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Characterization and classification of soils along the toposequence at the Wadla Delanta Massif, North Central Highlands of Ethiopia

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The knowledge of soil properties and availability of reliable soil data play vital role in understanding the soil environment and its services. This study was conducted with the objective of characterizing and classifying soils of Wadla Delanta Massif, North Central Highlands of Ethiopia. Twelve representative soil pedons (profile pits) were opened on various landscape positions, described in the field and horizon-wise samples collected for morphological and physicochemical analysis. Variations in color (moist and dry) within a pedon and among pedons along the toposequence were observed with grayish, dark brownish or black colors dominating the surface layers, while stronger and brighter colors with shades of reddish brown and light brownish gray dominated the surface layers. The soils are heavy clays (35 to 80%), of low bulk density (1.02 to 1.35 g cm^{-3}), acceptable ranges of particle density for mineral soils (2.41-2.82 g cm^{-3}) relatively high total porosity (46.51-60.55%), and high available water holding capacity (129.9-287.9 mm m^{-1}).The soils were slightly acidic to moderately alkaline (6.25 to 8.29) in their reaction, salt free (EC < 0.5 dS m^{-1}), very low to medium in organic matter (0.12 to 4.82%) and total N (0.02 to 0.28%) contents, and available P (0.52 to 18.44 mg kg^{-1}), high to very high in CEC (31.98 to 65.48 cmolc kg^{-1}), exchangeable bases and base saturations (60.22 to 98.97%), with medium status of micronutrients occurring in order of Fe (0.82-10.40 mgkg^{-1}) >Mn (2.01-9.22 mgkg^{-1}) > Cu (0.80-6.03 mgkg^{-1}) > Zn (0.80-5.80 mgkg^{-1}), all of which were above the critical limit. Based on morphological, physical and chemical analysis, and the FAO-WRB Soil Classification System, the soils are classified as Mazi-Pellic Vertisols, Mazi-Calcic Vertisols, Haplic Cambisols and Mollic Leptosols. The soil potentials are hampered by their stickiness when wet and hard when dry, waterlogging and soil erosion due to inappropriate tilling and timing of cultivation. Therefore, integrated soil management is essential in the area.

Key words: Altitude, horizon, pedon, topography.

INTRODUCTION

Topography is one factor contributing to variation in soil morphological, physical and chemical characteristics (Amhakhian and Achimugu, 2011). Inadequate information on the influence of landscape on soil properties is a contributing factor limiting agricultural production in Ethiopia in general and in the study area in particular. Productivity of agriculture in the study area is severely constrained by the lack of adequate scientific information on soil and land characteristics. Hitherto, there has not been any formal scientific study to characterize the soil resources of the area and map the soils using standard pedological classification systems. As a consequence, the potentials and limitations of the soils in the region are not adequately known. This has made the development of meaningful management scenarios all but impossible. As a result, the sustainable use of the soil resources for agriculture is facing future uncertainty.

Soil information gathered by systematic identification, grouping and delineation into different soil types is required if sound interpretations towards land use potential are to be made (Msanyaet al., 2003). A good inventory on soil properties and associated site characteristics is essential for advice on both current and potential land users on how to best use the resource. Soil fertility specialists need good soil information to identify the dominant soil types on which to conduct meaningful fertilizer trials and be confident that the findings are applicable to that soil type throughout region.

Although Ethiopia has long history of collecting basic information on soil characterization in the form of soil surveys (Eylachew, 1987, 1999;Mitiku, 1987; Mohammed, 2003;Abayneh, 2005), it is limited to a few selected high potential areas. Thus, much of the country information remains rather scanty relative to the large size of the country and the wide diversity of soils and landscapes. Furthermore, the few existing soil resource inventories that are available are characterized by their small scale nature with high level of generalization, generally based on few observations scattered over large areas. Moreover, these surveys have often used different methodologies and criteria. As a consequence, most existing studies cannot easily be correlated and all have limited utility, because of the coarse scale of the mapping. There is need for more efforts to be invested in a coordinated and systematic development of an inventory of the country's soil resources and other land information to facilitate sustainable land use planning activities. There is also a strong feeling that fertilizer trials should be done on well characterized soils to enhance transferability of information from one place to another.

Soil classification can also provide a basis for soil-related agro-technology transfer (Buol and Denton, 1984; Braimoh, 2002). Lawalet al. (2013) and Sharuet al. (2013) revealed that systematic soil classification links research results and their beneficial extension to field applications. Thus, soil classification is used to apply proper management practices, transfer technology and provide a ready-made map legend for soil surveyors. An example of the limited information on soil characterization and their classification can be found along the toposequence at the Wadla Delanta Massif in the North Central Highlands of Ethiopia. The present study was initiated to address the limited soils information in this region of the country. In the Wadla Delanta Massif of North Central Highlands of Ethiopia, the soils and land resources were systematically characterized, analyzed and mapped as part of a national effort to develop soil inventories for future planning and development.

MATERIALS AND METHODS

Description of the study area

This study was conducted at the Wadla Delanta Massif in Delanta District, north central highlands of Ethiopia (Figure 1). The study area lies between 11° 29' 29.82"and11° 41' 25.528" north latitudes and 39° 02' 19.186" to 39° 14' 05.038" east longitudes with elevation ranging from 2848 to 3486 meters above sea level (masl) and covering an area of 24,025 ha. It is located at about 499 km north of Addis Ababa and 98 km northwest of Dessie town.

The climate of the area is characterized by cold-dry and hot-dry seasons (from October to February and from March to June), respectively and wet season that extends from mid-June to September. The rainfall pattern is bimodal with peak periods from mid-July to early September. Fifteen years (1999-2013) mean annual rainfall is about 812 mm of which 60-70% is received in summer (*Kiremt)* and 30-40% in the spring (*Belg*) season (Figure 2).The mean annual minimum and maximum temperatures are 6.8 and 19.6°C, respectively (Figure 2).

Geology of the study area is characterized by the trap series of tertiary periods, similar to much of the central Ethiopian highlands (Mohr, 1971). Dereje et al. (2002) reported the area covered by Oligocene rhyolite and very thick ignimbrite units encompassing predominantly of alkaline basalt with numerous inter-bedded flow of trachyte. Granite, gneisses and basalt rock types exist in the area forming part of the basement complex and most of the soils are of basaltic parent material. Soils of the study area are greatly influenced by topography with high surface runoff during the main rainy season. There was no scientific studies in the area before this study except for FAO (1984) general soil survey (1:1 000 000 scale) made at the national level. The local people classified the soils into *Walka or Mererie Afer* (Vertisoils) in the plain area and *Nechatie or Gracha Af*er (Cambisoils) in steep slope or mountainous area.

The natural woodland and vegetation of the study area has disappeared due to overgrazing, increasing demand for fuelwood and charcoal, and conversion into cultivated lands. There are small patches of remnant natural forests on farm boundaries and around churches. Planted tree species like *Eucalyptus camaldulensis*, C*upressuslustanica, Acacia saligna*and A*cacia decurrens* are commonly found around homesteads and conserved lands. The *Eucalyptus camaldulensis* plantations are replacing the cultivated lands and expanding around backyards, stream banks and gully sides. Farming system is mixed livestock and crop production. The common rainfed crops grown in the area are bread wheat *(Triticumaestivum L.)*, food barley *(Hordenumvulgare* L.), faba bean (*Vicia faba L*.), lentil (*Lens culinaris L.*), grass pea (*Lathyrussativus* L.),

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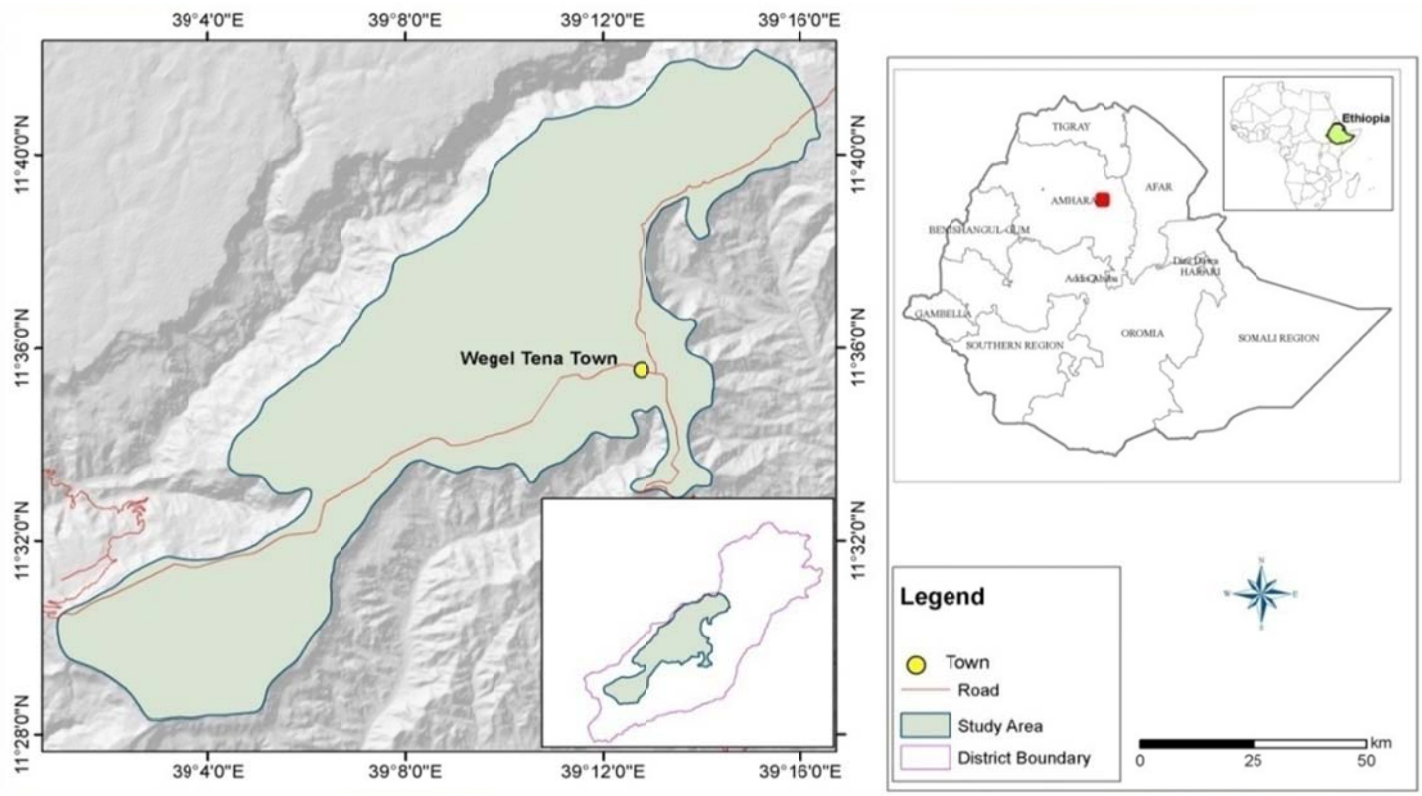

Figure 1. Location map of the study area.

