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Full Length Research Paper

Characterizing soils of Delbo Wegene watershed, Wolaita Zone, Southern Ethiopia for planning appropriate land management

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The soils of the Delbo Wegene watershed of Southern Ethiopia were characterized along toposequence for the development of land management plan for sustainable soil management practices. Four pedons along toposequence were studied. Delbo Wegene watershed is located between 06°52' 45.9'' and 06°53'34.8'' N latitude and between 37°48' 10.5'' and 37°48'42.4''E longitude, with altitude ranging from 2100 to 2300 m.a.s.l. The soils were generally dark reddish brown to very dark brown and very deep (> 150 cm). The overall friable consistency, low bulk density (1.0 to 1.26 gm/cm^3), sub angular to angular blocky structure, high total porosity (53 to 61%) indicated that the soils have good physical condition for plant growth. The soils were slightly (pH: 5.8) to moderately acidic (pH: 6.4). Organic carbon content, available micronutrients and cation exchangeable capacity of the soils decrease with soil depth. However, exchangeable cations increase with increasing soils depth. Available phosphorus content of the soils ranged from very low to high. However, available Cu content of the soils were marginal to deficient. The upper and middle pedons with argilic subsurface horizons were classified as Typic Paleustults (Soil Survey Staff, 1999). These soils correlate with Cutanic Luvisols (WRB, 2006). The lower and toe slope pedons with mollic epepedon and cambic subsurface horizon were classified as Typic Haplustepts. These soils correlate with Haplic Cambisols (WRB, 2006). The result indicated that the distribution and properties of the soils vary along the toposequence in the watershed.

Key words: Soil characteristics, soil classification, Delbo-Wegene watershed

INTRODUCTION

Successful agriculture to meet the increasing demands of food, fiber and fuel from the decreasing per capita land, requires the sustainable use of soil because soil is an important non-renewable land resource determining the agricultural potential of a given area. The study and understanding of soil properties and their distribution over an area has proved useful for the development of soil management plan for efficient utilization of limited land resources. Moreover, it is very important for agro-technology transfer (Buol et al., 2003).

Ethiopia has diverse soil resources largely because of diverse topography, climatic conditions and geology (Abayneh, 2001). The soil resource of the whole country was studied at a scale of 1:2,000,000 (Wijntje-Bruggeman, 1984). In addition, the soil resource assessment under the River Basins Project alone has covered more than 40% of the country at 1:250,000 scale (Abayneh, 2001). These studies are of small scale and not comprehensive enough to draw development planning at watershed level. Consequently, sustainable soil management practices that are based on the understanding of soil system are not available for most part of the country (Fikre, 2003). Hence, there is a need to commence detail soil characterization works.

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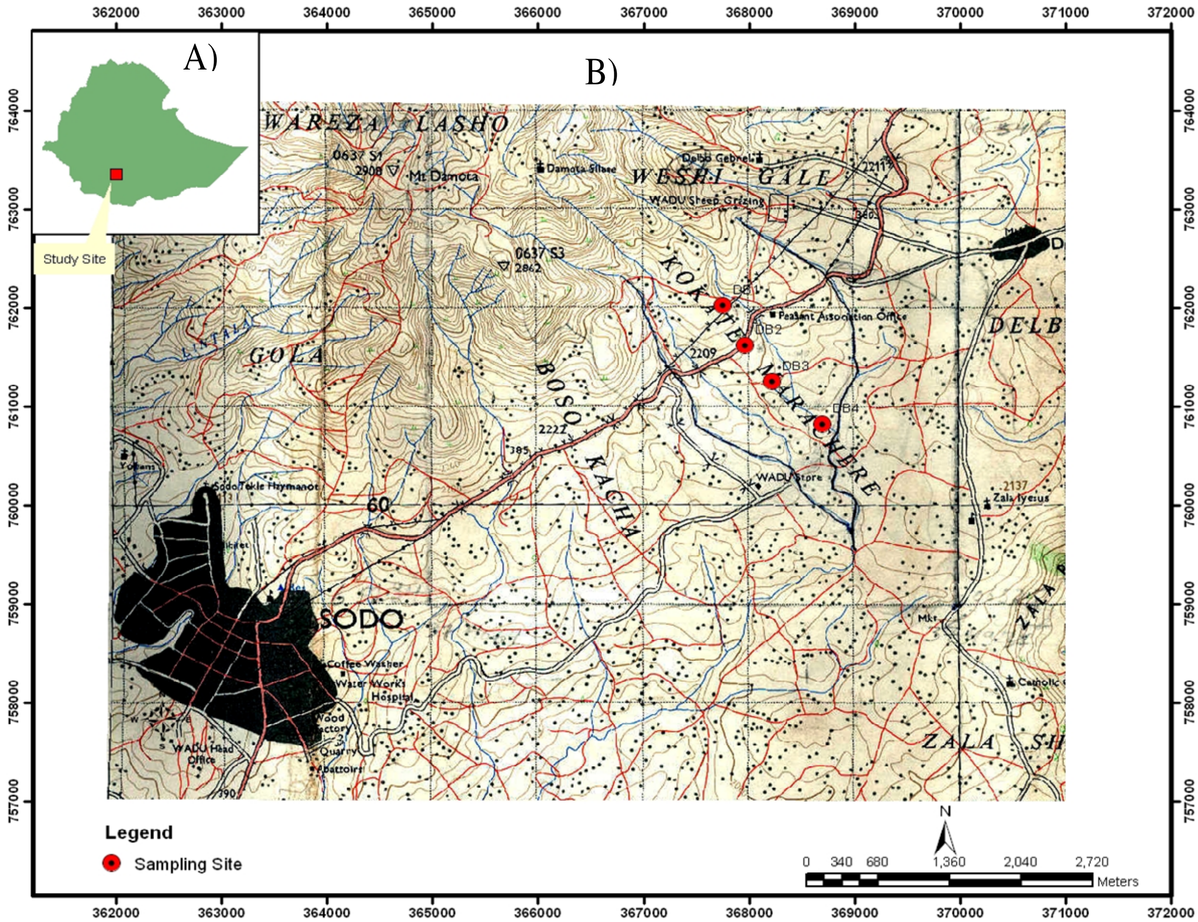

