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Characteristics of Nitisol profiles as affected by land use type and slope class in some Ethiopian highlands

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Abstract

Background: The success of soil management depends on understanding of how soils respond to agricultural land use practices over time. Nitisols are among the most extensive agricultural soils in the Ethiopian highlands but soil degradation threatens their productive capacity. In this study, the effects of two land use systems, intensive cereal and agroforestry systems, and slope class on physical and chemical characteristics of some Nitisol profiles were investigated. In total 12 sample profiles were described and soil samples were collected from each of the identified master horizon. Soil physical characteristics evaluated were particle size distribution, structural aggregate stability, water holding capacity and bulk density. Chemical characteristics determined were exchangeable bases and cation exchange capacity, soil pH and the contents of organic carbon (OC), total nitrogen (TN), available phosphorus (AP) and some micronutrients.

Results: Among the physical characteristics, land use and slope significantly ($p < 0.05$) affected particle size distribution and plant available water content. The mean sand (28%) and silt (26%) particles in the intensive cereal system were significantly ($p < 0.05$) higher compared to 15% sand and 18% silt in the agroforestry system. Conversely, the mean values of fine grained texture materials including 39% fine sand, 42% fine silt and 67% clay in the agroforestry system were significantly higher than 30% fine sand, 21% fine silt and 46% clay in the cereal system. Similarly, the lower slope had significantly ($p < 0.05$) higher fine texture materials (39% fine sand, 30% fine silt, and 63% clay) compared to 17% fine sand, 14% fine silt and 51% clay fractions in the upper slope. The proportion of water stable aggregate (WSA) were high (63–94%) and there was no significant difference between land types and slope classes. Following from high structural aggregate stability, the soils have high water holding capacity that ranged from 22 to 32% at PWP to 34–49% at FC while plant available water content (AWC) was in the 120–230 mm m^{-1} range. Considering the chemical characteristics, land use significantly affected soil pH, total nitrogen (TN), exchangeable magnesium (Mg^{2+}), potassium (K^+), percent base saturation (PBS), and available micro nutrients—iron (Fe^{2+}), manganese (Mn^{2+}) and zinc (Zn^{2+}). The mean pH value (5.29) in the intensive cereal system strongly acidic while the pH value for the agroforestry system (6.12) was taken moderately acidic. The mean OC content was 2.0 and 2.1% for the intensive cereal and agroforestry systems that were rated very low. The mean TN values were 0.15 and 0.22% for intensive cereal and agroforestry systems that were taken as low to very low. Similarly the mean values for AP were 8 and 10 mg kg^{-1} for cereal and agroforestry systems that were rated low. On the other hand, the CEC, exchangeable bases (Ca^{2+} , Mg^{2+} , K^+) and PBS of the soil were rated high while Na^+ appeared only in trace amount, and there was no significant difference between land use type and slope classes except for Mg^{2+} , K^+ and PBS. Mean values of Mg^{2+} and K^+ (15 and 3 cmol(+) kg^{-1}) and PBS (75%) in the agroforestry system were significantly higher than those in the cereal system (6 and 1.6 cmol(+) kg^{-1} of Mg^{2+} and K^+ and 51% PBS). Among micronutrients, land use significantly ($p < 0.05$) affected

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available Fe^{2+} , Mn^{2+} and Zn^{+} . The mean values of Fe^{2+} (97 mg kg^{-1}) and Mn^{2+} (68 mg kg^{-1}) in the agroforestry system were taken as excessively high while they were moderately sufficient (37 , 39 mg kg^{-1} , respectively) in the cereal system. Slope effects were significant for OC, TN and AP having higher mean values (2.5% OC, 0.22% TN and 17 mg kg^{-1} AP) in the lower slope than in the upper slope (1.5% OC, 0.13% TN and 8 mg kg^{-1} AP).

Conclusion: Land use and slope had significant effect on some soil physical and chemical characteristics. The land use practices in the intensive cereal system are adversely affecting important soil characteristics as compared to the soil under the agroforestry system. These include alteration of particle size distribution, strongly acidic soil reaction, organic matter and nutrient depletion (N, P, K and Zn) and low plant available water content. Among the inappropriate land use practices include repeated cultivation to create fine seedbed that predisposes the soil to erosion, unbalanced fertilizer application, rotation of maize with potato that are depleting soil nutrient stocks (e., K and Zn), and removal of crop residues from fields. Therefore, a more balanced fertilizer blend application that contain N, P, K and Zn combined with liming to raise soil pH, organic matter management and integrated soil water conservation are recommended.

Keywords: Land use, Nitisol profiles, Physical and chemical characteristics, Slope

Background

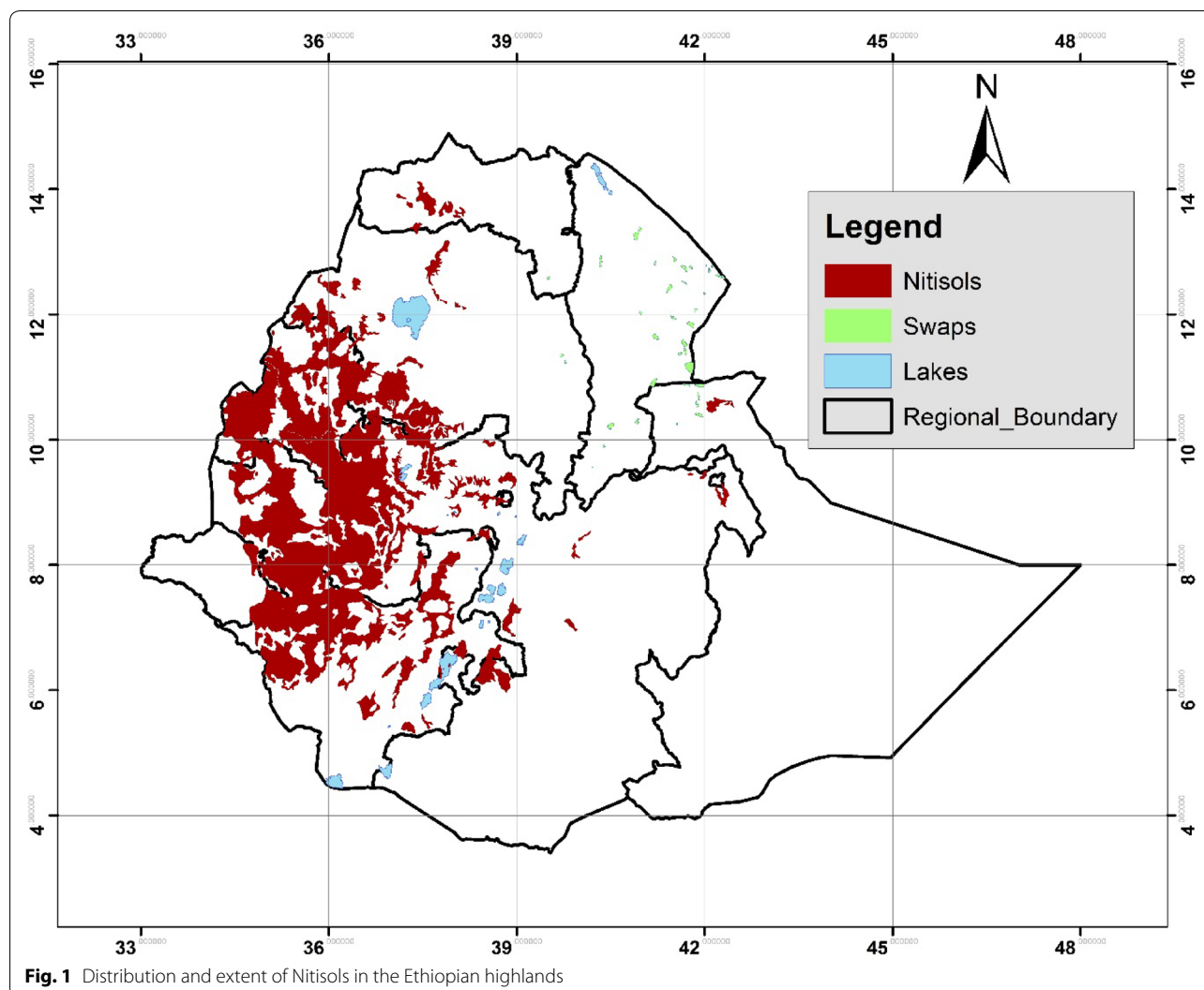
In Ethiopia, diversities in state factors such as topography, parent materials, climate and vegetation have resulted in the development of 18 soil types of which Nitisols are among the most extensive soils (FAO 1984; Elias 2016). Indeed, more than half of all the Nitisols of tropical Africa are found in the Ethiopian highlands followed by Kenya, Congo and Cameroon (Stocking 1988; FAO 2001). Different reports provide different area estimates of Nitisols in the Ethiopian highlands (FAO 1984; Zewdie 2013). The most recent survey puts the extent of Nitisols to cover about one million hectares that account for 31% of the agricultural lands in the Ethiopian highlands (Elias 2016). The soils are particularly extensive in the south-western and north-central highlands representing 64 and 25% of the agricultural landmass, respectively (Fig. 1). Nitisols are among the most productive agricultural soils along with Vertisols, Luvisols, and Planosols (Stocking 1988). They support the bulk of the cereal and livestock production in the Ethiopian highlands. More importantly, the production of coffee (*Coffea arabica*), the most important export commodity in Ethiopia, relies almost exclusively on Nitisols. In addition, the large proportion of tea production comes from strongly acidic Nitisols in the western part of the country (Elias 2002).