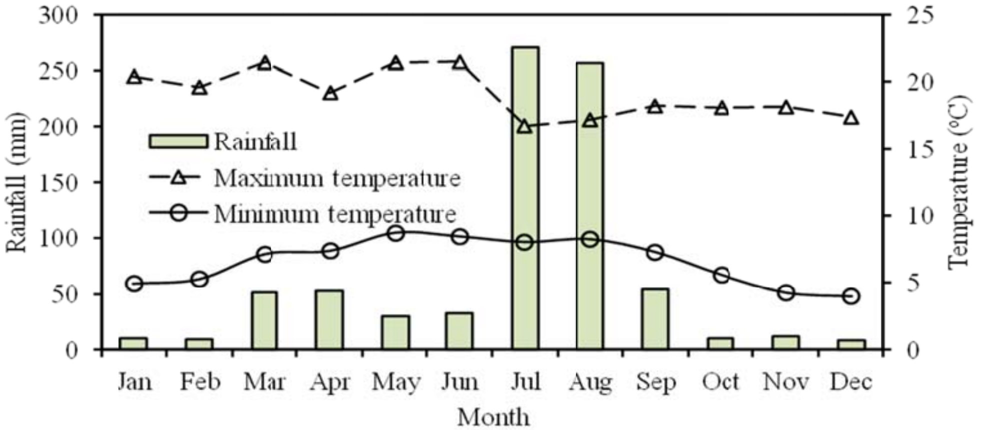

Figure 2. Mean (1999-2013) monthly rainfall, maximum and minimum temperatures of the study area.

chickpea (*Cicerarietinum L.*), teff (*Eragrostis tef L.*) and sorghum (*Sorghum bicolor L.*). All these crops are managed using traditional techniques and equipment (WAOR, 2013).

Site selection, field description and soil sampling

Before collecting soil samples, the existing land information were gathered from farmers and elders coupled with a visual observation in various parts of the district, obtaining base map (1:50,000 scale), preparing provisional map, extensive auguring to identify mapping units and sites for opening profile pits. The survey technique was a free survey following a stratified sampling technique and transect was drawn from the crest to the foot at the Wadla Delanta Massif, northcentral highlands of Ethiopia.Altitude along the toposequences ranged from 2600 to 3500 meter and was divided into three topographic categories: upper (> 3000 m), middle (2900-3000 m)

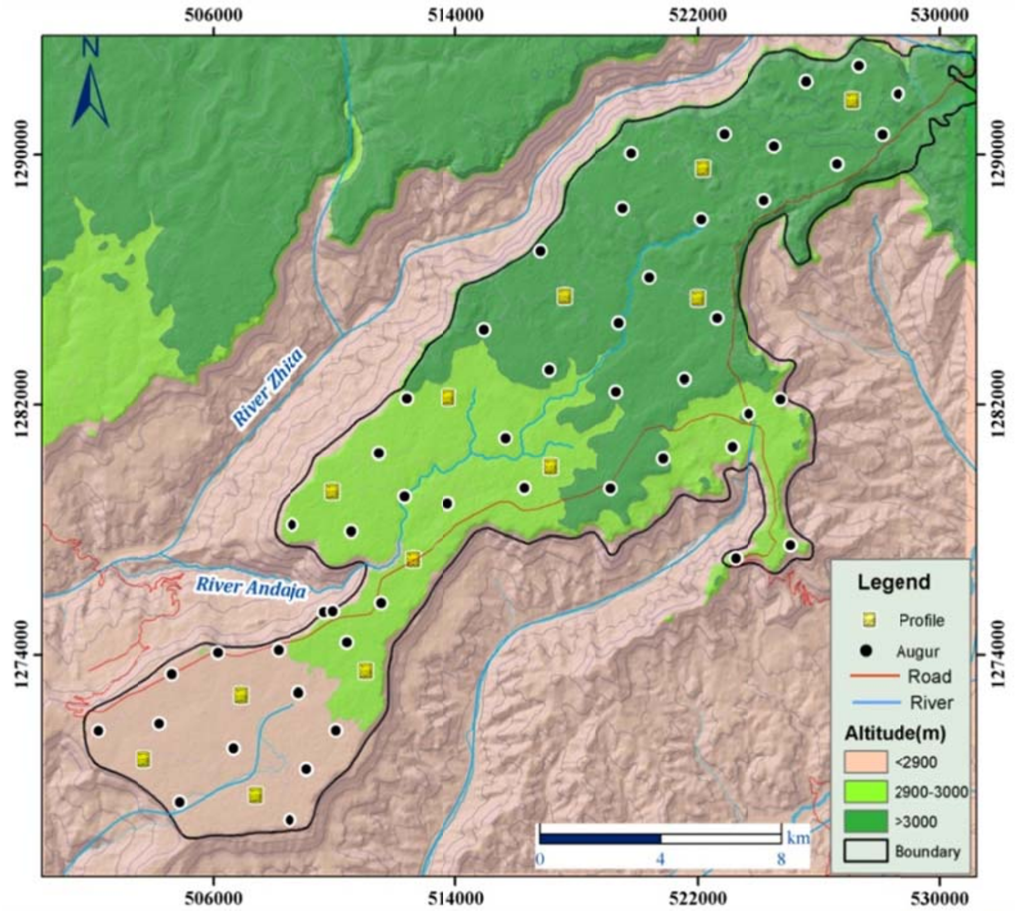

Figure 3. Elevation map of the study area.

and lower (< 2900 m). topographic positions. The study area was covered by an approximately 1:50,000 scale topographic map produced by Ethiopian Mapping Agency to determine different land units on the basis of topography and other external land characteristics. Topographic maps were also used for locating important land features to assist in soil mapping (Figure 3).

After having the preliminary site visit and verified interpretation of maps, pedons (profile pits) were opened on representative sites. Pedons were made to a depth of 2± m unless soil depth was limited due to stoniness or compactness. A total of twelve representative soil pedons (2 m wide x 2 m long x 2m deep) were excavated, described and sampled (Figure 3 and Table 1) following standard procedures to investigate morphological, physical and chemical properties of the soils. The horizons were designated *in situ* using FAO (2006a) guideline and soil color notation described using Munsell Soil Color Chart (1994). All sites were examined from February to April, 2012.

General site information and soil description were recorded; soil samples were collected from each generic horizons; properly labeled; air dried and crushed to pass through 2 mm sieve for analysis of most soil properties except for total N and soil OC in which case the samples were crushed further to pass through 0.5 mm sieve prior to laboratory analysis. Moreover, undisturbed (core) soil samples of known volume were collected, using core sampler, from each identified genetic horizons for bulk density determination and soil moisture retention characteristics. All pedons were geo-referenced using GPS, the elevation was recorded using an altimeter and the slope gradient was measured using clinometers. The soils of the study area were classified according to FAO-WRB (2006) Soil Classification Systems.

Laboratory analysis

Particle size distribution was determined by the modified sedimentation Bouyoucos hydrometer procedure (Bouyoucos, 1962). Bulk density (ρ_b) and particle density (ρ_s) were measured by core (Baruah and Barthakur, 1997) and pycnometer methods (Black and Hartge, 1986), respectively. Total porosity (*f*) was calculated from the measurements of bulk density (ρ_b) and particle density (ρ_p) as:

$$f = \left(1 - \frac{\rho_b}{\rho_s}\right) \times 100$$

Water retention at field capacity (FC) and permanent wilting point (PWP) were measured at -1/3 and -15 bars soil water potential, respectively, using pressure plate apparatus as described in Gupta (2004). Available water holding capacity (AWHC) was calculated as the difference between water contents at -1/3 and -15 bars of air-

Table 1. Site characteristics and land uses of the study area.

Pedon*	Latitude	Longitude	Altitude (masl)	Land use
MG01	11° 35' 11.940" N	39° 10' 46.980" E	2997	Grazing land
MC02	11° 33' 08.893" N	39° 06' 55.615" E	2931	Lentil crop already harvested
UC03	11° 39' 37.614" N	39° 12' 08.927" E	3143	Barley crop already harvested
UC04	11° 41' 25.528" N	39° 14' 05.038" E	3286	Barley crop already harvested
LG05	11° 31' 07.380" N	39° 04' 27.540" E	2880	Grazing land
LC06	11° 29' 29.820" N	39° 04' 59.940" E	2852	Wheat crop already harvested
LC07	11° 30' 19.226" N	39° 02' 19.186" E	2848	Wheat crop already harvested
MG08	11° 34' 18.597" N	39° 05' 28.309" E	2962	Grazing land
UC09	11° 37' 39.792" N	39° 12' 06.728" E	3050	Barley crop already harvested
UC10	11° 40' 25.158" N	39° 17' 31.078" E	3326	Barley crop already harvested
MC11	11° 36' 50.223" N	39° 09' 23.672" E	2910	Barley crop already harvested
UG12	11° 46' 5.395" N	39° 19' 53.728" E	3486	Grazing land

*The first number indicates the topography (1= upper, 2 = middle and 3 = lower), the 2nd and 3rd numbers indicate pedon (pit) number (01 = pedon 1, 02 = pedon 2, 03 = pedon 3…, 12 = pedon 12); C = cultivated, G = grass, L = lower, M = middle, U = upper topography and masl = meters above sea level.

dried soil sample, expressed in equivalent depth of water (mm/m) obtained by multiplying the gravimetric water content by the ratio of dry bulk density to density of water (taken as 1 g cm^{-3}) and 1000 (conversion factor)

Soil pH was determined in H_2O (pH-H_2O) and 1M KCl (pH-KCl) using a glass electrode pH meter at the ratio of 1:2.5 soil to solution (Van Reeuwijk, 1993). Electrical conductivity (EC) was determined using a conductivity meter in a soil-water extract. Organic carbon (OC) was determined using the wet combustion method (Walkley and Black, 1934) and soil OM calculated by multiplying soil OC by 1.724. Total nitrogen was determined by the micro-Kjeldahl digestion, distillation and titration method (Bremner and Mulvaney, 1982). Available phosphorus (P) was analyzed using the sodium bicarbonate extraction solution (pH 8.5) method (Olsen et al., 1954) and amount measured by spectrophotometer.