Figure 1. Map of Ethiopia (A) showing location of the study area (Delbo Wegene Watershed) and (B) topographic map of the study area showing locations of sampling sites.

The dominant soils of the Wolayita area are reported to be Nitosols (FAO/UNESCO, 1974), which are sesquioxidic and moderately to strongly acidic (Mesfin, 1998). Abayneh et al. (2006a) also indicated the existence of Rhodic Nitisols (WRB, 1998) around Wolaita area. Fikre (2003) also confirmed the occurrence of Alfisols around the same area. In addition, according to Mulgeta (2006) Ultisols, Inceptisols and Entisols are present around Wolaita area on diverse topography.

An increase in agricultural production, particularly rain fed cropping, is a function of soil, climate and agro-technology. The proper understanding of the nature and properties of the soils of the country and their management according to their potentials and constraints is imperative for maximization of crop production to the potential limits (Abayneh and Brehanu, 2006). However, the morphological, physical and chemical characteristics of soils of Delbo Wegene watershed area in relation to nutrient retention and management alternatives not well documented. Therefore, the purpose of this study was to characterize and classify soils of Delbo Wegene watershed, on the topo-sequence to generate baseline information, which will be important for formulating the management alternatives for different soil types identified. The specific objectives of the study were to: (1)

Determine the morphological, physical and chemical characteristics and (2) Classify the soils according to Soil Taxonomy and World Reference Base Legend.

MATERIALS AND METHODS

Description of the study area

The Delbo Wegene watershed is located in Wolayita Zone of Southern Nations, Nationalities and Peoples Regional State, Ethiopia (Figure 1). It is located at about 8 km East of Sodo town and 368 km South of Addis Ababa. Its geographical extent is between 06°52' 45.9” and 06°53'34.8” N latitude and between 37°48' 10.5”and 37°48' 42.4” E longitude with altitude ranging from 2100 to 2300 m.a.s.l. It has a total area of 922 ha.

The geology of the study area is dominated by ignimbrite

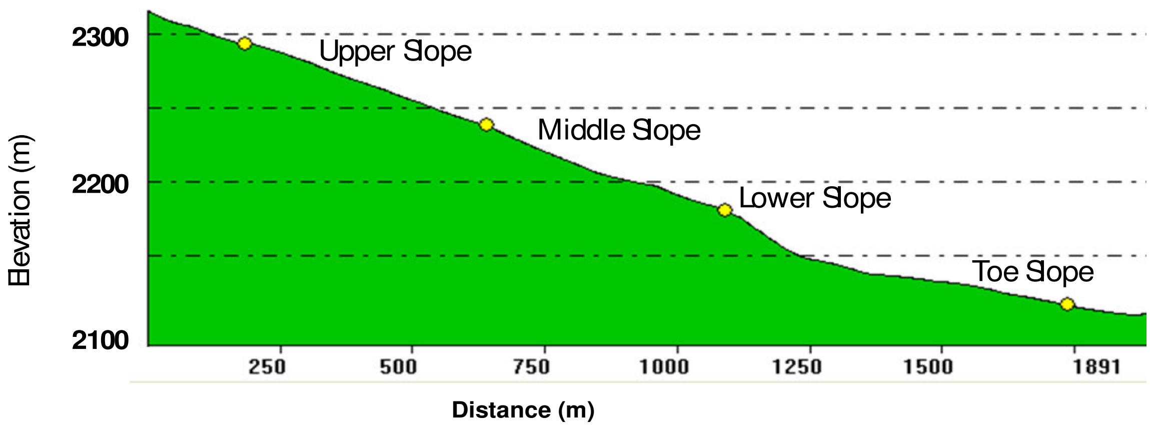

Figure 2. Cross section of the study area showing locations of sampling sites.

Table 1. Location and physiographic settings of the pedons studied.

