary minerals and 2:1 phyllosilicate minerals, they do not comply with the current general definition of Nitisols as strongly weathered, highly leached soils. Using these unique features as diagnostic properties, we suggest that the WRB considers classifying the kinds of Nitisols in the Ethiopian highlands as special subunit (third level) within the Nitisol reference group. Such reclassification and redefinition of the diverse range of Nitisol reference groups is essential to facilitate information exchange and technology transfer for sustainable management of the soil resources of the world.

Implications for soil-specific fertilizer advisory in the Nitisol areas of Ethiopia

The study showed that in spite of the distinctive features and the generally young nature, the Nitisols in the Ethiopian highlands have some serious soil fertility management constraints. These include depletion of organic matter due to complete removal of crop residues from fields and manure for household energy source, and deficiency of macronutrients (N, P, S) and some micronutrients (Cu and B) (Zeleke *et al*., 2010). Several previous reports also indicated widespread deficiency of N, P, S and some micronutrients (Abera and Kebede, 2013; Agegnehu *et al*., 2019; Haque *et al*., 2000). Since 2015, a new compound fertilizer – NPS (19% N, 38% P_2O_5, 7% S) – has been introduced for blending with some micronutrients, chiefly Zn and B forming Zn-B blend. This is the most popular blend recommended for Nitisol areas with nutrient analysis 17N-34P_2O_5+7S+ 2.2Zn+0.6B (Karltun *et al*., 2013). However, although Zn is a prominently promoted nutrient of the fertilizer blend, our study found no Zn deficiency in the Nitisol areas of the Ethiopian highlands. Another study reported no correlation between Zn levels of the soils and cereal yields in the Nitisol areas, confirming the availability of sufficient Zn stocks in the soil (Elias *et al*., 2019). Therefore, we conclude that sustainable crop production on these soils depends on supply of NPS + Cu + B blends in the right combinations and amounts but there is no need for Zn in the fertilizer blends, at least for now. Regarding K, the situation is mixed. Historically, the Ethiopian soils are believed to be rich in K and therefore K-fertilizer was not supplied to farmers. Our finding, however, suggests that there are some pocket areas particularly in the north-central and south-eastern highlands where maize-potato rotation is widely practiced. In these areas, therefore, including K in the fertilizer blend formulation is advisable, but this is not needed in the feldspar dominated southern and south-western highlands of Ethiopia.

Acknowledgements

This paper is based on the data generated as part of the CASCAPE project implemented in Ethiopia with financial assistance from the Dutch Government through its Embassy based in Addis Ababa (Grant No ADD 0121353).

References

Abera Y, and Kebede M. 2013. Assessment on the Status of Some Micronutrients in Vertisols of the Central Highlands of Ethiopia. *Int. Research J. Agric. Sci. Soil Sci.* 3: 169-173.

Agegnehu G, Yirga C, and Erkossa T. 2019. "Soil Acidity Management," Ethiopian Institute of Agricultural Research (EIAR), German International Technical Cooperation (GIZ), Addis Ababa, Ethiopia, pp. 82.

Baligar V, Ageria NKF, Eswaran H, Wilson MJ, and Zehenli H. 2004. Nature and Properties of the Red Soils of the World. *In*: "The Red Soils of China: Their Nature, Management and Utilization" (M. J. Wilson, Z. He and X. Yang, eds.), pp. 7-27. Kluwer Academic Publishers, Dordrecht, the Netherlands.

Benton, J. 2003. "Agronomic Hand Book. Management of crops, Soils and their Fertility," CRC Press Washington, D.C.

Bergmann J, Friedel P, and Kleeberg R. 1998. BBGMN - a new fundamental parameter based Rietveld program for laboratory X-ray sources, its use in quantitative analysis and structure investigations. . CPD Newsletter, Commission of Powder Diffraction, *International Union of Crystallography* 20: 5–8.

Buol SW, Southhard R, Grham R, and Mcdaniel PA. 2011. "Soil genesis and classification," 6th Ed. John Wiley & Sons, Pondicherry, India.

Chileshe L, and Tingtiang W. 1988. Red soils of Zambia. *In:* "International Symposium on Red soils of East and Southern Africa" (K. Nyamapfene, J.

Hussein and K. Asumadu, eds.), pp. 197-215. International Development Research Centre (IDRC), Harare, Zimbabwe.

De Wispelaere L, Marcelino V, Regassa A, De Grave E, Dumona M, Mees F, and van Ranst E. 2015. Revisiting nitic horizon properties of Nitisols in SW Ethiopia. *Geoderma* 243: 69-79.

Dumon M, Tolossa AR, Capon B, Detavernier C, and Van Ranst E. 2014. Quantitative clay mineralogy of a Vertic Planosol in southwestern Ethiopia: Impact on soil formation hypotheses. *Geoderma* 214:184–196.

Elias E. 2016. "Soils of the Ethiopian Highlands: Geomorphology and Properties," ALTERA, Wageingen University and Research Centre, the Netherlands, Addis Ababa.

Elias E. 2017. Characteristics of Nitisol profiles as affected by land use type and slope class in some Ethiopian highlands. *Environ. Syst. Research* 6: 1-15.

Elias E, Okoth PF, and Smaling EMA. 2019. Explaining bread wheat (*Triticum aestivum*) yield differences by soil properties and fertilizer rates in the highlands of Ethiopia. *Geoderma* 339: 126-133.

Eswaran H. 1988. Taxonomy and management related properties of the red soils of Africa. *In*: "International symposium on the red soils of east and southern Africa" (K. Nyamapfene, H. Janet and K. Asumadu eds.). International Development Research Centre, Harare, Zimbabwe.