Cation exchange capacity and exchangeable basic cations were extracted by 1M ammonium acetate (pH 7) method (Van Reeuwijk, 1993). From the leachate, exchangeable Ca and Mg were determined by atomic absorption spectrophotometer (AAS), while exchangeable K and Na were read by flame photometer. Percent base saturation was calculated as the ratio of the sum of exchangeable bases (Ca, Mg, Na and K) to the CEC of the soil multiplying by 100. Extractable micronutrients (Fe, Mn, Cu and Zn) were extracted by diethylenetriaminepenta-acetic acid (DTPA) method and the reading was quantified using AAS (Lindsay and Norvell, 1978). Calcium carbonate content was determined following acid neutralization method (Jackson, 1970). The analyses were undertaken at the Haramaya University Soil Chemistry Laboratory, Water Works Design and Supervision Enterprise Laboratory, and Sirinka Agricultural Laboratory Center.

RESULTS AND DISCUSSION

Soil morphological characteristics

The depth of the investigated soils ranged from slightly shallow to very deep with irregular A, B and C horizons (Table 2). Among the topographic positions, the upper pedons were relatively shallow in depth, moderate in stoniness and moderate to well drained soils. The lower topographic pedons were deeper, high in clay accumulation and gently sloping (2-4%). Generally, the thickness of the soils increased down topographic positions indicating the dominance of erosion over accumulation on the upper positions and otherwise in the lower topographic positions. The surface soils had higher concentration of plant roots and coarser texture, while the subsurface soils are finer in texture, denser and harder. At the surface horizons, the soil color matrix varied from dark gray (7.5YR 4/1, dry) to dark gray (2.5Y 4/1, dry) in the upper land pedons, very dark gray (7.5YR 3/1, dry) to brown (10YR 4/3, dry) in the middle land pedons, and dark gray (7.5YR 4/1, dry) to very dark gray (10YR 3/1, dry) in the lower land pedons. At the subsurface layers, it ranged from light reddish brown (2.5Y 6/4, dry) to light gray (2.5Y 7/1, dry) in upper topographic pedons, weak red (2.5YR 4/2, dry) to yellowish brown (10YR 5/6, dry) in middle topographic pedons and reddish gray (5YR 5/2, dry) to grayish brown (10YR 5/2, dry) in the lower topographic pedons.

The variations in soil color observed within and among the pedons might be reflections of differences in chemical and mineralogical composition, topographic positions, soil OM content, texture, parent materials and moisture regime. The dark color, in surface horizons, might be attributed to the effect of higher OM contents, while the reddish color, in the subsurface horizons, might be due to the presence of iron compounds in various states of oxidation and low OM content. Similar finding were reported by Dengizet al. (2012) who stated that variation in soil color could be related to OM, waterlogging, $CaCO_3$ accumulations and redox reaction in the soil.

Table 2. Selected morphological characteristics of soils at WadlaDelanta Massif, North Central Ethiopia.

Pedon	Horizon	Depth (cm)	Matrix color		Structure*1			Consistence*2			Boundary*3
			Moist	Dry	Grade	Size	Shape	Dry	Moist	Wet	
MG201	A	0-38	7.5YR 2.5/2	7.5YR 3/1	5	fn	cu	h	fr	ssk-pls	A-S
	Ass1	38-110	7.5YR 2.5/1	7.5YR 3/2	6	mid	prs	vh	fr	sk-pls	C-W
	Bss1	110-122	5YR 3/1	5YR 4/1	3	mid	prs	h	vfr	vsk-vpls	G-W
	Bss2	122-225+	5YR 3/2	5RY 3/3	1	mid	grn	Sh	vfr	sk-pls	A-S
MC202	Ap	0-20	10YR 2.5/1	10YR 3/1	5	mid	grn	vh	vfr	sk-pls	A-S
	Ass1	20-102	10YR 2.5/1	10YR 4/2	6	mid	abk	vh	fr	vsk-vpls	C-W
	Ass2	102-123	2.5Y 3/2	2.5YR 4/2	5	mid	prs	h	fr	sk-pls	A-S
	Bss	123-215+	5YR 3/2	5YR 3/3	3	mid	sbk	sh	fr	sk-pls	A-S
UC103	Ap	0-22	10YR 3/1	10YR 4/1	5	mid	grn	vh	vfr	vsk-vpls	A-S
	Bss1	22-33	10YR 2.5/1	10YR 4/2	6	mid	abk	vh	vfr	vsk-vpls	C-W
	Bss2	33-58	7.5YR 3/2	7.5Y 3/3	5	mid	prs	h	fr	sk-pls	A-S
	C	58-89+	5YR 3/2	5RY 3/3	3	mid	sbk	sh	fr	sk-pls	A-S
UC104	Ap	0-23	10YR 3/1	10YR 4/1	5	coarse	grn	vh	fr	sk-pls	A-S
	Ass1	23-58	10YR 5/2	10YR 6/2	6	coarse	prs	vh	fm	vsk-vpls	C-S
	C	58-95+	2.5Y 8/2	10Y8/2	1	mid	prs	sh	fr	nsk-npls	A-S
LG305	A	0-35	10YR 2/1	10YR 2/2	5	mid	cu	sh	fr	sk-pls	A-S
	Ass1	35-76	10YR 2.5/1	10YR 4/2	6	mid	prs	vh	fm	sk-pls	A-W
	Bss1	76-114	2.5Y 3/2	10YR 4/	5	mid	prs	vh	fm	vsk-vpls	C-W
	Bss2	114-205+	2.5Y 4/3	2.5Y 3/3	1	mid	prs	sh	vfr	ssk-spls	C-W
LC306	Ap	0-32	2.5Y 4/1	10YR 3/1	5	fn	grn	h	fr	sk-pls	A-S
	Ass1	32-76	10YR 2/2	10YR 3/2	6	mid	prs	h	fm	vsk-vpls	C-W
	Bss1	76-115	2.5Y 3/3	2.5Y 5/4	5	mid	prs	h	fm	vsk-vpls	C-W
	Bss2	115-216+	5YR 3/3	5YR 5/2	3	mid	prs	sh	fr	ssk-spls	A-W
LC307	Ap	0-28	7.5YR 3/3	7.5YR 4/1	5	fn	grn	vh	fm	vsk-vpls	A-S
	Ass1	28-110	10YR 3/1	5YR 4/1	6	mid	prs	vh	vfm	vsk-vpls	C-W
	Bss1	110-135	10YR 4/2	10YR 5/2	6	mid	prs	vh	fr	sk-pls	G-W
	Bss2	135-208+	10YR 3/4	10RY 4/4	1	mid	prs	sh	fr	sk-pls	A-S
MG208	A	0-37	10YR 2.5/1	10YR 4/2	2	fn	cu	sh	fm	sk-pls	A-S
	Ass1	37-140	10YR 2.5/2	10YR 4/1	6	mid	prs	vh	fm	vsk-vpls	C-W
	Bss1	140-189	7.5YR 3/3	7.5YR4/3	6	mid	abk	vh	vfm	vsk-vpls	C-W
	Bss2	189-198	10YR 4/4	10YR 5/6	6	mid	prs	h	vfm	sk-pls	C-S
	BC	198-245+	5YR 3/2	5YR 5/3	3	fn	grn	sh	fr	nSk-nspl	C-S
MC109	A	0-25	7.5YR 3/1	7.5YR 3/2	6	mid	grn	vh	fm	vsk-vpls	C-S
	B	25-48	7.5Y 2.5/2	7.5YR 3/2	6	coarse	abk	vh	fm	vsk-vpls	C-S
	C	48-75+	10YR 4/4	10YR 5/6	1	coarse	grn	sh	fr	nsk-npls	C-S
UC110	Ap	0-25	7.5YR 3/1	7.5YR 4/1	6	mid	grn	h	fr	sk-pls	A-S
	Ass1	25-62	10YR 2/2	10YR 3/3	6	coarse	prs	vh	fm	vsk-vpls	A-I
	Bss	62-78	2.5Y 4/2	2.5Y 5/2	4	mid	prs	h	vfr	sk-pls	A-S
	C	78-99+	2.5Y 6/2	2.5Y 7/1	1	mid	prs	sh	vfr	ssk-spls	A-S
MC211	Ap	0-25	10YR 3/3	10YR 4/3	5	coarse	grn	vh	fm	sk-pls	A-S
	Ass1	25-65	10YR 3/1	10YR 4/1	6	coarse	wdg	vh	fm	vsk-vpls	C-S
	Bss	65-95	5YR 4/4	5YR 3/4	5	mid	prs	vh	fm	vsk-vpls	C-W
	C	95-115+	5YR 3/4	5YR 5/6	1	mid	prs	sh	fr	nsk-npls	A-S
UG112	A	0-33	2.5Y 4/1	2.5Y 4/2	2	fn	cu	h	fm	sk-pls	S-C
	B	33-47	2.5YR 5/4	2.5YR 6/4	6	mid	prs	vh	fm	sk-pls	S-W
	C	47-65+	5YR 4/2	5YR 5/3	3	fn	prs	sh	vfr	nsk-npls	C-W

*1: 1 = Weak; 2 = Moderate; 3 = Slightly strong; 4 = Moderately strong; 5 = Strong; 6 = Very strong; vfn = Very fine; fn = Fine; mid = Medium; c = Coarse; vc = Very coarse; cu = Crumb; grn = Granular; prs = Prismatic; abk = Angular blocky; sbk = Subangular blocky. *2: sh = Slightly hard; mh = Moderately hard; h = Hard; vh = Very hard; fr = Friable; vfr = Very friable; fm = Firm; vfm = Very firm; pls = Plastic; vpls = Very plastic; sk = Sticky; vsk = Very sticky; spls = Slightly plastic; ssk = Slightly sticky; nsk = Non sticky; npls = Non plastic. *3: A = abrupt; C = clear; G = gradual; I = irregular; S = smooth; W = wavy.

There were considerable variation in the grade, size and shape of the soil structure among the pedons. Accordingly, the structure of the soils in the study area varied from weak to very strong, fine to coarse, granular to sub angular blocky structure. Most pedons had predominantly crumb and granular structure at the surface horizons to angular and sub angular blocky/prismatic structure in subsoil horizons. Similar results were reported by Buolet al. (2011) and Rai (2002) who found that the surface horizons had crumb (in grassland) and granular (in cultivated) soil structure, whereas the prismatic and angular soil structure were common in the subsurface horizons (Table 2).