Pedon	Geographic location		Slope	Altitude	Surrounding landform	Physiographic position
	Latitude	Longitude	(%)	(m.a.s.l)		
DB1	06°53'34.8”	37°48' 10.5”	12	2300	Undulating to mountainous	Upper slope
DB2	06°53' 21.5”	37°48' 18.2”	14	2230	Undulating	Middle slope
DB3	06°52' 52.3”	37°48' 39.8”	9	2155	Undulating	Lower slope
DB4	06°52' 45.9”	37°48' 42.4”	6	2140	Undulating	Toe slope

belonging to the Dino Formation of the Quaternary volcanics (Tefera et al., 1996). According to the records from 1992 to 2007 taken from the nearby meteorological station at Wolayita Sodo town**,** the mean annual rainfall at Delbo Wegene watershed area is 1343 mm. The rainfall season is from May to October and it has two peaks (May and August) without having a distinct dry season between the peaks. The mean annual temperature is 19.9°C and monthly values range between 17.7°C in July and 22.1°C in February and March.

The major crops and vegetation in the area include maize (*Zea mays*), barley (*Hordem vulgare*), sweet potato (*Ipomoea batatas*), teff (*Eragrotis teff*) and grasses such as *Digitaria diagonalis*. Besides these, the vegetation is dominated by eucalyptus trees (*Eucalyptus camaldulensis*), as homestead and farm forest. Remnants of indigenous tree species such as podocarpus, junperus, croton, cordia and ficus are present.

Selection of toposequence and sampling site

The study area is covered by approximately 1:50,000 scale black and white photography flown in December 1999. Aerial photo interpretation was carried out both with a Topcon pocket and mirror stereoscope to determine different land units on the basis of slope and other external land characteristics. In addition to aerial photos, topographic maps at 1:50,000 scale produced by the Ethiopian Mapping Authority in 1994 were used. These topographic maps were used for locating the study area studying important land features to assist in soil mapping.

After having the preliminary site visit and verified photo interpretation maps, auger observations were made to study land and soil characteristics of the farmland. The augerings were made with "Edelman" auger to a depth of 1.2 m unless soil depth is limited or augering is impracticable due to stoniness or compactness. Auger observations were recorded on a standard form where observed soil characteristics were recorded. The survey technique was a free survey which follows random sampling technique.

A toposequence was selected along north-south facing slopes encompassing landform components from upper slope (shoulder) to toe slope of the watershed. The slopes along the toposequences range between 6 to 14%. The toposequence was divided into four slope categories: upper slope (UP), middle slope (MS), lower slope (LS) and toe slope (TS) (Figure 2). A total of four pedons, were excavated on the toposequence, one pedon on each slope category (Table 1). The location of each pedon was selected on a site which was representative to each slope category following auger observation.

Soil Description and Sampling

The representative soil profiles for each slope category were described and the horizons were designated *in situ* according to the guidelines of FAO (2006). Soil colour notation was described according to Munsell Color Chart (KIC, 2000). Both disturbed (bulk) and undisturbed (core) soil samples (12 in number) were collected from each horizon designated for laboratory determination of soil moisture retention characteristics. From the same horizons, 31 samples were collected for physico-chemical analyses.

Laboratory analysis

Particle size analysis was carried out by the modified sedimentation hydrometer procedure (Bouyoucos, 1951). Bulk density was determined by using core-sampling method (BSI, 1975). Particle density (PD) was determined by the pycnometer method as outlined by Tan (1996).

Water retention of the soils (< 2 mm) was measured at 33 and 1500 kpa suction values, which are equivalent to filed capacity and permanent wilting point, respectively. For the determination of water retention at 33 and 1500 kpa suction, undisturbed core samples were subjected to pressure plate extraction (Van Reewijik, 1993). The plant available water was calculated as the difference between water contents at 33 and 1500 kpa of air-dried soil sample, expressed in weight percent (Wt%). The result was converted into volume percent (Vol %) by multiplying with bulk density.

The pH of the soils was determined in H_2O (pH-H_2O) and 1M KCl (pH-KCl) using 1:2.5 soil to solution ratio using pH meter as outlined by Van Reeuwijk (1993).

Organic carbon content of the soil was determined using the wet combustion method of Walkley and Black as outlined by Van Ranst et al. (1999). Soil total nitrogen was analyzed by wet-oxidation procedure of the Kjeldahal method (Bremner and Mulvaney, 1982).

The Available Phosphorus contents of the soils were analyzed using the Olsen sodium bicarbonate extraction solution (pH 8.5) method as outlined by Van Reeuwijk (1993) and the amount of Av.P was determined by spectrophotometer at 882 nm.

Exchangeable basic cations and the cation exchange capacity (CEC) of the soils were determined by using the 1M ammonium acetate (pH 7) method according to the percolation tube procedure (Van Reeuwijk, 1993). The exchangeable cations (Ca and Mg) in the leachate were determined by Atomic Absorption Spectrophotometer (AAS), whereas K and Na were measured by flame photometer.