However, soil nutrient and organic matter depletion, acidification and soil erosion losses as result of inappropriate land use practices have become major cause of concern for agricultural soils in the Ethiopian highlands (Elias 2002; IFPRI 2010). In particular, due to the land form of occurrence (high to mountains relief hills with moderately steep slopes) and intensive cereal cultivation and cattle grazing, Nitisols have become prone to degradation in spite of their high structural aggregate stability to resist erosion (FAO 2001; Elias 2016). Land

use changes and cultivation of fields without adequate conservation practices, low levels of fertilizer application and failure to recycle crop residues are among the causal factors. Traditionally, soil fertility is replenished through fallow cycles of up to 20 years during which time the land gains fertility through atmospheric deposition, biological fixation and the supply of fresh organic matter and nutrients to the soils (Smaling and Braun 1996; Elias et al. 1998). As population increases, fallow periods are either shortened or abandoned altogether resulting in continuous cultivation of the land. In some parts of the Ethiopian highlands, steep slopes with gradients as steep as 50% are cultivated without installing adequate conservation measures (Assen and Tegene 2008). Often, resource-poor farmers have a short time horizon, i.e., they are primarily concerned with the crop and animal production of the forthcoming season than the long-term productivity of the soil. Longer-term processes that adversely affect agricultural sustainability such as depletion of soil organic matter and nutrient stocks are less visible and perhaps less noteworthy by farmers (Hailu et al. 2015; Elias 2016).

As result, land degradation has become a major policy concern in Ethiopia that is experiencing one of the highest rates of soil erosion and nutrient depletion in Africa (Elias et al. 1998; Hailu et al. 2015; Laekemariam et al. 2016). The rate of soil erosion losses, 130 tons ha^{-1} for cultivated fields, was estimated to be one of the highest in Africa (FAO 1986; Elias 2016). The depletion rate of macronutrients, $-122 \text{ kg N ha}^{-1}$, -13 kg P ha^{-1} and -82 kg K ha^{-1} , was estimated to be high (Haileslassie et al. 2005). The field level nutrient balances on Nitisols reported from southern Ethiopia (-102 , -45 and $-67 \text{ kg N, P and K ha}^{-1}$) are even more threatening (Elias 2002).

Among the unsustainable land use practices farmers that fuel soil degradation include low and unbalanced



fertilizer application leading to mining of soil nutrient stocks, complete removal of crop residues, and dung burning as household energy rather than recycling to augment soil fertility and intensive tilling to create smooth seed bed for small cereals that predisposes the soil to erosion (Elias 2002; Hailu et al. 2015). In addition, research reports suggest that continued application of nitrogen and phosphorus alone would accentuate the uptake and deficiency of other nutrients that are not supplied in the fertilizer. Application of N and P fertilizer alone would particularly increase the uptake of micronutrients (e.g., Zn, Bo, Mn) and eventually depletes them unless included in the fertilizer scheme (FAO 2006b; Elias 2016).

The government of Ethiopia has initiated various interventions to arrest soil degradation primarily mass mobilisation and participatory watershed protection and fertilizer extension. Until 2015, a blanket recommendation of 150 kg DAP ha⁻¹ (Di-ammonium Phosphate: 18%

N, 46% P₂O₅) and 100 kg ha⁻¹ of urea (46% N) has been promoted. In actual practice, the recommended rate is applied only in some high potential highland cereal zones such as west Gojam, central Shewa and Arsi-Bale highlands while the national average rate of 43 kg urea ha⁻¹ and 65 kg DAP ha⁻¹ is at best low (Elias 2016). Since 2015, the government of Ethiopia initiated preliminary fertilizer blend formulas in which new compound fertilizer (NPS: 19% N, 38% P₂O₅, 7% S) was introduced to replace DAP for blending with potassium (K) and some micronutrients chiefly zinc (Zn) and boron (B). This has resulted in the formulation of two poplar blends, namely, Zinc blend (14% N, 23% P₂O₅, 8.2% S, and 1.2% Zn) and zinc-boron blend (14% N, 21% P₂O₅, 15% K₂O, 6.5% S, 1.3% Zn and 0.5% B) (Karlun et al. 2013). Efforts are underway to prepare regional soil fertility maps to guide fertilizer recommendations but site, crop and soil specific fertilizer rate recommendations are yet to be developed. This remains crucially important to maximize crop

production while at the same time maintaining soil quality (through balanced nutrition) and reversing nutrient depletion.

A more nuanced approach should, therefore, take into considerations of the spatial diversities in soil nutrient stocks and land use practices, which are factors driving crop demand for soil nutrients (Elias 2016). On the one hand, studies suggest that soil fertility depletion and land use effects on soil physical and chemical characteristics vary strongly across land use type, slope gradients and soil types (Gebreselassie et al. 2015; Hailu et al. 2015; Laekemariam et al. 2016). On the other hand, reports suggest that land use effects vary considerably with soil types with some soils being more prone to physical and chemical deterioration than others (USDA-NRCS 2014). For example, Gebreselassie et al. (2015) working on Luvisols in the central highlands of Ethiopia reported significantly higher mean values of organic matter, TN and exchangeable bases in the lower slope than in the upper slopes. Information on the effects of land use type and slope class on the physical and chemical characteristics of Nitisol is largely lacking for the Ethiopian highlands thus impinging up on more nuanced soil fertility management decisions. Such information is crucially important for planning soil management strategies that curb the adverse effects of inappropriate land use on soil characteristics. Hence, this study was set out to evaluate how Nitisols profiles occurring in upper and lower slope positions respond to different land use types in terms of their physical and chemical characteristics.