Considering topographic locations, consistence of the studied pedons, on upper and middle topographic positions varied from slightly hard to hard (dry), friable/loose to firm (moist) and slightly sticky and plastic to very sticky and very plastic (wet), whereas the lower topographic pedons exhibited hard to very hard (dry), friable to firm (moist) and sticky and plastic to very sticky and very plastic (wet) consistence. Variation in soil consistence within pedons could be related to the particle size distribution, but mainly clay content and mineralogy of the clay particles. Similar findings were reported by Singh and Agarwal (2003) and Thangasamyet al.(2005). They revealed that soil consistence variation was affected by clay contents and types. Moradi (2013) also revealed the effect of soil texture on soil consistence.

Soil physical properties

The particle size distributions of the studied soils are predominantly of a clay texture, except for Pedons UC04, MC09 and UG12 which are clay loams. Moreover, none of the fractions showed consistent pattern with topographic positions, although the clay content irregularly increased with decreasing topographic positions and increasing soil depths (Table 3). Clay content ranged from 60 to 85% in subsurface horizons and lower topographic position. Similar findings were reported by Buolet al. (2011), Lambin and Esu (2011) and Prasad and Govardhan (2011) who found accumulation of clay in subsurface horizons and attributed this to the *in situ* formation of secondary clays, the weathering of primary minerals in B-horizon or the residual concentration of clays from the selective dissolution of more soluble minerals. The clay texture of the lower topography was heavy and could be associated with large accumulation due to the lateral movement of finer fractions from higher elevation as a result of erosion or clay translocation within the pedons. The silt to clay ratio, which decreased with soil depth, was < 1 in all the pedons. It was also evident in the progressive decrease in the silt: clay ratio with depth of pedons. The low silt to clay ratio in the subsoil layers indicate that the soils are at an advanced stage of development (Abayneh, 2005; Basavaet al., 2005), and confirm the existence of both clay migration and translocation in the pedons.

The bulk density was comparatively lower at the surface horizons than the subsurface horizons ranging from 1.02-1.27 g cm^{-3} in surface horizons, and 1.16-1.35 g cm^{-3} in subsurface horizons (Table 3). Therefore, the bulk density values of the studied soils were found to be within the acceptable range (1.0-1.5 g cm^{-3}) for agricultural use (Whiteet al., 1997). This implies that any compaction is not restricting root development (Nugaet al., 2008; Mulugeta and Sheleme, 2010). There were inverse relationships between soil OM and pore space with bulk density.

In all the topographic positions, particle density decreased consistently with increasing soil depths. The highest (2.82 g cm^{-3}) and lowest (2.41g cm^{-3}) values of particle density were recorded at the surface and subsurface horizons, respectively. Furthermore, it increased with increase in altitude (Table 3). Skopp (2002) revealed that typical particle density values for mineral soils ranged from 2.5-2.8 g cm^{-3}, with 2.65 g cm^{-3} being representative of most soils. Based on this range, particle density values recorded in soils of the study area fall within the normal range. Nevertheless, the relatively high particle density values recorded at the surface layers are contrary to established facts and could not be explained.

Total porosity (f) of the soils varied from 51.9 to 60.7% at surface horizons of the upper and lower elevations, while the subsurface horizons had relatively lower values that ranged from 46.2 to 57.1% (Table 3). Brady and Weil (2008)stated that optimum total pore space value for crop production is > 50%. Similarly, Michael (2008) revealed that total pore spaces in the clayey textured soils may vary between 40 and 60%. Therefore, the total porosity of the studied soils, considering these ranges, was in the acceptable range for crop production. Furthermore, the total porosity values observed in soils of the study area are generally high and this could be attributed to the high clay content and lower bulk density values of the soils.

The soil water content retained at field capacity (-1/3 bars) and permanent welting point (15 bars) varied from 355.8 to 581.0 and 240.3 to 480.8 mm/m, respectively. Although, the moisture retention varied inconsistently with soil depth, relatively higher values were recorded under the subsurface horizons, while the lowest values were observed in the surface horizons and at the extreme depth of the C-horizons (Table 3). It can clearly be seen that the water retention capacity of the soils at both suctions is relatively high indicating that the soils are slowly draining and waterlogging could be one major problem that requires attention in these soils. This high water retention capacity of the soils could be the result of the high clay content recorded in the study area.

Available water holding capacity (AWHC) showed an increasing trend with soil depth and decreased with topographic positions in most of the pedons. It ranged from

Table 3. Selected physical properties of soils at the WadlaDelanta Massif, North Central Ethiopia.

Pedon	Horizon	Depth	Particle size distribution (%)			Textural	ρb	ρs	TP	FC	PWP	AWHC
		(cm)	Sand	Silt	Clay	class	(g cm^{-3})	(g cm^{-3})	(%)	*(%v/v)*	*(%v/v)*	(mm/m)
MG201	A	0-38	22	26	52	C	1.10	2.63	58.27	49.11	37.88	112.3
	Ass1	38-110	18	24	58	C	1.20	2.52	52.41	54.98	43.69	112.9
	Bss1	110-122	17	23	60	C	1.22	2.52	51.62	58.10	46.08	120.2
	Bss2	122-225+	18	20	62	C	1.23	2.43	49.41	47.72	39.49	82.4
MC202	Ap	0-20	22	26	52	C	1.08	2.58	58.05	48.24	36.53	117.1
	Ass1	20-102	19	22	59	C	1.16	2.59	55.31	55.25	41.32	139.4
	Ass2	102-123	18	20	62	C	1.18	2.44	51.89	54.88	42.04	128.4
	Bss	123-215+	17	17	62	C	1.19	2.44	51.17	52.81	41.53	112.8
UC103	Ap	0-22	21	26	53	C	1.08	2.62	58.67	48.07	28.70	193.7
	Bss1	22-33	18	22	60	C	1.19	2.47	51.87	53.29	29.44	238.5
	Bss2	33-58	12	16	72	HC	1.20	2.42	50.45	53.96	28.97	249.9
	C	58-89+	9	13	78	HC	1.23	2.41	49.05	55.25	28.13	271.3
UC104	Ap	0-23	29	36	35	CL	1.04	2.52	58.55	54.88	42.04	128.4
	Ass1	23-58	31	32	38	CL	1.27	2.51	49.38	55.25	43.32	119.4
	C	58-95+	37	28	35	CL	1.34	2.49	46.15	48.24	39.53	87.1
LG305	A	0-35	18	23	59	C	1.16	2.70	56.92	48.07	24.03	240.3
	Ass1	35-76	14	18	68	HC	1.18	2.65	55.53	53.29	25.65	276.5
	Bss1	76-114	13	15	72	HC	1.19	2.69	55.78	55.58	26.79	287.9
	Bss2	114-205+	10	12	78	HC	1.28	2.57	50.10	55.27	26.63	286.3
LC306	Ap	0-32	25	17	58	C	1.13	2.54	55.41	46.37	33.38	129.9
	Ass1	32-76	21	15	64	HC	1.22	2.52	51.58	52.74	32.42	203.2
	Bss1	76-115	14	10	76	HC	1.27	2.49	49.11	53.90	32.59	213.1
	Bss2	115-216+	12	8	80	HC	1.28	2.43	47.54	55.20	30.29	249.1
LC307	Ap	0-28	27	18	55	C	1.02	2.59	60.55	49.76	28.67	210.9
	Ass1	28-110	23	12	65	HC	1.21	2.46	50.74	53.85	32.26	215.9
	Bss1	110-135	13	14	73	HC	1.24	2.52	50.70	52.40	31.53	208.7
	Bss2	135-208+	14	11	75	HC	1.26	2.50	49.63	55.29	31.46	238.4
MG208	A	0-37	18	27	55	C	1.18	2.82	58.02	52.09	30.06	220.3
	Ass1	37-140	12	24	64	HC	1.23	2.81	56.27	55.09	32.18	229.1
	Bss1	140-189	18	14	68	HC	1.22	2.73	55.19	55.01	31.86	231.6
	Bss2	189-198	18	10	72	HC	1.28	2.60	50.57	59.76	33.52	262.5
	BC	198-245+	24	16	60	C	1.34	2.62	48.89	43.11	31.67	114.4
MC109	A	0-25	28	34	38	CL	1.22	2.72	54.94	53.42	38.31	151.1
	B	25-48	32	28	40	CL	1.29	2.73	52.75	55.05	39.33	157.2
	C	48-75+	38	26	36	CL	1.29	2.72	52.67	47.29	37.51	97.8
UC110	Ap	0-25	22	26	52	C	1.20	2.82	57.61	39.05	27.16	118.9
	Ass1	25-62	18	24	58	C	1.20	2.80	57.06	46.69	34.33	123.6
	Bss	62-78	22	18	62	C	1.23	2.65	53.42	43.72	30.26	134.5
	C	78-99+	38	22	40	CL	1.26	2.66	52.73	35.58	24.20	113.7
MC211	Ap	0-25	22	30	48	C	1.20	2.66	54.74	43.13	32.36	107.7
	Ass1	25-65	15	28	57	C	1.20	2.56	53.11	54.53	37.64	168.9
	Bss	65-95	25	20	55	C	1.22	2.61	53.31	48.16	37.51	106.6
	C	95-115+	34	28	38	CL	1.26	2.56	50.77	47.88	39.66	82.1
UG112	A	0-33	32	35	33	CL	1.27	2.63	51.79	49.48	36.86	126.2
	B	33-47	33	29	38	CL	1.35	2.64	48.96	50.35	35.03	153.2
	C	47-65+	36	29	35	CL	1.34	2.62	48.91	39.95	29.04	109.1

FC = Field capacity; PWP = permanent wilting points; AWHC = available water holding capacity; TP = total porosity; C = clay; HC= heavy clay; Ass/Bss = A/B-horizon and ss = slickenside.

82.1 to 287.9 mm/m (at subsurface). The values of AWHC were influenced by OM and clay contents within the horizons. According to McIntyre (1974) rating of AWHC, the AWHC of the soils varies from very low (<100 mm/m) to high (>200 mm/m).