Available micronutrients (Fe, Mn, Zn, and Cu) contents of the soils were extracted by diethylenetriaminepentaacetic acid (DTPA) method (Tan, 1996) and the contents of available micronutrients in the extract were determined by AAS.

RESULTS AND DISCUSSION

Morphological and physicochemical properties of the soils

Morphological properties of the soils

All the studied soils have a very deep profile (> 150 cm). Pedons in the upper (DB1), middle (DB2), lower (DB3) and toe slope (DB4) positions were characterized by A-B-Bt-BC, A-Bt-BC, A-Bt-C and A-AB-Bt-BC horizon sequences, respectively.

The thickness of the A horizon varied along the toposequence. The pedon at the toe slope position had relatively the thickest surface horizon (66 cm) followed by the lower (50 cm) and the middle (45 cm) pedons whereas the upper pedon has a relatively shallow (34 cm) surface layer. The increment in the thickness of A horizon down the slope, could be attributed to soil erosion at the upper position and deposition at the lower position as suggested by Woods and Schuman (1988). The relatively gentler slope at the lower position aids deposition of materials eroded from the upper part.

The thickness of the B horizons ranged from 46 to 155 cm. Soils situated at the upper slope position have thick B horizon compared to soils situated at other slope positions. In general, unlike the thickness of A horizon, the thickness of the B horizon decreased from the upper to toe slope position.

Significant amount of clay translocation was observed in the upper and middle pedons, as evidenced by distinct clay coatings and considerable increase in the clay content of the Bt horizon (Table 2). In the upper and middle pedons, distinct horizons and argillic B-horizon were readily observed which indications of relatively well-developed soils are.

Although few to many distinct clay coatings were observed in the Bt horizon of the lower and toe slope pedons, both had slight clay increase with soil depth and did not qualify for argilic B horizon in soil taxonomy and argic B horizon in World Reference Base for soil resources (WRB) classification systems. The distinctness of the boundaries between the A and B-horizons, in the three pedons, was clear with smooth topography, whereas the toe slope pedon had gradual and smooth boundary. The transition within the sub-horizons of B in upper, middle and toe slope pedons had clear, diffuse and gradual smooth boundary, respectively (Table 2).

Thicker and distinct horizonation in the upper positions indicates that under the original intact forest cover, there has been adequate moisture percolation down the profile to foster soil forming process and cause horizon differentiation. In the lower positions, however, frequent rejuvenation and high moisture regime some how hindered clay translocation.

The moist color of the surface horizons varied from dark reddish brown (5YR 3/2), in the upper pedon, to very dark brown (10YR 2/2) in lower and toe slope position pedons (Table 2). Surface layers had darker color as compared to the subsurface horizons within each pedon (Table 2). This is attributed to the effect of relatively higher OM content in the surface horizons compared to the sub surface.

According to Foth (1990), reddish color is due to the presence of iron compounds in various states of oxidation. Hence, the possible reason for the relative dark moist colour of the soils of the lower and toe slope position pedons compared to upper and middle pedons could be due to differences in forms of iron oxide.

Abayneh (2005) found that wet soil profiles have darker hues in the B horizons compared to those with relatively dry horizons. Accordingly, the moist color of the subsurface horizons ranged from dark reddish brown

Table 2. Some morphological properties of soils at **D**elbo **W**egene **w**atershed.

Horizon	Depth(cm)	Moist color	Texture	Structure	Consistency		Horizonboundary
					Moist	Wet	
				Upper slope			
A	0-34	5YR3/2	L	MO,ME, SB	FR	SST, SPL	C, S
B	34-73	5YR3/2	L	MO,ME, SB	FR	ST, PL	C, S
Bt1	73-99	5YR3/3	C	ST, ME, SB	FR	ST, PL	D, S
Bt2	99-136	5YR3/3	C	ST, FM, SB	FR	ST, PL	C, S
Bt3	136-163	5YR3/3	C	ST, FM, SB	FR	ST, PL	C, S
BC1	163-188	5YR2.5/2	C	ST, FM, SB	FR	ST, PL	C, S
BC2	188-205	5YR 3/4	C	MO, FM, SB	FR	ST, PL	--------
				Middle slope			
A	0- 18	5YR3/3	CL	MO,ME, SB	FR	SST, SPL	G, S
A2	18-45	5YR3/3	L	WE,ME, SB	FR	SST, SPL	C, S
Bt1	45-62	2.5YR2.5/4	C	MO,CO,SB→ GR	FR	ST, PL	D, S
Bt2	62- 93	2.5YR2.5/4	C	ST, FM, SB	FR	ST, PL	D, S
Bt3	93-127	2.5YR2.5/4	C	MO, FM, SB	FR	ST, PL	D, S
BC1	127-154	2.5YR2.5/4	C	MO, FM, SB	FR	ST, PL	D, S
BC2	154-200	2.5YR2.5/4	C	MO, FM, SB	FR	ST, PL	---------
				Lower slope			
Ap	0- 22	7.5YR2.5/2	L	WE, ME, SB	FR	SST, SPL	C, S
A	22-50	10 YR2/2	CL	MO,ME, SB	FR	SST, SPL	C, S
Bt	50-106	7.5YR2.5/3	CL	ST, ME, SB	FR	ST, PL	C, S
C	106- 180	7.5YR3/4	L	MA	FM	SST, SPL	--------
				Toe slope			
Ap	0- 22	7.5YR2.5/2	CL	WE, ME, SB	FR	SST, SPL	C, S
A	22-66	10 YR2/2	CL	MO,ME, SB	FR	SST, SPL	G, S
AB	66-98	10YR2/2	C	MO,ME, SB	FR	ST, PL	G, S
Bt	98- 127	7.5YR3/3	CL	MO,ME, SB	FR F	ST, PL	G, S
BC	127- 180	5YR3/3	C	MO,ME,SB→ GR	FR F	ST, PL	--------