Soil sites and methods

Location, landform and geology

The study was conducted in two districts (Jabi Tehnan and Gera) representing the cereal and agroforestry systems in the north-central and south-western highlands where Nitisols are most dominant (Fig. 1). The landforms in the north central highlands are characterized by the undulating to rolling high plateaus with scattered moderate relief hills, dissected side slopes and river gorges including the popular Blue Nile gorge (Elias 2016). The landform in the south-western highlands is characterized by moderate to high relief mountains and undulating to rolling hills. Trap Series volcanic rocks (basalt, trachyte, ignimbrite ash flows, and tuff) predominate the high plateau landscapes in the north-central highlands. Basaltic basement complex was overflowed by lavas in the Tertiary-Quaternary volcanic rocks resulting in geologically young soils that are developed over pre-weathered materials (Elias 2016). According to Davidson (1983), the geological materials building the soil profiles in the south-western highlands are recent pyroclastic deposits over the volcanic rocks of

the late Eocene to the late Oligocene period. Major parent materials include basic rocks such as alkali-olivine basalts, gabbro, amphibole mixed with more recent flood basalts and tuff.

Climate

Much of the Nitisol areas in the Ethiopian highlands are characterized by humid to sub-humid agro-climatic conditions (Elias 2016). The main monsoon rains over much of the Ethiopian highlands are influenced by the Inter-Tropical Convergence Zone (ITCZ) weather system as blown from the Atlantic Ocean. The average annual rainfall ranges between 1300 and 1600 mm in the north-central highlands that falls between June and September months. The rainy season is much extended in the south-western highlands spanning from February to October with average annual rainfall in the range of 1800–2000 mm. The mean annual air temperature in much of the Ethiopian highlands is 22–25 °C (Elias 2016). According to Eswaren (1988) the Ethiopian highlands are categorized by *udic* soil moisture and *hyperthermic* soil temperature regimes.

Farming system and land use types

In the intensive cereal system, five major cereals form the staples for the population: *tef*¹ (*Eragrostis tef* (Zucc), maize (*Zea mays*), wheat (*Triticum aestivum*), barley (*Hordeum vulgare*) and sorghum (*Sorghum bicolor*). Maize-potato rotation is the main form of crop rotation and free range grazing in crop fields after harvest is commonly practiced. In the agroforestry based system, the fields are divided into home gardens and distant outfields. In the home gardens, enset² (*Enset ventricosum* or *Musa ensete*), coffee and shade trees (e.g., *Cordia africana*) and fruit trees such as avocado (*Persia americana*) and mango (*Mangifera indica*) are typical features with undergrowth of root crops, tubers and species. The distant out fields are planted to cereals (maize, wheat, *tef*) that are cultivated in rotation with legumes such as faba bean (*Vicia faba*), haricot bean (*Phaseolus vulgaris*) and soybean (*Glycinemax* sp.) in certain places. Trees such as *Cordia africana*, *Milletia ferruginea*, *Croton macrostachyus*, and various species of acacia are interspersed in the crop fields providing fresh supply of organic matter in the form of leaf litter to the soil.

¹ *Tef* (*Eragrostis tef*) is small cereal cultivated in Ethiopia for its grain that is used to make the most favorite national food—*Enjera*. The plant rarely known as food staple outside of Ethiopia.

² Enset (*Enset ventricosum* or *Musa ensete* otherwise called false banana) is a plant having pseudo-stem and corm that are pulped for food and fiber that provides subsistence for about 10 million people in the south-western highlands of Ethiopia.

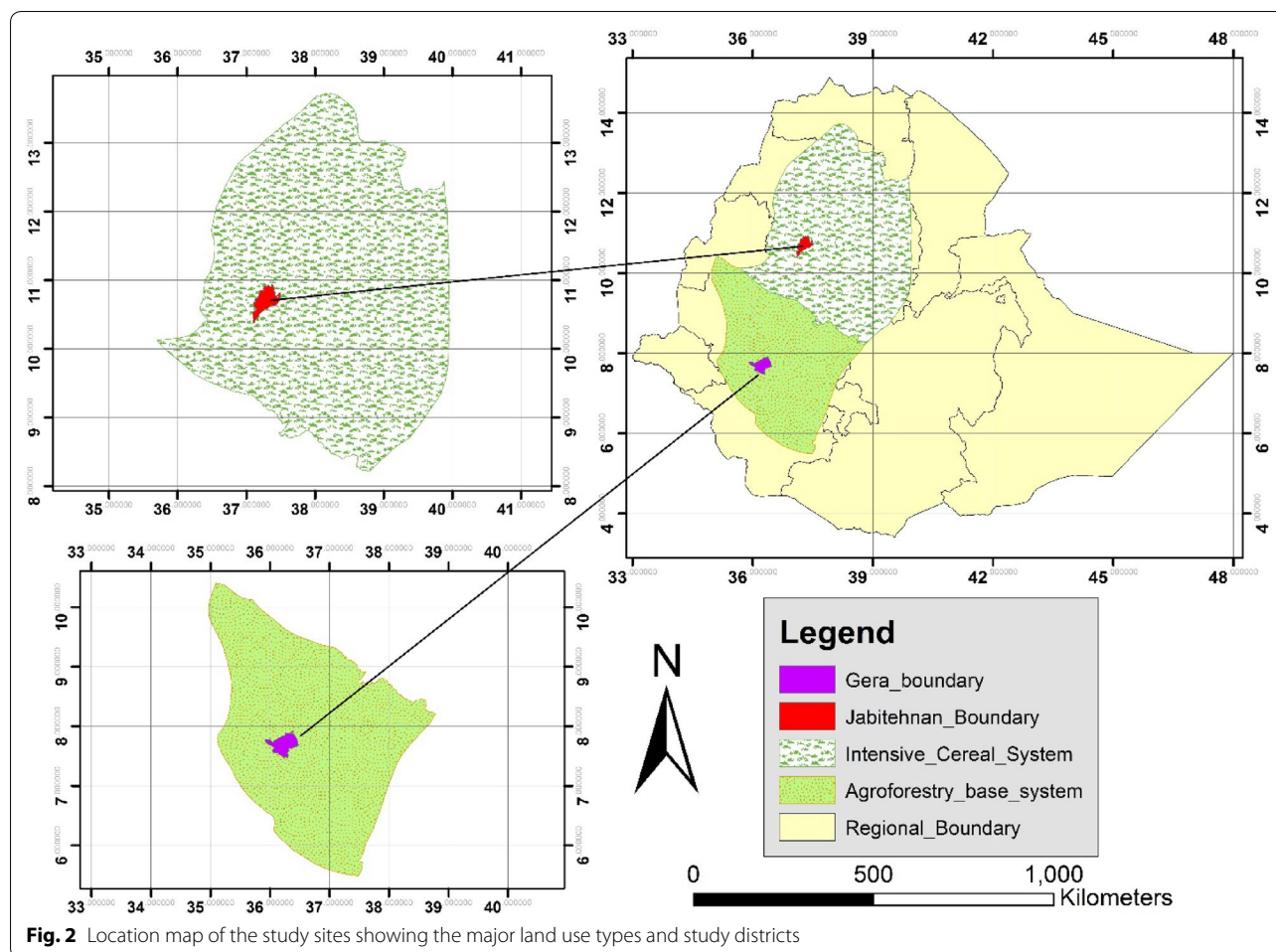


Fig. 2 Location map of the study sites showing the major land use types and study districts

Soil fertility management practices are also distinctly differentiated according to the farming system. In the intensive cereal system the majority of farmers apply 150 kg DAP ha⁻¹ and 100 kg urea ha⁻¹ as per the extension recommendation thus, supplying 73–69 kg N-P₂O₅ ha⁻¹. In the agroforestry system, the home gardens receive the application of farm yard manure and household refuse while the outer fields are treated with 75–50 kg DAP-urea ha⁻¹, thus, supplying 37–35 kg N-P₂O₅ ha⁻¹. This is supplemented by application of on average 1.5–2.0 ton ha⁻¹ of compost as well as systematic manuring through *kraaling*³ system (Elias 2016).