The soils with higher clay content generally had better available water than those with lower clay content. Clay offers a higher resistance to movement of water because of its high proportion of micro-pores that store water in film or hygroscopically (Edoga, 2010). In line with this, Rawls et al. (2003) found out that for soils with high clay content greater than 19%, the average water retention grows as the clay content increases. Udomet al. (2011) also categorized soils with 70% and above clay content as very poorly drained. Therefore, the presence of appreciable amount of finer fractions in subsurface soils could increase the water holding capacity of the soils and facilitate a longer period of soil water retention for crop utilization. On the other hand, this high water retention could result in waterlogging conditions, thus requiring drainage.

Soil chemical properties

Soil pH, electrical conductivity and calcium carbonate

The results showed that the soil reaction was slightly acidic to moderately alkaline in all the topographic positions (Jones, 2003). The pH-H_2O values varied from 6.25 to 7.53 on the surface horizons and 6.80 to 8.29 in the subsurface soils. In general, the lower topographic positions had relatively higher pH values than the others. This may be due to more accumulation of bases removed from uplands/hill slopes and subsequent depositions at the lower slopes. The pH-H_2O showed an increasing pattern with increasing soil depth, which could be attributed to the downward translocation of basic cations as well as leaching.

The pH-KCl ranged from 5.03 to 6.52 on the surface and 5.16 to 6.80 in subsurface soils. In all the pedons $\triangle$pH (pH-H_2O – pH-KCl) values were positive, ranging from 0.64 to 2.09. This indicates the presence of net negative charge on colloidal particles of the exchange site (Papierniket al., 2007). According to Landon (1991), the soils of the study area had a preferable pH for most crops since most of the essential nutrients become available at pH above 5.5.

All pedons, irrespective of topographic positions, showed very low electrical conductivity which varied from 0.011 to 0.13 dS m^{-1}. Similar to soil pH, it showed an increasing trend with depth and topographic positions.

According to FAO (1988) ratings, the studied soils are categorized under non-saline soils. The lower values of EC in the study area might be due to the combined effect of pH and parent materials.

On the other hand, calcium carbonate ($CaCO_3$) content of the studied soils showed an increasing pattern with soil depth and it ranged from 0.11 to 24.07% (Table 4). The relatively high values (24.07 and 21.32%) recorded in the subsurface horizons of the upper topographic position might be due to the calcareous parent material. Similar findings were reported by Ozsoy and Aksoy(2007), in which case the $CaCO_3$ contents increased with depth. Field determination of carbonates also confirmed that there were clear and visible fizzes when tested with diluted (10%) HCl.

Organic matter, total nitrogen, C:N ratio and available phosphorus

Soil organic matter (OM) content varied from 0.21 to 3.19% in the upper altitude, 0.12 to 4.82% in the upper, middle, and lower topographic position pedons, respectively. The soil OM content was generally higher in the surface (1.51 to 4.82%) horizons than the subsurface (0.12 to 2.13%) horizons, decreasing with depth in all the pedons. This could be ascribed to biomass effects on surface horizons and fallowing practiced especially at the (upper) and (middle) topographic positions. According to Tekalign (1991) ratings, soil OM content of soils of the study area was in the range of very low to low in all the pedons, except for the pedons opened on grassland (UG12 and MG01) which was in the range of medium (Table 5).

Total nitrogen (N) varied from 0.02 to 0.18, 0.03 to 0.23 and 0.03 to 0.11% in the upper, middle, and lower topographic positions, respectively. Its variation with soil depth followed that of soil organic matter. According to Tekalign (1991) ratings, the total N content of the studied soils was categorized under very low to medium ranges. This indicates low N release from the OM sources since soil N is positively correlated with soil OM content. Similar results were reported by Allotey *et* al. (2008) in that over 90% of N found in soils is in organic form. Hartz (2007) revealed that soils with < 0.07% total N have limited N mineralization potential, whereas those having > 0.15% total N would be expected to mineralize sufficient amount of N during the succeeding crop cycle showing that most of the soils have good potential of N mineralization.

The carbon to nitrogen ratio (C:N) showed irregular distribution with soil depth and topographic positions.In some cases, the C:N ratio of the studied soils was relatively higher than the common range (8:1-15:1) for arable soils proposed by Brady and Weil (2008). Such high C:N ratio of the soils indicates that OM of the soils was not fully decomposed and N loss was apprehended.

These differences among the pedons could be ascribed to the effect of variation in land uses along the toposequence. Intensive and continuous cultivation aggravates OM oxidation resulting in reduction of total N as compared to virgin, grass and fallow lands. Variations in available

Table 4. Soil pH, electrical conductivity and calcium carbonate at the WadlaDelanta Massif, North Central Ethiopia.

Pedon	Hori zon	Depth (cm)	pH (1:2.5)			EC (dS m^{-1})	$CaCO_3$ (%)
			H_2O	KCl	△pH		
MG201	A	0-38	6.72	5.45	1.27	0.020	2.84
	Ass1	38-110	7.23	6.21	1.02	0.024	3.56
	Bss1	110-122	7.56	6.38	1.18	0.037	9.34
	Bss2	122-225+	7.73	6.00	1.73	0.034	3.56
MC202	Ap	0-20	6.98	5.65	1.33	0.012	2.63
	Ass1	20-102	7.05	5.97	1.08	0.013	3.54
	Ass2	102-123	7.21	6.14	1.07	0.013	4.76
	Bss	123-215+	7.92	6.50	1.42	0.130	4.81
UC103	Ap	0-22	6.99	5.69	1.30	0.020	3.93
	Bss1	22-33	7.66	5.75	1.91	0.022	5.17
	Bss2	33-58	7.99	6.45	1.54	0.029	9.54
	C	58-89+	8.12	6.47	1.65	0.033	12.72
UC104	Ap	0-23	6.57	5.17	1.40	0.013	3.24
	Ass1	23-58	7.78	6.24	1.54	0.016	5.11
	C	58-95+	8.02	6.63	1.39	0.017	24.07
LG305	A	0-35	7.16	6.52	0.64	0.046	5.37
	Ass1	35-76	7.78	6.59	1.19	0.047	8.52
	Bss1	76-114	7.88	6.63	1.25	0.048	17.36
	Bss2	114-205+	8.07	6.65	1.42	0.052	6.94
LC306	Ap	0-32	6.73	5.42	1.31	0.013	3.44
	Ass1	32-76	7.55	5.46	2.09	0.018	3.90
	Bss1	76-115	8.01	6.26	1.75	0.027	9.65
	Bss2	115-216+	8.11	6.18	1.93	0.028	9.59
LC307	Ap	0-28	6.83	5.12	1.71	0.012	2.97
	Ass1	28-110	7.39	5.67	1.72	0.011	3.09
	Bss1	110-135	8.09	6.46	1.63	0.023	12.02
	Bss2	135-208+	8.17	6.43	1.74	0.028	11.21
MG208	A	0-37	6.25	5.36	0.89	0.012	3.95
	Ass1	37-140	6.80	5.71	1.09	0.017	4.06
	Bss1	140-189	6.95	5.91	1.04	0.022	4.17
	Bss2	189-198	7.15	6.15	1.00	0.025	4.66
	BC	198-245+	7.60	6.40	1.20	0.027	2.09
MC109	Ap	0-25	7.00	5.21	1.79	0.015	0.11
	B	25-48	7.18	5.58	1.60	0.018	0.22
	C	48-75+	7.59	5.87	1.72	0.024	0.45
UC110	Ap	0-25	6.51	5.31	1.20	0.013	3.74
	Ass1	25-62	7.09	5.38	1.71	0.012	21.32
	Bss	62-78	8.11	6.60	1.51	0.024	15.21
	C	78-99+	8.19	6.80	1.39	0.025	15.12
MC211	Ap	0-25	6.90	5.33	1.57	0.023	2.75
	Ass1	25-65	7.26	6.01	1.25	0.024	3.74
	Bss	65-95	8.07	6.33	1.74	0.039	4.02
	C	95-115+	7.96	6.26	1.70	0.034	2.93
UG112	A	0-33	6.78	5.03	1.75	0.012	1.58
	B	33-47	6.84	5.16	1.68	0.013	2.54
	C	47-65+	7.60	6.60	1.00	0.021	1.24

∆pH = pH (H_2O –KCl); EC = Electrical conductivity; $CaCO_3$ = Calcium carbonate.

Table 5. Soil organic matter, total nitrogen, C:N ratio and available phosphorous at the Wadla Delanta Massif, North Central Ethiopia.

Pedon	Horizon	Depth (cm)	Soil OM (%)	Total N (%)	C:N ratio	Av. P (mg kg^{-1})
MG201	A	0-38	4.82	0.23	12	18.39
	Ass1	38-110	2.14	0.12	10	10.88
	Bss1	110-122	1.09	0.04	16	3.48
	Bss2	122-225+	0.52	0.03	10	2.83
MC202	Ap	0-20	1.71	0.12	8	10.36
	Ass1	20-102	1.91	0.08	14	8.73
	Ass2	102-123	1.26	0.05	15	3.63
	Bss	123-215+	0.86	0.04	13	1.52
UC103	Ap	0-22	1.88	0.10	11	12.53
	Bss1	22-33	1.60	0.07	14	10.33
	Bss2	33-58	1.05	0.05	13	6.30
	C	58-89+	0.69	0.03	13	5.45
UC104	Ap	0-23	2.03	0.11	11	10.92
	Ass1	23-58	1.29	0.06	12	11.68
	C	58-95+	0.74	0.02	17	2.56
LG305	A	0-35	2.05	0.12	10	18.44
	Ass1	35-76	1.29	0.07	11	8.86
	Bss1	76-114	1.17	0.05	15	8.33
	Bss2	114-205+	0.67	0.03	13	2.61
LC306	Ap	0-32	2.14	0.11	12	14.01
	Ass1	32-76	2.03	0.11	11	14.73
	Bss1	76-115	1.41	0.06	14	4.75
	Bss2	115-216+	0.69	0.03	13	4.75
LC307	Ap	0-28	1.71	0.07	13	7.30
	Ass1	28-110	1.67	0.06	17	7.19
	Bss1	110-135	0.69	0.03	13	5.64
	Bss2	135-208+	0.55	0.03	10	5.83
MG208	A	0-37	1.97	0.14	8	14.53
	Ass1	37-140	1.91	0.11	10	2.10
	Bss1	140-189	1.62	0.08	12	2.04
	Bss2	189-198	1.55	0.05	20	1.98
	BC	198-245+	1.02	0.03	19	1.05
MC109	Ap	0-25	1.64	0.09	10	11.80
	B	25-48	1.57	0.11	8	4.53
	C	48-75+	0.12	0.03	2	3.36
UC110	Ap	0-25	2.76	0.12	13	9.84
	Ass1	25-62	1.84	0.09	12	1.92
	Bss	62-78	1.34	0.05	16	2.00
	C	78-99+	1.02	0.03	18	2.07
MC211	Ap	0-25	2.33	0.18	5	8.44
	Ass1	25-65	1.55	0.11	8	8.19
	Bss	65-95	0.67	0.03	13	2.33
	C	95-115+	0.53	0.03	11	3.11
UG112	A	0-33	3.19	0.18	10	10.46
	B	33-47	1.91	0.07	15	11.00
	C	47-65+	0.21	0.03	4	6.15

OM = Organic matter; N = Nitrogen; C:N = Carob to nitrogen ration; Av .P. = Available phosphorus.

phosphorus with soil depth and along the toposequence were also observed. Accordingly, it ranged from 1.92 to 11.68, 1.05 to 18.39 and 2.61 to 18.44 mg kg^{-1}, respectively, in pedons of the upper, middle and lower topographic positions. In general, available P showed an increasing trend down the topographic position and a decreasing trend with depth, which might be attributed to an increase in clay content and a decrease in soil OM content. The surface soils had relatively higher available P (7.30 to 18.44 mg kg^{-1}) than the subsurface soils (1.05 to 14.73 mg kg^{-1}). This might be due to better levels of soil OM content at the surface layers and application of P fertilizers. As per available P ratings suggested by Cottenie (1980), the available P content of soils of the study area falls under very low to low category in most of the pedons indicating that available P could be one of the most limiting nutrients for crop production in the study area.