Notes: L=loam, C=clay, CL=clay loam; WE=weak, MO=moderate, ST=strong, ME=medium, FM= fine and medium, CO=coarse; SB=subangular blocky, SB GR= subangular blocky parting to granular structure, MA= massive; FR=friable, FM= frim, FRF=friable to firm, ST=sticky, SST=slightly sticky, Pl=plastic, SPL=slightly plastic; C=clear,G=gradual, D=diffuse ,S=smooth.

(2.5YR 2.5/4), in middle pedon, to dark brown (7.5YR 3/3) in the toe slope pedon where there is a possibility of water saturation leading to reduction reaction. There were few color variations within the sub horizons of B in the upper and middle slope position pedons. In general, in the two pedons hue gets redder and the value and chroma increase with soil depth from the soil surface down to the lowest B horizons.

All surface horizons of the studied soils had a weak to moderate subangular blocky structure (Table 2). The subsurface horizons had moderate to strong subangular blocky structure except two horizons, which had moderate compound sub angular blocky structure parting to fine granular structure. The C horizon in the lower slope position had massive structure. The better developed structure of the subsurface soils could be due to the relatively higher clay content of the subsurface horizons than that of the surface horizons (Ahn, 1993).

The moist and wet consistencies of the surface layers and the wet consistency of the B horizons were similar in

Table 3. Selected physical characteristics of soils of Delbo Wegene watershed.

Horizons	Depth (cm)	Particle Size			Textural class	BD	PD	TP (V%)
		Sand	Silt	Clay				
		%				gm cm^{-3}		
				Upper slope				
A	0-34	50	35	15	L	1.00	2.5	61
B	34-73	35	40	25	L	1.10	2.7	59
Bt1	73-99	25	35	40	C	1.17	2.5	53
Bt2	99-136	20	35	45	C	1.20	2.6	54
Bt3	136-163	20	35	45	C	-	-	-
BC1	163-188	20	35	45	C	-	-	-
BC2	188-205	20	20	60	C	-	-	-
				Middle slope				
A	0- 18	25	40	35	CL	1.16	2.5	53
A2	18-45	35	40	25	L	1.15	2.6	56
Bt1	45-62	20	20	60	C	1.24	2.6	53
Bt2	62- 93	10	15	75	C	1.26	2.7	54
Bt3	93-127	10	5	85	C	-	-	-
BC1	127-154	10	15	75	C	-	-	-
BC2	154-200	15	10	75	C	-	-	-
				Lower slope				
Ap	0- 22	35	40	25	L	1.14	2.6	57
A	22-50	35	35	30	CL	1.15	2.6	56
Bt	50-106	30	40	30	CL	1.23	2.7	54
C	106-180	40	35	25	L	-	-	-
				Toe slope				
Ap	0- 22	35	30	35	CL	1.14	2.6	56
A	22-66	35	30	35	CL	1.15	2.7	57
AB	66-98	40	15	45	C	1.20	2.6	53
Bt	98-127	40	20	40	CL	-	-	-
BC	127- 180	20	25	55	C	-	-	-

Notes: L = loam, C = clay, CL = clay loam; BD = bulk density, PD = particle density, TP = total porosity.

all the studied pedons. In all cases, the consistency was friable and slightly sticky and slightly plastic, when moist and wet, respectively, in the surface layers and sticky and plastic when wet in the B horizons. Whereas the moist consistency of the B horizons had shown slight variation in the toe slope positioned pedon which was friable to firm. The C horizon of the lower position pedon had firm moist consistency.

The overall friable consistency of the soils indicates that the soils are workable at appropriate moisture content. The lack of very sticky and very plastic consistency, despite relatively high clay content could be indicative of lack of smectitic clays in the soils.

Physical properties

The particle size distribution of the studied soils varied along the toposequence. Soils situated at the middle slope position had relatively higher clay content (25 - 85%), throughout the profile, followed by soils located at upper (15 - 60%), toe (35 - 55%) and lower slope (25 - 30%) positions (Table 3). The sand contents also varied among the studied soils, with values ranging from 20 -

Table 4. Moisture content and available water capacity of soils of Delbo Wegene watershed.