Fageria NK, Baligar VC, and Jones CA. 2011. "Growth and Mineral Nutrition of Field Crops." 3rd Edition. Taylor and Francis Group, LLC, New York, USA.

FAO. 1984. "Geomorphology and soils of Ethiopia. Assistance to land use planning "Food and Agriculture Organization, Rome.

Gebreselassie Y, Anemut F, and Addisu S. 2015. The effects of land use types, management practices and slope classes on selected soil physicochemical properties in Zikre watershed, North-Western Ethiopia. *Environ. Syst. Research* 4: 1-7.

Haque I, Lupwayi NZ, and Tadesse T. 2000. Soil Micronutrient Contents and Relation to Other Soil Properties in Ethiopia. *Commun. Soil Sci. Plant Anal*. 31: 2751-2762.

Hazelton P, and Murphy B. 2007. "Interpreting soil test results: What do all the numbers mean?" CSIRO publishing Collingwood, Australia.

Hillel D. 2004. "Introduction to Environmental Physics," Elsevier Academic Press, San Diego, California - USA.

Hillier S. 1999. Use of an air brush to spray dry samples for X-ray powder diffraction. *Clay Minerals* 34: 127–135.

Hubert F, Caner L, Meunier A, and Ferrage E. 2012. Unraveling complex <2μm clay mineralogy from soils using X-ray diffraction profile modeling on particle-size sub-fractions: Implications for soil pedogenesis and reactivity. *Am. Mineral.* 97, 384–398.

IUSS Working Group WRB. 2006. "World reference base for soil resources 2006: A framework for international classification, correlation and communication." Food and Agriculture Organization of the United Nations, Rome.

IUSS Working Group WRB. 2014. "World reference base for soil resources 2014: International soil classification system for naming soils and creating legends for soil maps." Food and Agriculture Organization (FAO), Rome, Italy.

Juo A, and Franzluebbers K. 2003. "Tropical soils. Properties and Management for Sustainable Agriculture," Oxford University Press, Oxford New York.

Karltun E, Mamo T, Bekele T, Gameda S, and Kidanu S. 2013. "Towards improved fertilizer recommendations in Ethiopia – Nutrient indices for categorization of fertilizer blends from EthioSIS woreda soil inventory data," Agricultural Transformation Agency (ATA), Addis Ababa, Ethiopia.

Leenaars JGB, Elias E, Wösten H, Ruiperez M, Kempen B, Ali A, and Brouwer F. 2016. "Major soil-landscape resources of the cascape intervention woredas, Ethiopia: Soil information in support to scaling up of evidence-based best practices in agricultural production (with dataset)." ISRIC-ALTERA, WUR, Wageningen, the Netherlands.

Mateete B, Nteranya S, and Paul W. 2010. Restoring Soil Fertility in Sub-Sahara Africa. *Adv. Agron.* 108: 183-235.

Mestdagh MM, Vielvoye L, and Herbillon AJ. 1980. Iron in Kaolinite: II. The relationship between kaolinite crystallinity and iron content. *Clay Minerals* 15: 1–13.

Mishra B, Gebrekidan H, and Kibebew K. 2004. Soils of Ethiopia: Perceptions, appraisal and constraints in relation to food security. *J. Food*, *Agric. Environ.* 2:269-279.

Mohr P. 1971. "The Geology of Ethiopia" Haile Selassie I University Press, Addis Ababa.

Nachtergaele F, Remmelzawaal A, Hof J, van Wambeke J, Souriji A, and Brinkman R. 1994. Guidelines for distinguishing soil subunits. *In*: "15th World Congress of Soil Science", Vol. Volume 6a. The International Society of Soil Science, Acapulco, Mexico.

Regassa A, Van Daele K, De Paepe P, Dumon M, Deckers J, Asrat A, and Van Ranst E. 2014. Characterizing weathering intensity and trends of geological materials in the Gilgel Gibe catchment, south-western Ethiopia. *J. African Earth Sci.* 99: 568-580.

Santra P, Kumar M, Panwar NR, and Das B. 2017. Digital Soil Mapping and Best Management of Soil Resources: A Brief Discussion with Few Case Studies. *In*: "Adaptive Soil Management: From Theory to Practices" (A. Rakshit, P. C. Abhilash, H. B. Singh and S. Ghosh, eds.), pp. 3-39. Springer Nature Singapore PTE Ltd., Singapore.

Smaling EMA, and Braun AR. 1996. Soil fertility research in sub-Saharan Africa: New dimensions, new challenges. *Commun. Soil Sci. Plant Anal*. 27: 365-386.

Stocking M. 1988. Tropical red soils: fertility management and degradation. *In:* "International symposium on the red soils of east and southern Africa" (K. Nyamapfene, H. Janet and K. Asumadu, eds.), pp. 24-55. International Development Research Centre (IDRC), Harare, Zimbabwe.

Stoorvogel J, Smaling E, and Janssen B. 1993. Calculating soil nutrient balances in Africa at different scales. *Fertilizer Research* 35: 227-235.

Van Reeuwijk L. 2006. "Procedures for soil analysis, 6th edition." International soil reference and information centre (ISRIC), Wageningen, and the Netherlands.

Van Wambeke A, and Nachtergaele F. 2004. Tropical soils—properties and management for sustainable agriculture. *Geoderma* 123: 373–375.

Williams F. 2016. "Understanding Ethiopia Geology and Scenery," Springer New York.

Zeleke G, Agegnehu G, Abera D, and Rashid S. 2010. Fertilizer and soil fertility potential in Ethiopia: Constraints and opportunities for enhancing the system. International Food Policy Research Institute (IFPRI). pp. 63, Washington, DC, USA.