Soil sampling units

Following the intervention sites of the project⁴ that supported the study and using the soil landscape map (Elias

2016), Jabi Tehnan (west Gojam) and Gera (Jimma area) districts were selected representing the intensive cereal and agroforestry systems, respectively (Fig. 2). In each district, a “representative” sub-watershed was selected using the slope map that was prepared following slope classes categorization provided in FAO (2006a). Accordingly, Jimat sub-watershed in Jimat Peasant Association of Jabitehnan district and Garee Weychara sub-watershed in Wanja Kersa peasant association of Gera district were delineated (Fig. 3). The soil-landscape map of the two districts indicate that about 80% of the Nitisols are found within lower limits of 2–5% (gently sloping) and upper limits of 15–30% (moderately steep slope). For this reason, the study delineated these two slope classes as lower and upper limits for soil profile sampling. In each slope, three sample profiles were described giving a total sample of 12 profiles (Fig. 3). In the agroforestry system, profiles were opened in the distant outfields as digging pits inside the gardens is culturally not allowable. Table 1 provides the list of profiles, their geographic location, slope class and elevation. Soil profile pits were opened to

³ During the dry season, cattle kraals are set up in crop fields that rotate to new fields every two weeks thus systematically distributing animal dung over much of the cultivated outfields.

⁴ The Dutch project, Capacity building for scaling up of evidence based best practices in Ethiopia (CASCAPE for short) has supported the study.

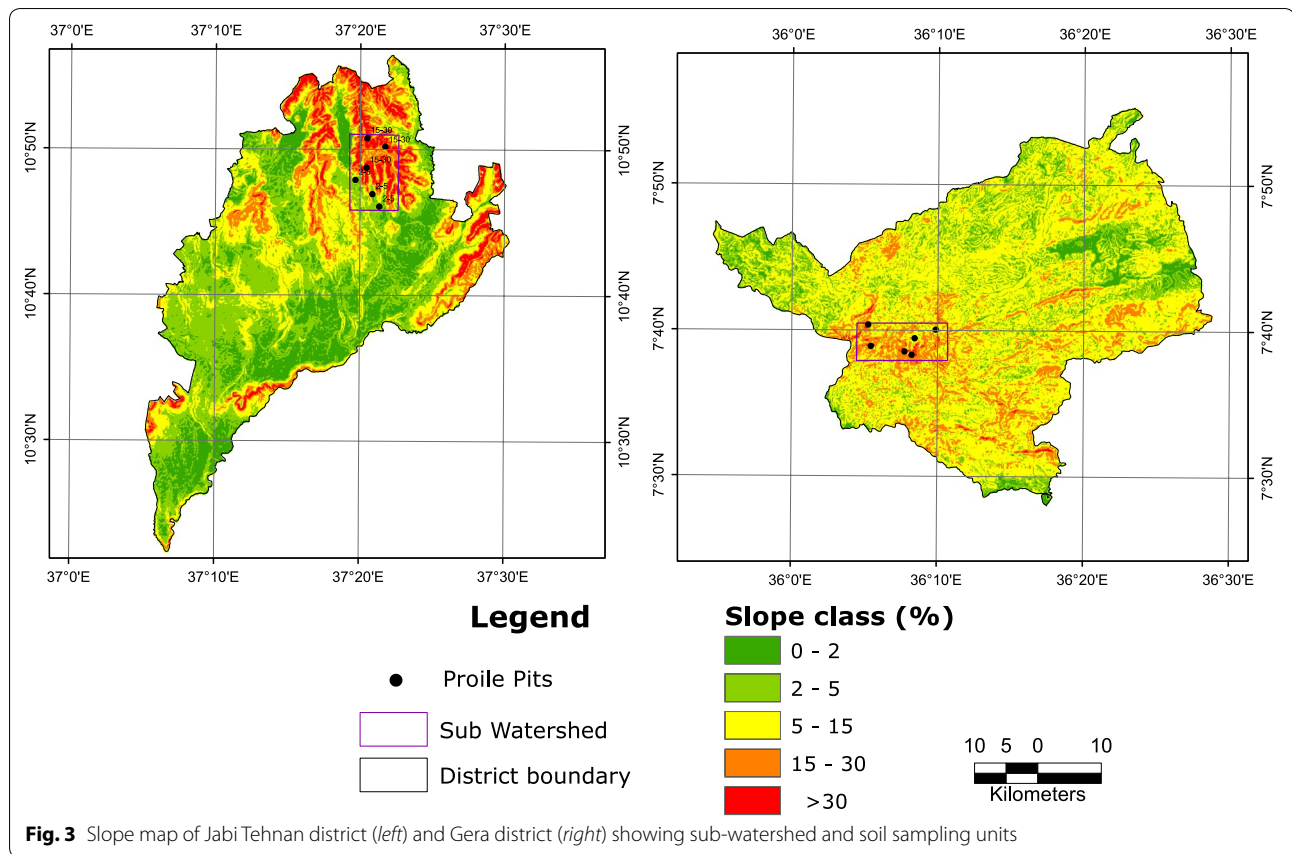


Fig. 3 Slope map of Jabi Tehnan district (left) and Gera district (right) showing sub-watershed and soil sampling units

Table 1 Geographic location, slope class, elevation and land use types in the profiles sites

Profile ID	Latitude	Longitude	Slope (%)	Altitude (m)
Intensive cereal-livestock system (north-central highlands)				
ET_AJJIP001	10°39'33.407"N	37°19'29.398"E	2–5	2790
ET_AMAMP001	11°24'26.593"N	37°3'36.276"E	2–5	2800
ET_ASAA-P001	11°21'49.326"N	36°57'8.624"E	2–5	2446
ET_ASAA-P002	11°20'21.373"N	36°55'52.203"E	15–30	1946
ET_MTA-HBP1	9°26'23.008"N	41°42'56.008"E	15–30	2272
ET_GIR-GGP3	8°11'36.640"N	36°56'27.632"E	15–30	2954
Agroforestry-livestock system (south-western highlands)				
ET_JIMG-SLP2	7°46'36.005"N	36°24'33.012"E	2–5	1917
ET_JIMG-WKP1	7°47'05.003"N	36°22'17.011"E	2–5	1932
ET_BAK-AGP3	8°59'21.779"N	37°12'21.316"E	2–5	1665
ET_JIMLS-SP2	8°11'36.640"N	36°56'27.632"E	15–30	1953
ET_JIMG-GCP2	7°43'39.994"N	36°15'09.014"E	15–30	2025
ET_ILUD-MMP1	8°29'07.994"N	36°20'05.014"E	15–30	2163

a depth of 200 cm (bedrock permitting) and the soil was described according to the FAO guidelines for soil description (FAO 2006a). Soil samples were taken from each of the identified genetic horizons for laboratory investigation.