Horizon(cm)	Moisture Content		Available water	TP	Macropore	AWC(mm/m)
	33 kPa	1500 kPa				
	Wt%			Vol%		
			Upper slope			
0 - 34	35.58	24.61	10.97	61	25	104.31
34 - 73	29.73	21.64	8.88	59	26	
73 - 99	30.82	20.59	11.97	53	17	
99 - 136	30.72	20.28	12.53	54	17	
			Middle slope			
0 - 18	32.39	18.12	16.48	53	16	111.34
18 - 45	30.78	20.84	11.44	56	21	
45 - 62	30.08	22.77	9.06	53	15	
62 - 93	32.69	25.27	9.31	54	12	
			Lower slope			
0 - 22	25.74	17.41	9.50	57	27	
22 - 50	26.90	18.61	9.53	56	25	118.03
50 - 106	29.18	17.34	14.60	54	18	
			Toe slope			
0 - 22	24.50	17.42	8.07	56	28	130.64
22- 66	27.73	16.33	13.17	57	25	
66 - 98	25.04	11.58	16.16	53	23	

50%, 30 - 40%, 20 to 40% and 10 - 35% at upper, lower, toe and middle slope positions, respectively.

Soils at the upper and middle slope positions have discernable increase in clay content with soil depth compared to those found at lower and toe slopes, which have slight clay increase. Although the abundance varies, clay cutans were observed in all pedons. According to Buol et al. (2003), the presence of clay cutans or clay skins and textural differentiation in the profile are indicators of clay migration. The accumulation of clay in the subsurface horizon could have been contributed by the *in situ* synthesis of secondary clays, the weathering of primary minerals in the B horizon, or the residual concentration of clays from the selective dissolution of more soluble minerals of coarser grain sized in the B horizon (Buol et al., 2003).

The bulk density of the soils was in the range of 1.00 in the A horizon of the upper pedon to 1.26 gm cm^{-3} in the Bt2 horizon of the middle pedon (Table 3). Higher OM content in the A horizon makes soils loose, porous and well aggregated, thereby reducing bulk density (Hilel, 1980).In all pedons, the lowest bulk densities were found at the surface horizons, which have higher OM content. The correlation analysis have confirmed that bulk density is negatively correlated with OC (r = -0.61) and TN (r = -0.64) and positively correlated with clay content (r = 0.73).

Bulk densities values of the soils increased with soil depth from A to B horizons. However, the bulk density values of the surface horizons were less than the critical values (1.4 g/cm^3) for agricultural use (Hillel, 1980). This implies that no excessive compaction and no restriction to root development (Werner, 1997).

Total porosity (TP) of the soils ranged from 53 to 61 (V%) (Table 3) and macro pores (pores at field capacity) between 12 and 28 (V%). According to Brady and Weil (2002), ideal total pore space values, which are acceptable for crop production, are around 50%. Hence, the soils have an acceptable range of total porosity values for crop production.

Gravimetric water content of the soils at field capacity (33 kPa) ranged from 24.50 - 35.58% while the amount at permanent wilting point (1500 kPa) was between 11.58 - 25.27% (Table 4). The volumetric plant available water content (AWC) of the soils varied from 8.07 - 16.48 % on horizon basis. According to Beernaert (1990), available

Table 5. Soil pH and electrical conductivity of soils of Delbo Wegene watershed.

Horizons	Depth(cm)	pH (H_2O)	pH (KCl)	ΔpH	EC (dS/m)
		Upper slope			
A	0-34	5.9	4.7	-1.2	0.05
B	34-73	6.1	4.7	-1.4	0.04
Bt1	73-99	6.3	4.7	-1.6	0.03
Bt2	99-136	6.3	4.6	-1.7	0.02
Bt3	136-163	6.1	4.5	-1.6	0.02
BC1	163-188	6.2	4.4	-1.8	0.02
BC2	188-205	6.0	4.2	-1.8	0.02
		Middle slope			
A	0- 18	5.9	4.4	-1.5	0.04
A2	18-45	5.8	4.4	-1.4	0.03
Bt1	45-62	6.3	4.8	-1.5	0.03
Bt2	62- 93	6.2	4.8	-1.4	0.03
Bt3	93-127	6.2	4.8	-1.4	0.03
BC1	127-154	6.3	5.0	-1.3	0.03
BC2	154-200	6.3	5.0	-1.3	0.03
		Lower slope			
Ap	0- 22	6.4	5.1	-1.3	0.04
A	22-50	6.4	4.8	-1.6	0.03
Bt	50-106	6.4	4.5	-1.9	0.02
C	106-180	6.4	4.6	-1.8	0.02
		Toe slope			
Ap	0- 22	6.3	4.8	-1.5	0.03
A	22-66	6.3	4.6	-1.7	0.02
AB	66-98	6.3	4.6	-1.7	0.02
Bt	98-127	6.3	4.6	-1.7	0.02
BC	127-180	6.3	4.5	-1.8	0.02

water content values are rated < 8 as very low, 8 – 12 as low, 12 – 19 as medium, 19 – 21 as high and >21 V% as very high. Accordingly, the available water content of the soils ranged from very low to medium. The total AWC of the upper 1 m soil layers is 104.30 in the upper pedon and 130.64 mm/m in the toe slope pedon.