Exchangeable bases, cation exchange capacity and percent base saturation

The extent of exchangeable bases followed unsystematic pattern of distribution along the toposequence. However, the trends showed an increase with soil depth for all the exchangeable bases except for exchangeable K resulting in high base accumulation in the subsurface horizons. This might be due to the existence of Ca and Mg bearing parent materials, the leaching process and the presence of K rich primary minerals. Therefore, exchangeable K is adequate for the production of most crops and K deficiency would not be expected in soils of the study area. Similar findings were reported by Ashenafiet al. (2010) who stated that the increment of exchangeable bases with depth was due to leaching process.The abundance of exchangeable bases on the exchange complex followed the order Ca> Mg > K > Na throughout the pedons. According to FAO (2006b) ratings, the exchangeable bases were high to very high for Caand Mg, medium to very high for K, and medium to high for Na for all the pedons.

The values of CEC at the surface and subsurface horizons were high for all pedons, which might be related to the soil OM and high clay contents, respectively. On the surface soils, it ranged from 31.98 to 48.06 cmolc kg^{-1}, while it varied from 32.16 to 65.48 cmolc kg^{-1} in the subsurface soils. In accordance with Landon (1991) ratings, it has high to very high ranges (Table 6). This relatively high CEC indicates good nutrient retention and buffering capacity of soils of the study area.

Following the high to very high exchangeable bases recorded in soils of the study area, the base saturation (BS) was also high. Landon (1991) rated soils having base saturation that is greater than 60% as fertile soils. In accordance with this rating, soils of the study area with their high BS can be categorized as fertile soils. Furthermore more, as per Hazelton and Murphy (2007) ratings, the BS of the studied soils varies between high to very high range.

Extractable micronutrients

The results obtained show that the extractable micronutrients in all the pedons decreased with increasing soil depth and values were in the order of Fe >Mn> Zn > Cu in all topographic positions. However, there were some cases where Mn> Fe, and Cu > Zn (Table 7). The extractable micronutrients of the surface soils were higher than the subsurface soils due probably to the relatively higher soil OM content in the surface soils. According to Jones (2003) ratings, the extractable micronutrients of the studied soils are categorized under low to high in Fe and Cu, medium in Mn, and medium to high in Zn (Table 7). In general, the extractable micronutrients content of most of the studied soils was above the critical levels of the respective micronutrients, implying that there is no urgent need for available micronutrients application for the time being.

Soil classification based on FAO-WRB system

Based on morphological, physical and chemical properties, the soils were classified according to FAO-WRB (2006) system (Table 8 and Figure 4). As the result shows most of the pedons have well developed structure (granular or fine sub angular blocky), dark colored sur-face horizons having a chroma of ≤ 3 and a value of ≤ 3 when moist, and ≤ 5 when dry. The surface layers of the pedons had more than 0.6% organic carbon; base satu-ration (by 1M NH_4OAc) of 50% or more throughout the horizon; pH-H_2O value of 6 or more; minimum thickness of 20 cm or more. All these satisfy the diagnostic criteria for Mollic horizon.

PedonMC09 and UG12 have limited soil depth, with continuous rock within 25 cm of the soil surface. Less than 20% (by volume) of fine textured materials was found in the upper 75 cm of the soil surface or extremely gravelly whichever is shallower; and no calcic, gypsic or spodic horizon. The pedon are located at high altitude (above 3000 m) and with strongly dissected topography. As a result, Pedons MC109 and UG12 qualify for reference soil group (RSG) Leptosols. The pedon were having a base saturation (by 1M NH_4OAc) of 50% or more throughout their profile and therefore qualifies for Mollic Leptosols (Eutric). Pedons UC03 and UC04, on the other hand have petro-calcic horizon to a contrasting layer between 50 and 100 cm, 30% or more clay,crack periodically, with intersecting slickensides and a thickness of 25 cm or more which qualify for reference soil group (RSG)Vertisols.They developed foam upon addition of 1 M HCl, indicating a calcium carbonate equivalent near or more than 15% which qualifies for calcic subsurface

Table 6. Exchangeable bases, cation exchange capacity and percent base saturation at the WadlaDelanta Massif, North Central Ethiopia.

Pedon	Horizon	Depth	Exchangeable cations and CEC (cmolc kg^{-1})					PBS
		(cm)	Ca	Mg	K	Na	CEC	(%)
MG201	A	0-38	23.72	6.58	0.65	0.26	31.98	97.59
	Ass1	38-110	27.40	10.76	0.60	0.59	44.94	87.57
	Bss1	110-122	26.65	8.84	0.56	1.04	60.76	61.04
	Bss2	122-225+	25.28	7.12	0.54	1.11	41.76	81.52
MC202	Ap	0-20	22.12	7.62	0.63	0.37	33.34	92.20
	Ass1	20-102	27.72	10.08	0.62	0.58	43.74	89.16
	Ass2	102-123	27.85	8.48	0.38	0.74	39.74	94.24
	Bss	123-215+	21.61	7.88	0.28	0.96	37.40	82.17
UC103	Ap	0-22	19.37	7.24	0.82	0.58	41.33	67.77
	Bss1	22-33	29.56	7.45	0.85	0.82	47.67	81.14
	Bss2	33-58	29.83	8.25	0.78	1.00	44.33	89.92
	C	58-89+	24.41	8.42	0.72	1.03	39.67	87.17
UC104	Ap	0-23	22.36	8.86	0.69	0.29	40.22	80.06
	Ass1	23-58	26.32	13.94	0.62	0.52	51.74	80.02
	C	58-95+	29.43	6.55	0.42	0.54	44.06	83.85
LG305	A	0-35	20.78	7.70	2.01	0.59	32.18	96.59
	Ass1	35-76	30.22	7.35	1.51	0.63	62.17	64.04
	Bss1	76-114	31.88	8.58	1.39	0.73	47.03	90.52
	Bss2	114-205+	23.15	8.14	0.45	0.96	34.94	93.60
LC306	Ap	0-32	24.28	6.58	0.91	0.29	36.16	88.67
	Ass1	32-76	24.71	7.64	0.85	0.82	37.34	91.10
	Bss1	76-115	28.28	7.40	0.82	1.03	46.28	81.08
	Bss2	115-216+	25.44	7.32	0.83	1.22	40.34	86.28
LC307	Ap	0-28	18.22	8.08	0.98	0.33	44.14	62.55
	Ass1	28-110	23.81	9.60	0.85	0.59	38.16	91.32
	Bss1	110-135	33.48	5.80	0.80	1.03	58.34	70.47
	Bss2	135-208+	32.23	6.36	0.76	1.14	45.14	89.71
MG208	A	0-37	23.85	7.86	0.93	0.53	40.20	82.50
	Ass1	37-140	25.58	9.86	1.03	0.80	45.68	81.58
	Bss1	140-189	32.50	7.53	0.99	0.96	65.48	64.10
	Bss2	189-198	31.03	7.64	0.82	1.02	40.94	98.97
	BC	198-245+	25.65	5.83	0.33	1.14	49.89	66.04
MC109	Ap	0-25	26.02	6.22	1.05	0.33	47.62	70.59
	B	25-48	25.04	8.02	0.66	0.56	52.14	65.75
	C	48-75+	21.80	7.76	0.36	0.76	32.16	95.39
UC110	Ap	0-25	20.72	6.52	1.29	0.41	48.06	60.22
	Ass1	25-62	31.61	6.82	0.84	0.65	61.26	65.16
	Bss	62-78	32.06	7.82	0.79	0.94	60.74	68.51
	C	78-99+	31.49	5.68	0.44	1.14	56.58	68.49
MC211	Ap	0-25	20.58	6.56	0.98	0.57	35.68	80.42
	Ass1	25-65	25.47	8.36	0.88	0.77	58.72	60.41
	Bss	65-95	27.61	8.02	0.75	1.20	52.14	72.08
	C	95-115+	31.92	6.15	0.24	1.15	45.74	86.28
UG112	A	0-33	17.74	7.82	0.73	0.52	44.06	60.85
	B	33-47	18.34	7.94	0.66	0.66	42.26	65.31
	C	47-65+	26.56	8.50	0.22	0.85	55.96	64.55

CEC = Cataion exchangeable capacity; PBS = percent base saturation.

Table 7. Extractable micronutrient contents at the WadlaDelanta Massif, North Central Ethiopia.