Soil analytical procedures

A total of 53 samples were collected from 12 profiles and taken to the soil fertility lab of the Water Works Design and Supervision Enterprise (WWDSE) in Addis Ababa, Ethiopia. The analytical methods followed the standard

Table 2 Particle size limits for coarse, medium and fine sand and silt fractions (USDA-NRCS 2014)

Particle size fraction	Sand (0.05–2 mm)	Silt (0.002–0.05 mm)
Coarse	0.8–0.40	0.06–0.02
Medium	0.4–0.20	0.02–0.006
Fine	0.2–0.06	0.006–0.002

procedures as outlined in Van Reeuwijk (2006). The percentage of sand (0.05–2.0 mm), silt (0.002–0.05 mm) and clay (<0.002 mm) fractions of the fine earth (<2 mm) was determined using the modified sedimentation hydrometer procedure (Bouyoucos 1962). Particle grain size analysis to separate coarse, medium and fine sand and silt fractions was carried out following the procedures outlined in USDA-NRCS (2014). Particle size limits for the coarse, medium and fine fractions are given in Table 2. This was to evaluate the effect of land use and slope on particle size fractions which in turn have impact on erosion and management practices to be implemented. Soil aggregate stability test was conducted by wet sieving method as outlined in USDA-NRCS (2014). It involves abrupt submergence of air dry aggregates in water followed by wet sieving using 0.5 mm sieve. Figures reported are percentage of aggregates retained after wet sieving. Soil moisture contents (w/w, %) were determined by means of pressure membrane extractor at different pressure forces to the crushed samples (Baruah and Barthakur 1997). The field capacity (FC) was determined at 1/3 bar and the permanent wilting point (PWP) at 15 bars for sieved and air dry soil samples. The plant available water content (AWC) was determined as the difference between FC (the upper limit) and PWP (the lower limit).

Soil pH was determined in water (pH—H₂O) using a 1:2.5 soil to water solution ratio with a pH meter as outlined in Van Reeuwijk (2006). Organic carbon (OC) content of the soil was analyzed using the Walkley and Black method (Nelson and Sommers 1982). Total nitrogen (TN) was analyzed according to the Macro-Kjeldahl method that involves digestion of the sample and a wet-oxidation procedure (Bremner and Mulvaney 1982). Available phosphorus (AP) content was determined using Olsen⁵

sodium bicarbonate extraction solution at pH 8.5 (Olsen et al. 1954) and the amount of AP (mg kg⁻¹) was determined by spectrophotometer (Van Reeuwijk 2006). Exchangeable cations and CEC (cmol(+) kg⁻¹) were determined by Ammonium Acetate method at pH 7. In the leachate, Exchangeable Ca²⁺ and Mg²⁺ were determined using Atomic Absorption Spectrophotometer (AAS) and Na⁺ and K⁺ by flame photometer as outlined in Van Reeuwijk (2006). The contents of selected micronutrients (Fe²⁺, Mn²⁺, Zn²⁺ and Cu²⁺) was determined using the di-ethylene tri-amine-penta-acetic acid (DTPA) extraction method (Tan 1996).

Statistical analysis and data presentation

Descriptive statistics was applied and mean values for the surface horizons of all profiles investigated were computed by means of weighted average. The presence of significant difference in mean values between the two land use types and slope classes was tested using paired T test in SPSS (Statistical Package for Social Science) software Version 23. The results of the Paired T test analysis present the weighted mean values of all profiles investigated. Full profile information (analytical data) on physical and chemical characteristics is presented for four sample profiles representing the two land use types and slope classes.

Results and discussion

Soil physical characteristics as affected by land use type and slope class

The soils are clayey with clay content ranging from 51 to 55% in the A-horizon and from 58 to 72% in the B-horizon (Table 3). The clay enrichment in the B-horizon is as result of clay migration. The silt/clay ratio ranges from 0.28 to 0.41 in the A-horizon and from 0.22 to 0.41 in the B-horizon that were rated as high according to the ratings of Hazelton and Murphy (2007). This suggests the presence of weatherable mineral reserve in the soil. The bulk density was within 1.04–1.14 g cm⁻³ range in the A-horizon and 1.02–1.12 g cm⁻³ in the B-horizon. These values are below the critical values for agricultural use (1.4 g cm⁻³) suggested by Hillel (2004) indicating the absence of excessive compaction or restrictions for root development.

Land use and slope significantly ($p < 0.05$) affected particle size distribution and plant available water contents. The mean values of fine grained texture materials including 39% fine sand, 42% fine silt and 67% clay in the agroforestry system were significantly higher than 30% fine sand, 21% fine silt and 46% clay in the cereal system (Tables 4, 5). These findings suggest that although texture is an inherent property of the soil, it can be altered by land use practices over a longer period

⁵ In Ethiopia, the Olsen's NaHCO₃ method (pH 8.5) is widely used for determining soil available P. A study on the evaluation of soil test methods for available phosphorus on 32 Ethiopian soils reported that the Olsen method followed by Warren and Cooke, and Truog methods is the best of the eight chemical methods they used to assess available P (Mamo and Hague 1991). This was further confirmed by Mamo, Christian and Heiligtag (2002) who found the magnitude of soil available P extraction in the order Truog > CAL > Olsen > Bray II > Warren and Cooke. Since Truog and CAL methods are not practiced in the analytical labs in Ethiopia, the Olsen, Cole, Watanabe and Dean (1954) remains the best method for available P-extraction in Ethiopia to date.

Table 3 Particle size distribution, textural class and bulk density of Nitisol sample profiles

Horizon	Depth (cm)	Sand (%)	Silt (%)	Clay (%)	Silt/clay	Class	BD (g/cm ³)
Profile 1: Intensive cereal upper slope (ET_AS AAP002)							
Ap	0–20	30	19	51	0.28	Sandy clay	1.14
AB	20–40	26	16	58	0.27	Clay	1.07
Bt1	40–80	22	18	60	0.30	Clay	1.02
Bt2	80–200	27	11	62	0.20	Clay	1.20
Profile 2: Intensive cereal lower slope (ET_AJJIP001)							
Ap	0–20	14	21	63	0.35	Clay	1.12
AB	20–42	12	21	67	0.31	Clay	1.10
Bt1	42–90	12	18	70	0.26	Clay	1.10
Bt2	90–200	10	20	72	0.27	Clay	1.10
Profile 3: Agroforestry upper slope (ET_JIMLS-SP2)							
Ah	0–12	23	23	55	0.41	Clay	1.14
BA	12–30	13	23	63	0.36	Clay	1.12
Bt1	30–0	12	26	61	0.43	Clay	1.12
Bt2	90–145	12	29	60	0.48	Clay	1.04
Bt3	145–200	12	27	62	0.43	Clay	1.06
Profile 4: Agroforestry lower slope (ET_JIM-G-SLP2)							
Ap	0–10	17	37	56	0.33	Clay	1.04
AB	10–30	14	22	64	0.15	Clay	1.02
Bt1	30–60	13	21	66	0.32	Clay	1.04
Bt2	60–105	11	22	63	0.42	Clay	1.07
Bt3	105–180	8	27	66	0.41	Clay	1.04

BD bulk density

of time (Schaetzl and Anderson 2005). Slope effect was also significant for particle size distribution. The mean values of fine sand (39%), fine silt (30%) and clay (63%) in the lower slope were significantly ($p < 0.05$) higher than mean values in the upper slope—17% fine sand, 14% fine silt and 51% clay in the upper slope (Table 6). The findings suggest residual accumulation of coarser particles and removal of finer particles from in the upper slopes by runoff water and its deposition in the lower slopes. The result is in agreement with the findings of Gebrelassie et al. (2015) and Gebrekidan and Negassa (2006) that reported increasing trends of coarse fractions with increasing slope and increasing clay fractions with decreasing slope gradients.