Chemical properties

The pH-H_2O values of soils varied from 5.8 to 6.4 (Table 5). The lowest (5.8) value was observed in the A2 (18 to 45 cm) horizon of middle slope position pedon, whereas the highest (6.4) was found in all the horizons of the pedon found at the lower slope position. According to Tan (1996), the pH range of the soils is slightly to moderately acidic, which is preferred range for most crops. The pH-H_2O values had shown a general tendency to increase with soil depth in the pedons found at upper and middle slope positions compared to the lower and toe slope position pedons.

The pH-KCl values of the soils ranged from 4.2 - 5.1 and had a general tendency to decrease with increasing soil depth, except in the middle pedon, which showed increment (Table 5). According to Uehara and Gilman (1981) and Anon (1993) soil pH determination using KCl solution showed the presence of high potential acidity and weatherable minerals. In all the soil profiles ΔpH (pH-KCl - pH-H_2O) values were negative, ranging from –1.2 to –1.9. According to Uehara and Gillman (1981) negative ΔpH values is an indication of the presence of net negative charges in soils.

Electrical conductivity (EC) of the soils ranged from 0.02 - 0.05 dSm^{-1}. According to Havlin et al. (1999) this

Table 6. Exchangeable cations and cation exchange capacity of the soils at Delbo Wegene watershed.

Horizon	Depth	Na	K	Mg	Ca	CEC	Sum of base	PBS	ESP
	(cm)	mol (+)/kg of soils						%	
				Upper slope					
A	0-34	0.11	0.97	1.56	8.43	24.56	11.08	45	0.44
B	34-73	0.17	1.31	1.89	10.68	26.11	14.05	54	0.66
Bt1	73-99	0.11	1.22	1.64	8.08	23.19	11.05	48	0.47
Bt2	99-136	0.17	1.04	1.64	9.38	23.74	12.24	52	0.73
Bt3	136-163	0.24	0.65	1.81	7.63	23.67	10.34	44	1.01
BC1	163-188	0.30	0.87	2.06	9.23	23.58	12.46	53	1.29
BC2	188-205	0.26	0.64	2.14	9.03	22.76	12.07	53	1.14
				Middle slope					
A	0- 18	0.07	1.57	1.32	5.94	22.82	8.89	39	0.29
A2	18-45	0.11	0.92	1.64	7.93	26.37	10.61	40	0.41
Bt1	45-62	0.20	0.52	1.56	10.23	21.16	12.51	59	0.92
Bt2	62- 93	0.09	0.74	2.71	9.43	26.49	12.97	49	0.33
Bt3	93-127	0.17	1.08	3.29	11.13	27.19	15.67	58	0.64
BC1	127-154	0.13	1.20	2.88	8.33	24.94	12.55	50	0.52
BC2	154-200	0.15	1.33	2.22	4.69	24.32	8.39	34	0.62
				Lower slope					
Ap	0- 22	0.13	0.93	1.48	10.53	19.23	13.07	68	0.68
A	22-50	0.26	0.59	1.73	11.23	21.93	13.80	63	1.19
Bt	50-106	0.20	0.47	0.74	6.00	15.67	7.41	47	1.25
C	106-180	0.22	0.35	1.48	6.19	11.85	8.23	70	1.83
				Toe slope					
Ap	0- 22	0.15	0.88	1.23	8.68	18.61	10.95	59	0.82
A	22-66	0.24	0.68	1.32	10.08	18.49	12.31	67	1.29
AB	66-98	0.24	0.59	1.40	8.88	19.33	11.11	58	1.23
Bt	98-127	0.15	0.38	1.32	5.49	16.87	7.34	44	1.11
BC	127-180+	0.26	0.73	2.71	9.88	20.74	13.58	65	1.26

range is categorized as very low and implies that the soils are not salt affected.

The cation exchange capacity (CEC) of the soils ranged from 11.85 to 27.19 cmol (+) kg^{-1} of soil (Table 6) and the values were generally higher in surface than in subsurface horizons except for the middle pedon, which had relatively higher CEC values in the sub surface horizons. Furthermore, the upper and middle pedons have relatively higher CEC than the lower and toe slope pedons. According to Landon (1991), CEC values are rated < 5 as very low, 5 - 15 as low; 15 - 25 as medium, 25 - 40 as high and > 40 as very high.

The CEC of the soils in the surface layers ranged from medium to high. In general, there was a decrease in CEC with depth, except in the middle pedon, which could be due to the strong association between organic carbon and CEC. According to Brady and Weil (2002), CEC depends on the nature and amount of colloidal particles.