Pedon	Horizon	Depth (cm)	Micronutrients (mg kg^{-1})			
			Mn	Fe	Cu	Zn
MG201	A	0-38	4.80	4.81	3.80	2.40
	Ass1	38-110	4.60	1.22	1.21	2.03
	Bss1	110-122	4.01	1.23	1.21	1.21
	Bss2	122-225+	2.01	0.82	0.82	0.82
MC202	Ap	0-20	5.60	6.01	2.01	3.61
	Ass1	20-102	6.02	6.03	1.20	3.80
	Ass2	102-123	5.81	3.01	0.82	3.60
	Bss	123-215+	2.22	1.21	0.82	0.82
UC103	Ap	0-22	5.87	6.02	3.22	3.00
	Bss1	22-33	7.07	7.27	3.67	3.87
	Bss2	33-58	5.13	5.15	2.27	2.80
	C	58-89+	4.07	3.88	2.40	1.20
UC104	Ap	0-23	7.60	8.80	4.81	3.61
	Ass1	23-58	6.05	6.01	0.83	3.60
	C	58-95+	5.61	4.01	0.80	2.80
LG305	A	0-35	4.62	6.22	2.07	3.05
	Ass1	35-76	7.62	9.20	2.80	5.80
	Bss1	76-114	4.73	5.60	2.21	2.40
	Bss2	114-205+	2.03	3.81	1.21	1.08
LC306	Ap	0-32	5.20	5.22	4.40	2.50
	Ass1	32-76	5.60	5.80	4.01	3.94
	Bss1	76-115	4.03	4.04	2.02	1.23
	Bss2	115-216+	4.80	4.22	3.60	1.60
LC307	Ap	0-28	6.81	6.82	3.22	2.85
	Ass1	28-110	8.02	8.18	5.82	3.80
	Bss1	110-135	5.61	7.41	4.01	3.60
	Bss2	135-208+	5.21	6.81	2.81	1.20
MG208	A	0-37	9.20	10.40	6.03	4.26
	Ass1	37-140	6.81	6.82	4.01	5.20
	Bss1	140-189	6.50	5.88	3.81	2.85
	Bss2	189-198	6.02	5.69	3.75	1.20
	BC	198-245+	4.02	4.60	1.20	0.80
MC109	Ap	0-25	6.01	6.02	2.41	3.61
	B	25-48	5.60	6.00	2.41	2.80
	C	48-75+	5.60	5.81	1.21	1.20
UC110	Ap	0-25	8.40	10.00	6.00	4.41
	Ass1	25-62	7.02	7.60	5.22	5.01
	Bss	62-78	6.88	7.22	5.20	3.60
	C	78-99+	5.22	3.20	0.82	3.20
MC211	Ap	0-25	9.22	9.22	3.20	4.01
	Ass1	25-65	6.61	7.81	2.81	4.00
	Bss	65-95	6.40	6.54	1.20	2.80
	C	95-115+	3.20	4.81	0.82	1.30
UG112	A	0-33	7.20	7.80	3.20	3.60
	B	33-47	7.21	6.81	1.21	2.80
	C	47-65+	6.02	5.41	1.21	1.20

diagnostic horizon and having hard to very hard structure, finer than very coarse granular in the upper 20 cm of the soils that fulfill the criteria of Mazic prefix qualifier. Therefore, the Pedons are classified as Mazi-Calcic Vertisols (Eutric).

Among the upper pedons, Pedon UC10 showed color alteration and had higher chroma and value (moist), redder hue, higher clay content in its subsurface horizon than the overlying and underlying layers, less carbonate than an underlying horizon and loamy very fine sand. The layer was an altered horizon more than 15 cm in thickness with a clay loam texture and moderately developed structure, genetically young subsurface horizon. The pedon had been identified as having cambic subsurface horizon. This pedon qualifies for RSG Cambisols. The pedon were also having a base saturation (by 1M NH_4OAc) of 50% or more throughout the profile fulfilling the requirements for eutric suffix, but not visible prefix qualifier. Thus, the pedons were classified as Haplic Cambisols (Eutric).

The subsurface horizons of the middle and lower topographic pedons (Pedens 01, 02, 08 and 05, 06, 07, respectively) qualify for a vertic horizon starting within 100 cm of the soil surface; the upper 20 cm have been mixed; containing 30% or more clay throughout the profile; formation of slickensides and wedge-shaped structural aggregates in the subsurface soil; alternate swelling and shrinking of clays resulting in deep wide cracks that open and close periodically and gilgai micro-relief. These criteria meet the requirements for vertic subsurface diagnostic horizon. The soils therefore qualify for RSG Vertisols. The pedons were having hard to very hard structure, finer than very coarse granular structure in the upper 20 cm of the soils that fulfill the criteria of Mazic prefix qualifier and therefore are classified as Mazi Vertisols (Eutric) which had base saturation (by 1M NH_4OAc) of 50% or more throughout the horizon, having in the upper 30 cm of the soil, a Munsell value of 3.5 or less and a chroma of 1.5 or less when moist. They fulfill the criteria of Pellic prefix and hypereutric suffix qualifiers, thus classified as Mazi-Pellic Vertisols (Hypereutric) (Table 8).

Conclusions

The studied soils are formed from Oligocene rhyolite and very thick ignimbrite units mainly from alkaline basalt parent materials and highly influenced by topography. The measured morphological, physical, and chemical properties exhibited spatial variations of different degrees with soil depth in a pedon and along the toposequence. This indicates the existence of different degrees of limitations, potentials and management requirements, the consideration of which is fundamental for sustainable use of soil resources in the study area. Based on morpholo-

Table 8. Diagnostic horizons, properties, quantifiers and soil types of the study area according to FAO-WRB soil classification system

Pedon	Diagnostic horizon		Diagnostic properties	Soil types
	Surface	Subsurface		
MG201	Mollic	Vertic	Vertic	MaziPellicVertisols (Hypereutric)
MC202	Mollic	Vertic	Vertic	MaziPellicVertisols (Hypereutric)
UC103	Mollic	Calcic	Vertic	Mazi Calcic Vertisols (Eutric)
UC104	Mollic	Calcic	Vertic	Mazi Calcic Vertisols (Eutric)
LG305	Mollic	Vertic	Vertic	MaziPellicVertisols (Hypereutric)
LC306	Mollic	Vertic	Vertic	MaziPellicVertisols (Hypereutric)
LC307	Mollic	Vertic	Vertic	MaziPellicVertisols (Hypereutric)
MG208	Mollic	Vertic	Vertic	MaziPellicVertisols (Hypereutric)
MC109	Mollic	-	-	MollicLeptosols (Eutric)
UC110	-	Cambic	Vertic	HaplicCambisols (Eutric)
MC211	Mollic	Vertic	Vertic	MaziPellicVertisols (Eutric)
UG112	Mollic	-	-	MollicLeptosols (Eutric)

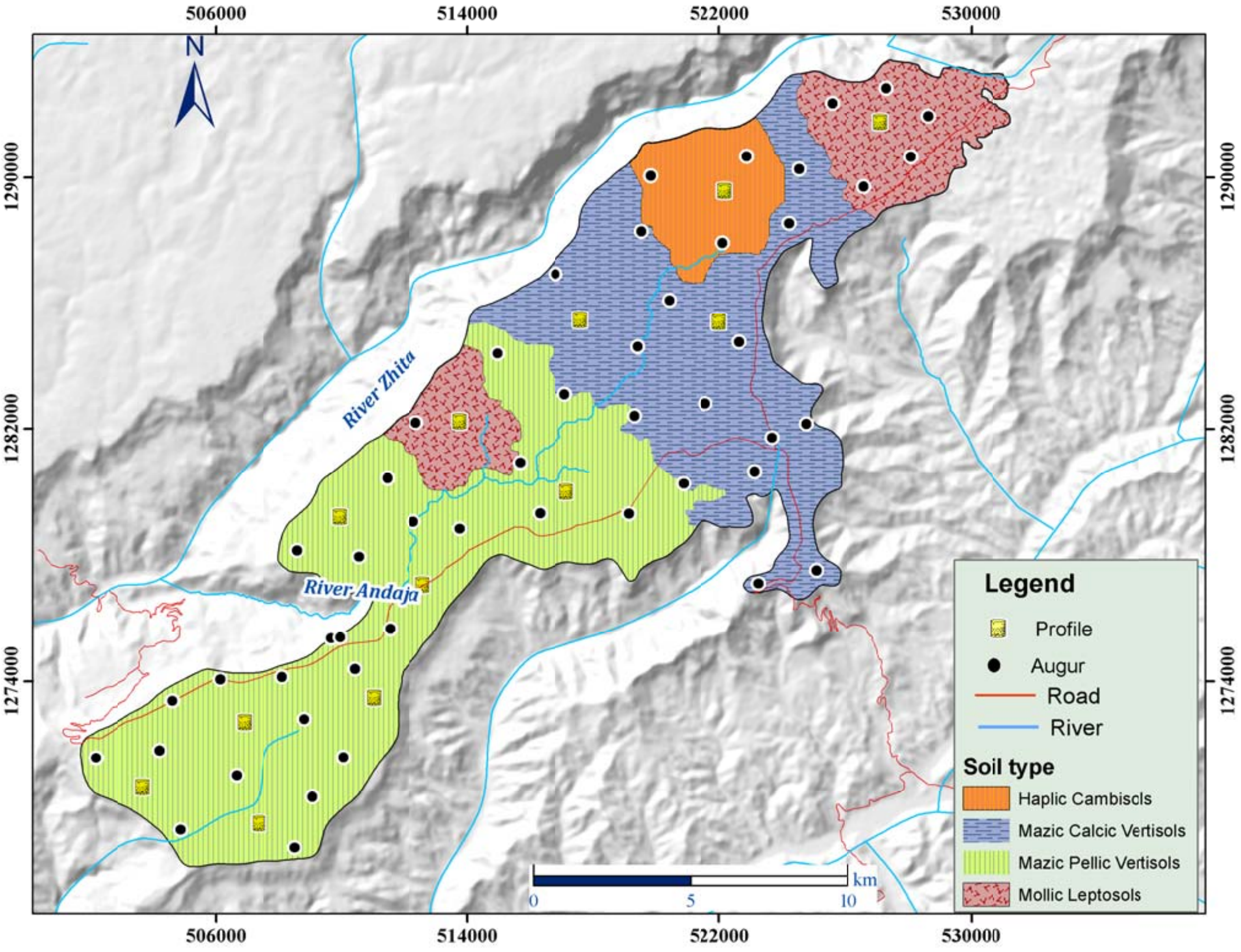

Figure 4. Soil map of the study area.

gica, physical, and chemical properties, and following the FAO-WRB classification and correlation system, the soils are classified as Mollic Leptososl, Haplic Cambisols, Mazi-Calcic Vertisols, and Mazi-Pellic Vertisols.

Conflict of Interests

The author(s) have not declared any conflict of interests.

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REFERENCES

Abayneh E (2005). Characteristics, genesis and classification of reddish soils from Sidamo Region of Ethiopia. A PhD Dissertation, Putra Malaysia University.