Soil structural aggregate stability has a key role in the functioning of soil such as water retention, aeration, infiltration and therefore resistance to erosion (Abrishamkesh et al. 2010; USDA-NRCS 2014). The mean values of water stable aggregate (WSA), the proportion of structural aggregates retained after wet sieving in 0.5 mm sieve, were 79 and 87% for the intensive cereal and agroforestry systems, respectively (Table 5). According to the ratings of Hazelton and Murphy (2007), the WSA was rated as very high and were not significantly

different between land use types (Table 7). This indicates that Nitisols have little water dispersible aggregates and hence they are fairly resistant to erosion. This is part of the reason why the Nitisols remained deep and productive in spite of centuries of intensive cultivation and severe erosion hazards in the Ethiopian highlands (Elias 2016).

The water content of the soil at FC (1/3 bar) and PWP (15 bar) were 35 and 23% in the cereal system and 37 and 24% in the agroforestry system (Table 5). According to the rating of Hazelton and Murphy (2007), the water content at FC and PWP were rated as high while AWC was in the medium to high range. The generally favourable water holding capacity of the soil can be attributed to high clay content, well-developed soil structural aggregates and reasonably good organic matter contents of the soils. The result is in agreement with another report from Welega, western Ethiopia that found higher water holding capacity for soils with higher clay content (Chimdi et al. 2012). On the other hand, the mean AWC in the agroforestry system (135 mm/m) was significantly higher than that in the cereal system (112 mm/m) suggesting differences in particle grain size distribution and organic matter content.

Table 4 Grain size fractionation of sand (>0.05 mm) and silt (0.05–0.002 mm) particles (%)

Horizon	Depth (cm)	CS	MS	FS	CSi	MSi	FSi
Profile 1: Intensive cereal upper slope (ET_AS AAP002)							
Ap	0–20	62	20	18	52	27	21
AB	20–40	64	15	21	66	20	14
Bt1	40–80	62	22	16	45	20	35
Bt2	80–200	58	21	21	56	27	17
Profile 2: Intensive cereal lower slope (ET_AJJIP001)							
Ap	0–20	13	13	64	39	18	43
AB	20–42	12	22	66	20	25	55
Bt1	42–90	18	20	62	28	15	55
Bt2	90–200	16	22	62	13	24	63
Profile 3: Agroforestry upper slope (ET_JIMLS-SP2)							
Ah	0–12	45	21	34	55	25	25
BA	12–30	50	18	32	68	23	11
Bt1	30–90	48	20	32	51	34	15
Bt2	90–145	42	35	23	30	42	28
Bt3	145–200	45	27	28	44	36	20
Profile 4: Agroforestry lower slope (ET_JIM-G-SLP2)							
Ap	0–10	12	23	65	20	14	66
AB	10–30	10	28	62	39	19	42
Bt1	30–60	7	30	63	29	23	57
Bt2	60–105	17	25	63	29	20	51
Bt3	105–180	15	30	55	28	24	48

CS coarse sand, MS medium sand, FS fine sand; CSi coarse silt, MSi medium silt, FSi fine silt

Soil chemical characteristics as affected by land use and slope

Tables 8 and 9 summarize important chemical characteristics of the sample profiles of Nitisols while mean values as affected by land use type and slope class are presented in Tables 10 and 11. The mean pH values were 5.29 and 6.12 for the cereal and agroforestry systems (Table 8) which are statistically significantly ($p < 0.05$) different. Based on the ratings of Hazelton and Murphy (2007), the soil pH is rated as strongly acidic and moderately acidic respectively. The strongly acidic soil reaction in the cereal system was attributed to intense leaching of bases and continued application of DAP and urea fertilizers. The base saturation 62 and 77% for the cereal and agroforestry systems that are significantly ($p < 0.05$) different (Table 10). The implication is that there is more intense leaching of basic cations in the cereal system resulting in higher exchangeable acidity. In addition, the rate of fertilizer application in the cereal system (100 kg urea and 150 kg DAP ha^{-1}) was double the rate applied in the agroforestry system (i.e., 50 kg DAP and 75 kg urea ha^{-1}). Previous research findings suggest that continuous application ammonia fertilizers such as DAP and urea can contribute to increased exchangeable acidity of the soil (Smaling and Braun 1996; Elias et al. 1998; Elias 2016).

The mean OC content was 2.0 and 2.1% for the intensive cereal and agroforestry systems (Table 10). Based on the ratings of Landon (1991), the OC of the soil was rated very low showing no significant difference between the land use types. On the other hand, slope effect was significant ($p < 0.05$) with higher mean values (2.5% OC) in the lower slope compared to 1.5% in the upper slope (Table 11). This is attributed to the movement of humus particles down slope with runoff water. The finding is in agreement with Gebreselassie et al. (2015) that reported increasing OC contents with decreasing slope.

The mean TN values, 0.15 and 0.22% for the intensive cereal and agroforestry systems, were rated low based on the ratings of Landon (1991) and significantly ($p < 0.05$) different between the two land use types. Higher TN content in the agroforestry system was due to crop residues addition and leaf litter accumulation from land use practices that added to N-mineralization. This is further elaborated by significantly lower C/N ratios with mean value of 10 in the agroforestry system compared to 18 in the intensive cereal system (Table 10). Although rate of decomposition was not measured in this study, the significantly higher C/N ratios are indicative of somewhat depressed microbial

Table 5 Structural aggregate stability and water holding capacity of Nitisol sample profiles

Horizon	Depth (cm)	Water stable aggregates (%)	Water holding capacity (%)		
			FC (1/3 bar)	PWP (15 bar)	AWC (mm m ⁻¹)
Profile 1: Intensive cereal upper slope (ET_ASAAP002)					
Ap	0–20	63	34	22	120
AB	20–40	70	35	23	120
Bt1	40–80	79	38	26	120
Bt2	80–200	76	40	28	120
Profile 2: Intensive cereal lower slope (ET_AJJIP001)					
Ap	0–20	85	38	26	120
AB	20–42	88	42	29	130
Bt1	42–90	89	43	30	130
Bt2	90–200	91	46	31	150
Profile 3: Agroforestry upper slope (ET_JIMLS-SP2)					
Ah	0–12	78	39	25	140
BA	12–30	75	37	23	140
Bt1	30–90	74	38	24	140
Bt2	90–145	69	36	22	140
Bt3	145–200	70	38	23	150
Profile 4: Agroforestry lower slope (ET_JIM-G-SLP2)					
Ap	0–10	91	40	23	170
AB	10–30	88	47	32	150
Bt1	30–60	93	47	31	160
Bt2	60–105	93	48	31	170
Bt3	105–180	94	49	26	230

Table 6 Mean values of physical and chemical characteristics of Nitisol (0–20 cm) as affected by slope class

Soil properties	Upper slope (15–30%)	Lower slope (2–5%)	T value	Sign.
Sand (%)	27	12	4.829	0.017
Silt (%)	22	25	−0.441	0.689
Clay (%)	51	63	−1.604	0.027
Bulk density (g cm ⁻³)	1.2	1.1	1.787	0.172
Particle size fractions (%)				
Coarse sand	49	15	3.141	0.042
Medium sand	34	33	0.097	0.929
Fine sand	17	52	−4.447	0.041
Coarse silt	54	41	1.065	0.365
Medium silt	32	21	1.392	0.258
Fine silt	14	38	−2.637	0.078
Water stable aggregates	80	82	−0.935	0.419
Water holding capacity w/w, %				
FC (1/3 bar)	35	37	−1.095	0.353
PWP (33 bar)	23	24	−0.662	0.555
AWC (mm m ⁻¹)	120	127	−1.567	0.215

decomposition of organic matter and N-mineralization in the cereal system. Further, the land use system might be adversely affecting soil microorganisms which

remains subject for future research. Slope effect of TN was also significant ($p < 0.05$) with higher mean values in the lower slope (0.22%) compared to 0.13% in the

Table 7 Mean values of physical and chemical characteristics of Nitisols (0–20 cm) as affected by land use

Soil property	Intensive cereal system	Agroforestry based system	T value	Sign.
Sand (%)	28	15	3.677	0.032
Silt (%)	26	18	−2.320	0.103
Clay (%)	46	67	−5.536	0.012
Bulk density (g cm ^{−3})	1.2	1.1	1.163	0.329
Particle size fractions (%)				
Coarse sand	43	19	6.453	0.008
Medium sand	41	16	4.494	0.021
Fine sand	30	39	−3.307	0.045
Coarse silt	59	30	7.769	0.004
Medium silt	38	17	3.859	0.031
Fine silt	21	42	−3.23	0.045
Water stable aggregates	79	87	−3.068	0.055
Water holding capacity w/w, %:				
FC (1/3 bar)	35	37	−1.424	0.250
PWP (33 bar)	23	24	−0.132	0.903
AWC (mm/m)	112	135	−9.000	0.003

Table 8 Selected chemical characteristics of Nitisol profiles by land use type and slope

Horizon	Depth (cm)	PH H ₂ O	OC (%)	TN (%)	C/N	CEC and exchangeable bases (cmol(+) kg ^{−1})						
						CEC	Ca	Mg	Na	K	TEB	PBS
Profile 1: Intensive cereal upper slope (ET_ASAA-P002)												
Ap	0–20	4.8	2.1	0.16	13	44	15	4	0.1	1.4	20	43
AB	20–40	5.1	1.7	0.10	17	32	14	3	0.1	1.2	18	53
Bt1	40–80	5.5	1.0	0.05	20	30	13	2	0.1	1.3	16	50
Bt2	80–200	5.7	1.0	0.06	17	30	14	4	0.2	1.2	19	60
Profile 2: Intensive cereal lower slope (ET_AJJI-P001)												
Ap	0–20	4.7	3.6	0.20	18	42	15	7	0.4	1.2	22	52
AB	20–42	4.9	2.0	0.12	17	49	20	7	0.4	1.1	27	55
Bt1	42–90	4.5	1.1	0.06	18	48	20	6	0.5	1.4	26	54
Bt2	90–200	4.9	1.1	0.07	15	45	17	5	0.4	1.3	22	49
Profile 3: Agroforestry upper slope (ET_JIMLS-SP2)												
Ah	0–12	6.2	2.5	0.25	10	37	13	14	0.2	2.2	29	78
BA	12–30	5.5	1.3	0.12	11	41	18	10	0.6	2.0	29	70
Bt1	30–90	5.5	0.9	0.09	10	35	14	10	0.9	2.0	25	71
Bt2	90–145	5.3	0.6	0.06	10	32	14	8	0.2	2.1	23	72
Bt3	145–200	5.8	0.4	0.04	10	30	12	11	0.2	2.0	18	77
Profile 4: Agroforestry lower slope (ET_JIM-G-SLP2)												
Ap	0–10	5.5	3.6	0.33	11	30	11	8	0.2	3.0	21	70
AB	10–30	5.9	1.9	0.13	14	28	13	8	0.1	2.0	22	79
Bt1	30–60	5.6	1.5	0.13	12	27	12	9	0.1	2.2	22	81
Bt2	60–105	5.6	1.1	0.10	11	30	12	10	0.1	2.4	23	77
Bt3	105–180	5.5	0.4	0.03	12	30	14	8	0.1	2.2	23	76

TEB total exchangeable bases, PBS percent base saturation

upper slope (Table 11). Similar results are reported by Gebreselassie et al. (2015) who found increasing TN levels with decreasing slope.

The mean AP content, 10 and 8 mg kg^{−1} for the cereal and agroforestry systems, were rated as low based on the ratings of Hazelton and Murphy (2007). Although

Table 9 Available phosphorus and micronutrient contents (mg kg^{-1}) of the surface horizons in the Nitisol profiles

Profile ID	Land use	Slope	AP	Fe	Mn	Zn	Cu
ET_ASAA-P002	Cereal	15–30	8	29	63	3	2
ET_AJJI-P001	Cereal	2–5	16	32	69	2	2
ET_JIMLS-SP2	Agroforestry	15–30	9	66	94	13	3
ET_JIM-G-SLP2	Agroforestry	2–5	8	60	98	10	2

Table 10 Mean values of selected chemical characteristics of Nitisols (0–20 cm) as affected by land use

Soil property	Intensive cereal system	Agroforestry based system	T value	Sign
pH-H ₂ O	5.29	6.12	-6.935	0.006
OC (%)	2.00	2.12	-0.620	0.579
Tot. N (%)	0.15	0.22	-4.217	0.024
C/N	18	10	2.600	0.080
AP (mg kg^{-1})	10.0	8	0.504	0.649
CEC and basic cations ($\text{cmol}(+) \text{kg}^{-1}$):				
CEC	40	44	1.800	0.170
Ca	14	16	-1.507	0.229
Mg	6	15	-10.832	0.002
Na	0.02	0.14	0.522	0.638
K	1.60	3.0	-3.705	0.024
PBS (%)	51	75	-6.937	0.006
Micronutrients (mg kg^{-1}):				
Fe	37	97	-8.895	0.003
Mn	39	68	-9.731	0.002
Zn	3	13	-8.278	0.004
Cu	2	3	-1.732	0.182

Table 11 Mean values of selected chemical characteristics of Nitisols (0–20 cm) as affected by slope

Soil properties	Upper slope (15–30%)	Lower slope (2–5%)	T value	Sign.
pH-H ₂ O	5.85	5.67	0.835	0.465
OC (%)	1.50	2.52	-12.000	0.000
Tot. N (%)	0.13	0.22	-4.869	0.012
C/N	8	15	-25.000	0.000
AP (mg kg^{-1})	10.0	17.0	-5.085	0.015
CEC and basic cations ($\text{cmol}(+) \text{kg}^{-1}$):				
CEC	43.0	42.0	0.324	0.767
Ca	16.0	14.0	1.842	0.163
Mg	9.0	8.0	5.196	0.14
Na	0.04	0.06	-0.16	0.923
K	1.2	1.4	-1.092	0.355
PBS (%)	62.0	58.0	1.960	0.145
Micronutrients (mg kg^{-1}):				
Fe	61.0	68.0	-0.733	0.516
Mn	46.0	55.0	-1.741	0.180
Zn	9.0	9.0	1.000	0.391
Cu	3.0	2.0	0.775	0.95

some profiles in the cereal system had high AP contents (Table 9), the mean values were not significantly different between the two land use types. The low levels of AP in spite of relatively higher doses DAP application (i.e., 150 kg ha^{-1}) in the cereal system suggests the unavailability of the applied phosphate in the soil solution. This was attributed to increased exchangeable acidity and higher P-sorption capacity of the strongly acidic soils under the cereal system. Literature indicates the applied phosphate is fixed by iron and aluminum compounds (i.e., sesquioxides) and hence, rendered unavailable in the soil solution in low pH soils (Schaetzl and Anderson 2005; Hillel 2004). On the other hand, AP contents were significantly ($p < 0.05$) different between the two slope classes with higher mean values (17 mg kg^{-1}) in the lower slope compared to 10 mg kg^{-1} in the upper. The conventional practice of farmers is to apply DAP at planting (i.e., basal application) when the monsoon rains are at their peak that results in the runoff removal of some of the applied fertilizer from the upper slopes that are deposited in the lower slopes.