Allotey DFK, Asiamah RD, Dedzoe CD, Nyamekye AL (2008). Physicochemical properties of three salt affected soils in the Lower Volta Basin and management strategies for their sustainable utilization.West Afr. J. Appl. Ecol.12: 1-14.

Amhakhian SO, Achimugu S (2011). Characteristics of soil on toposequence in Egume, Dekina local Government Area of Kogi State.Prod. Agric. Technol.7 (2): 29-36.

Ashenafi A, Abayneh E, Sheleme B (2010). Characterizing soils of DelboWegene watershed, Wolaita Zone, Southern Ethiopia for planning appropriate land management.J. Soil Sci. Environ. Manag.1(8): 184-199.

Baruah TC, Barthakur HP (1997). A Textbook of Soil Analysis. Vikas Publishing House. Pvt. Ltd. New Delhi, India.

Basava RD, Naidu MVS, Ramavatharam N, Venkaiah K, Rama Rao G, Reddy KS (2005). Characterization, classification and evaluation of soils in Chandragirimandal of Chittoor District, Andhra Pradesh.Agropedology15:55-62.

BlackGR, Hartge KH (1986).Bulk density in methods of soil analysis. In: A. Klute, (editor),Part 1. Physical and mineralogical methods, American Society of Agronomy-Soil Science Society of America, Madison, Wiscosin, USA.

Bouyoucos GJ (1962). Hydrometer method improved for making particle size analysis of soils. Agron. J. 54: 464-465.

Brady NC, Weil RR (2008). The Nature and Properties of Soils.14th edition.Pearson Education International, Upper Saddle River, New Jersey.

Braimoh AK (2002).Integrating indigenous knowledge and soil science to develop a national soil classification system for Nigeria. Agric.Hum. Values 19: 75-80.

Bremner JM, Mulvaney CS (1982).Nitrogen total in methods of soil analysis. In: A.L. Page (editor) Part 2.Chemical and microbiological properties.Soil Science Society of America, Madison, USA.

Buol SW, Southard RJ, Graham RC, McDaniel PA (2011).Soil Genesis and Classification.6th edition.John Wiley and Sons, Inc.

Buol SW, Denton HP (1984).The role of soil classification in technology transfer.In: R.B. Grossman, R.H. Rust and H. Eswaran. Soil Taxonomy-achievements and challenges. Soil Science America Special Publication 14. Soil Science Society of America, Madison, Wisconsin.

Cottenie (1980).Soil and plant testing as a basis of fertilizer recommendations.FAO soil bulletin 38/2.Food and Agriculture Organization of the United Nations, Rome, Italy.

Dengiz O, Sağlam M, Sarioglu FE, Saygin F, Atasoy C (2012). Morphological and physicochemical characteristics and classification of Vertisols developed on Deltaic Plain.Open J. Soil Sci. 2: 20-27.

Dereje A, Barbey P, Marty B, Reisberg L, Gezahegn Y, Pik R (2002). Source, genesis and timing of giant ignimbrite deposits associated with Ethiopian continental flood basalts. Elsevier Science Ltd, Geochim. Cosmchim.Acta 66(8): 1429-1448.

Edoga RN (2010).Comparison of saturated hydraulic conductivity measurement methods for Samaru-Nigeria Soils.LibyanAgric. Res. Center J. Int.1 (4): 269-273.

Eylachew Z (1987). Study on phosphorous status of different soil types Chercher highlands, southeastern Ethiopia. A PhD Dissertation, Justus Leibing University, Germany.

Eylachew Z (1999). Selected physical, chemical and mineralogical characteristics of major soils occurring in Chercher highlands, Eastern Ethiopia.Ethiop. J. Nat. Resour. 1(2):173-185.

FAO (Food and Agriculture Organization) (1984). Ethiopia geomorphology and soils: Assistance to land use planning. Food and Agriculture Organization of the United Nations, Rome, Italy

FAO (Food and Agriculture Organization) (1988).Salt-affected soils and their management.FAO Soil Bulletin 39, Rome, Italy.

FAO (Food and Agriculture Organization) (2006a).Guidelines for soil description.4th edition. Rome, Italy.

FAO (Food and Agriculture Organization) (2006b). Plant nutrition for food security: A guide for integrated nutrient management. Fertilizer and Plant Nutrition Bulletin 16, Rome, Italy.

FAO-WRB (Food and Agriculture Organization-World Reference Base for Soil Resources) (2006). A framework for intenational classification, correlation and communication.2ndedition.*World Soil Resources Reports,* No 103. Rome, Italy.

Gupta PK (2004). Soil, plant, water and fertilizer analysis.AGROBIOS Publisher, India.

Hartz TK (2007). Soil Testing for Nutrient Availability. Procedures and Interpretation for California Vegetable Crop Production.University of California.

Hazelton P, Murphy B (2007). Interpreting Soil Test Results: What do all the numbers mean? 2ndEdition.CSIRO Publishing.

Jackson ML (1970). Soil Chemical Analysis. Prentice-Hall Inc.

Jones JB (2003). Agronomic handbook: management of crops, soils, and their fertility. CRC Press, Boca Raton, Florida, USA.

Lambin G, Esu IE (2011). Characteristics and Management Problem of Vertisoils in the Nagerian Savannah.

Landon JR (1991). Booker tropical soil manual: A handbook for soil survey and agricultural land evaluation in the tropics and subtropics. Longman Scientific and Technical Publishers, New York.

Lawal BA, Ojanuga AG, Tsado PA, Mohammed A (2013).Characterization, classification and agricultural potentials of soils on a toposequence in Southern Guinea Savanna of Nigeria. Int. J. Biol. Vet. Agric. Food Eng. 7(5): 148-152

Lindsay WL, Norvell WA (1978). Development of DTPA soil test for zinc, iron, manganese and copper.Soil Sci. Soc. Am. 42: 421-428.

McIntyre DS (1974).Water retention and moisture characteristics. In: J. Loveday (editor). Methods for analysis of irrigated soils. Technical communication No 54. Commonwealth Agricultural Bureau,farnham Royal, England.

Michael AM (2008). Irrigation Theory and Practice 2nd Edition.Vikas publishing house, PVT LTD.

Mitiku H (1987). Genesis, characteristic and classification of the Central Highland soils of Ethiopia. A PhD Dissertation, State University of Ghent, Belgium.

Mohammed A (2003). Land suitability evaluation in the Jelo Catchment, Chercher Highlands of Ethiopia.A PhD Dissertation, University of Free State, Blomfontein, South Africa.

Mohr PA (1971).The Geology of Ethiopia.HaileSellassie I University Press. Addis Ababa, Ethiopia.

Moradi S (2013). Impact of organic carbon on consistene limits in different soil textures. Int. J. Agric. Crop Sci. 5(12):1381-1388.

Msanya BM, Kaaya AKS, Araki Otsuka H, Nyadzi GI (2003).

Pedological characteristics, general fertility and classification of some benchmark soils of Morogoro District, Tanzania. Afr. J. Sci. Technol.(Science and Engineering Series) 4(2):101-112.

Mulugeta D, Sheleme B (2010). Characterization and classification of soils along the toposequence of KindoKoye Watershed in Southern Ethiopia.East Afr. J. Sci.4 (2):65-77.

Munsell Soil Color Charts (1994). Revised edition Macbeth Division of Kollmorgen Corporation, Baltimore, Maryland.Munsell Color Company Inc., Batimore 18, Maryland, USA.

Nuga BO, Eluwa NC, Akinbola GE (2008). Characterization and classification of soils along a Toposequence in Ikwuano Local Government Area of Abia State, Nigeria.Electronic J. Environ. Agric. Food Chem. 7(3):2779-2788.

Olsen SR, Cole CV, Watanabe FS, Dean LA (1954).Estimation of available phosphorous in soils by extraction with Sodium Bicarbonate. USDACircular 939: 1-19.

Ozsoy G, Aksoy E (2007). Characterization, classification and agricultural usage of Vertisols developed on Neogen Aged Calcareous Marl Parent Materials. J. Biol. Environ. Sci.1(1): 5-10.

Papiernik SK, Lindstrom MJ, Schumacher TE, Schumacher J, AMalo DD, Lobb DA (2007). Characterization of soil pedons in a landscape affected by long-term tillage.Soil Tillage Res.93: 335-345.

Prasad MR, Govardhan V (2011).Characterization and classification of soil and land resource environments of Deccan Plateau.J. Res. ANGRAU39 (1/2): 1-5.

Rai MM (2002). Principles of soil sciences.4thedition.Macmillan, Indian Ltd.

Rawls WJ, Pachepsky YA, Ritchie JC, Sobecki TM, Bloodworth H (2003).Effect of soil organic carbon on soil water retention.Geoderma 116: 61-76.

Sharu MB, Yakubu M, Noma SS, Tsafe AI (2013). Characterization and classification of soils on an agricultural landscape in Dingyadi District, Sokoto State, Nigeria. Niger. J. Basic Appl. Sci. 21(2): 137-147.

Singh IS, Agarwal HP (2003). Characteristics and classification of some rice growing soils of Chandauli district of Uttar Pradesh. Agropedology 13: 11-16.

Skopp MS (2002).Physical properties of primary particles. CRCPress.LLC.

Tekalign T (1991).Soil, plant, water, fertilizer, animal manure and compost analysis.Working document No. 13.International Livestock Research Center for Africa, Addis Ababa.

Thangasamy A, Naidu MVS, Ramavatharam N, Reddy CR (2005). Characterization, classification and evaluation of soil resources in SivagiriMicrowatershed of Chittoor District in Andhra Pradesh for sustainable land use planning. J. Indian Soc. Soil Sci.53(1):11-21.

Udom BE, Chukwu GO, Nuga BO (2011). Soil water retention, infiltration and aggregate stability of a seasonally flooded vertisol under intensive cattle grazing.J. Adv. Dev. Res.2(2):158-166.

Van Reeuwijk LP (1993). Procedures for soil analysis.4th edition.International Soil Reference and Information Center, the Netherlands.

Walkley A, Black TA (1934). An examination of digestion Jarett method for determining soil organic matter and proposed modification of the chromic acid titration method. Soil Sci. Soc. Am. J.37: 29-38.

WAOR (Wereda Agricultural Office Report). (2013). DelantaWereda Agriculture and Natural Resource Development Department Office Report. Wegeltena, Ethiopia.

White PF, Oberthur T, Sovuthy P (1997). Soils used for rice production in Cambodia. A manual for their recognition and management. Manila (Philippines): International Rice Research Institute.