On the other hand, the CEC, exchangeable bases (Ca^{2+} , Mg^{2+} , K^{+}) and PBS of the soil were rated high based on the

ratings of Landon (1991) while Na^+ appeared only in trace amount. The paired T-test showed no significant difference between land use type and slope classes except for Mg^{2+} , K^+ and PBS. Mean values of Mg^{2+} ($15 \text{ cmol}(+) \text{ kg}^{-1}$), K^+ ($3 \text{ cmol}(+) \text{ kg}^{-1}$) and PBS (75%) in the agroforestry system were significantly higher than those in the cereal system (6 and $1.6 \text{ cmol}(+) \text{ kg}^{-1}$ of Mg^{2+} and K^+ and 51% PBS). The PBS was in the medium to high range (43–60%) in the cereal system while it was high to very high (70–81%) in the agroforestry system (Table 8). The generally high base saturation of the soil was consistent with high contents of exchangeable bases (chiefly Ca^{2+} and Mg^{2+}) but not consistent with generally acidic soil reaction (pH 5.5–6.2) that needs some explanation. First, the soils in the Ethiopian highlands have developed on recent Trapean lava flows that have high base status (Mohr 1971). Secondly, according to Buol et al. (2011) the volcanic parent materials such as rhyolites, granite, trachytes, ignimbrites, andesites and some acidic basalts that dominate the Ethiopian produce inherently acidic clays. Thirdly, the humid climatic conditions might have resulted in increased microbial oxidation to produced organic acids, which provide H^+ to the soil that can also contribute towards low soil pH (Schaeztl and Anderson 2005).

The mean values for Fe^{2+} , Mn^{2+} , Zn^{2+} and Cu^{2+} were respectively 37, 39, 3 and 2 mg kg^{-1} in the cereal system while it was 97, 68, 13 and 3 mg kg^{-1} in the agroforestry system (Table 9). According to the ratings of Havlin et al. (1999), the micronutrient contents were rated as high to very high except for Zn^+ that was low to medium. The high levels of micronutrients is consistent with the low pH of the soil and the low Zn^{2+} contents are in agreement with previous report that indicated widespread Zn deficiency in the Nitisol areas of the Ethiopian highlands (Dibabe et al. 2007). According to FAO (2006b), low soil pH induces increase in micronutrient contents that may eventually lead to root toxicity unless soil pH is corrected through liming. The paired T-test showed significant ($p < 0.05$) difference between land use types for Fe^{2+} , Mn^{2+} , and Zn^{2+} but slope effect was nonsignificant. The mean value of Fe^{2+} (97 mg kg^{-1}), Mn^{2+} (68 mg kg^{-1}) and Zn^{2+} (13 mg kg^{-1}) in the agroforestry system were significantly higher than 37, 39 and 3 mg kg^{-1} of Fe^{2+} , Mn^{2+} , and Zn^{2+} in the cereal system (Table 10). According to Mohr (1971) and Davidson (1983), the soil parent materials in the agroforestry system are dominated by basic rocks such as alkali-olivine basalts, amphibole and mica that are rich in ferromanganese minerals thus explaining the exceptionally high Fe^{2+} and Mn^{2+} contents in these sites.

Conclusion

The study showed that land use practices and slope class significantly affects important soil physical and chemical characteristics. These include particle size distribution,

plant available water contents (AWC), soil pH and OC, TN, AP exchangeable bases and some micronutrients. The land use practices in the intensive cereal system was found to be adversely affecting important soil physical and chemical characteristics as compared to the agroforestry system. These include alteration of particle size distribution, strongly acidic soil reaction, organic matter depletion, multiple nutrient deficiencies (N, P, K and Zn) and low plant available water content. Among the inappropriate land use practices include repeated cultivation to create fine seedbed that predisposes the soil to erosion, unbalanced fertilizer application, rotation of maize with potato that are depleting some nutrient stocks (e., K and Zn), and removal of crop residues from fields. As can be seen from the significantly lower PBS in the cereal system, leaching of basic cations was intense that resulted in increased levels of exchangeable acidity. In addition, continued use of DAP and urea seems to have contributed to increased exchangeable acidity as well as accentuating the uptake and deficiency of other nutrients such as K and Zn that are not supplied in the fertilizer application. Slope position of the profiles also had significant effect on soil characteristics with significantly higher proportions of coarse textured particles that were low in OC, AP and TN contents in the upper slope compared to lower slopes. Organic matter and nutrient contents decreased with increasing slope gradient particularly in the cereal system indicating the effect of erosional losses of fine particles.

The data, therefore, provides useful information for planning soil management strategies that can address adverse effects of land use on soil characteristics. First and foremost, application of more balanced blend fertilizer that contains N, P, K and Zn combined with liming to raise the soil pH remains crucially important. In this connection, research needs to generate NPS and Zn-B blend fertilizer applications rates for different crops, soil types and land use systems. Increasing the rate of fertilizer application is particularly crucial in the agroforestry based system where current rates of fertilizer use are far too low. However, given the very high levels of Zn in the soil, Zn-blend should not be extended to farmers in the agroforestry system. Secondly, organic matter management including restitution of crop residues and recycling of farm yard manure is fundamental in order to reverse the OC depletion and increase water holding capacity of the soil. Third, although Nitisols have high structural aggregate stability that are fairly resistant to erosion, their landform of occurrence (i.e., high to mountainous relief hills with steep slopes) makes the soils susceptible to degradation by water erosion. This calls for the implementation of integrated soil and water conservation measures that combine physical,

biological and agronomic measures mainly in the cereal system. In addition, soil textural fractionation analysis indicates that repeated tillage practice is found to predispose the soil to erosion by adversely affecting the soil textural fractions. Therefore, minimum tillage combined with legume rotation (maize-*tef*-bean) observed in some parts of west Gojam (e.g., South Achefer and Bure) need to be widely disseminated among farmers in the cereal-livestock highlands.

Abbreviations

AP: available phosphorus (mg kg^{-1}); AWC: available water content; BD: bulk density (dgcm^3); C/N: carbon to nitrogen ratio; Ca/Mg: calcium to magnesium ratio; CEC: cation exchange capacity ($\text{cmol}(+) \text{kg}^{-1}$); Cu: copper (mg kg^{-1}); DAP: di-ammonium phosphate (18% N, 46% P_2O_5); FC: field capacity; ITCZ: Inter Tropical Convergence Zone; K: Potassium ($\text{cmol}(+) \text{kg}^{-1}$); Mg: Magnesium ($\text{cmol}(+) \text{kg}^{-1}$); Mn: Manganese (mg kg^{-1}); Na: Sodium ($\text{cmol}(+) \text{kg}^{-1}$); PBS: percent base saturation; SC: sandy clay; TN: total nitrogen (%); PWP: permanent wilting point; WSA: water stable aggregates; Zn: zinc (mg kg^{-1}).

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Availability of data and materials

I declare that the data and materials presented in this manuscript can be made publically available by Springer Open as per the editorial policy.

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