The exchange complex of the soils is dominated by Ca followed by Mg, K and Na (Table 6). According to Havlin et al. (1999), the prevalence of Ca followed by Mg, K, and Na in the exchange site of soils is favourable for crop production. The exchangeable cations content of the soils increased with increasing soil depth except K in the middle, lower and toe slope pedons which showed relative decrement. The increment was attributed to the leaching of exchangeable cations. This result is in agreement with the findings of Wakene (2001) on Alfisols

Table 7. Organic carbon, total nitrogen and available phosphorus content of the soils at Delbo Wegene watershed

Horizons	Depth(cm)	OC	TN	C/N	Av.P. (mg/kg)
		%			
		Upper slope			
A	0-34	2.40	0.25	10	3.36
B	34-73	1.67	0.18	9	3.28
Bt1	73-99	1.31	0.18	7	3.11
Bt2	99-136	1.47	0.15	10	2.98
Bt3	136-163	0.79	0.09	8	2.55
BC1	163-188	1.05	0.15	7	2.54
BC2	188-205	0.47	0.08	8	1.98
		Middle Slope			
A	0- 18	2.38	0.23	10	4.24
A2	18-45	2.06	0.25	8	3.14
Bt1	45-62	1.99	0.16	12	2.78
Bt2	62- 93	0.51	0.06	9	2.64
Bt3	93-127	0.49	0.07	7	2.25
BC1	127-154	0.39	0.05	8	9.36
BC2	154-200	0.21	0.03	7	7.00
		Lower slope			
Ap	0- 22	1.99	0.17	12	13.76
A	22-50	1.95	0.15	13	4.68
Bt	50-106	1.12	0.09	13	4.04
C	106- 180	0.75	0.07	11	6.84
		Toe slope			
Ap	0- 22	1.46	0.12	12	5.00
A	22-66	1.56	0.18	9	4.76
AB	66-98	1.33	0.11	12	4.48
Bt	98- 127	0.79	0.06	13	4.26
BC	127- 180	0.77	0.08	10	4.12

around Bako area, Ethiopia.

The exchangeable Na content of the soils is low and the exchangeable sodium percentage (ESP) of the soils was also less than 2%. This indicates that there is no sodicity problem in these soils. According to Brady and Weil (2002), ESP of 15% is considered as critical for most crops.

According to Sims (2000), the range of critical values for optimum crop production for K, Ca and Mg are from 0.28 - 0.51, 1.25 - 2.5, and 0.25 - 0.5 cmol (+)/kg soil, respectively. Accordingly, the exchangeable K, Ca and Mg content of the soils are above the critical values. However, this does not prove a balanced proportion of the exchangeable bases. Potassium uptake would be reduced as Ca and Mg are increased; conversely uptake of these two cations would be reduced as the available supply of K is increased (Havlin et al., 1999).

In addition, the ratio of exchangeable Ca/Mg should not exceed 10/1 to 15/1 to prevent Mg deficiency and also the recommended K/Mg are < 5/1 for field crops, 3/1 for vegetables and sugar beets and 2/1 for fruit and greenhouse crops (Havlin et al., 1999). The Ca/Mg ratio of the studied soils was in the range of 2 - 9 indicating that the response of crops to Mg is not likely. The K/Mg ratio of the studied soils varied from 0.2 to 1.2 and hence it is within the acceptable range for crop production.

The base saturation percentage of the soils is less than 50 in all surface and some parts of the subsurface horizons of the upper and middle pedons. The lower and toe slope pedons, however, have a base saturation percentage greater than 50 in all surface and some parts of the subsurface horizons. The organic carbon (OC) content of the soils generally decreased with soil depth in all pedons (Table 7). The OC content ranged from 0.21 in the subsurface horizon of the middle pedon to 2.4% in the surface horizon of the upper pedon. Its amount in surface horizons ranged from 1.5 in soils of toe slope to 2.4 % in upper slope position. According to Landon (1991) the categories for the organic carbon content of soils are: low (< 4), medium (4 - 10), high (> 10). Thus the OC content of the soils is low.

The total nitrogen (TN) content of the soils ranged from 0.06 in the subsurface horizon of the toe pedon to 0.25% in the surface horizon of the upper pedon. According to Havlin et al. (1999), TN content of soils are categorized < 0.15 as low, 0.15 - 0.25 as medium and > 0.25 as high. Accordingly, the TN content of the soils is categorized under the low to medium category. The distribution pattern of TN with soil depth was similar to that of OC. The amount of TN in the surface soils ranged between 0.11, in the toe slope to 0.25% in the upper and middle slope pedons.

In general, OC and TN content decrease from the upper to the toe slope position. The difference in OC and TN content among the pedons could be attributed to the effect of variation in landuse systems along the toposequence. Intensive and continuous cultivation aggravated OC oxidation, resulted in reduction of total N as compared to virgin land. The results are in accordance with the findings of Wakene and Heluf (2003) and Tuma (2007) who reported that intensive and continuous cultivation forced oxidation of OC and thus resulted in reduction of TN.

Positive and strong correlation (r = 0.76) was found between OC and TN indicating the strong association of OC and TN in the study area. Higher total nitrogen content in the surface layers as compared to the subsurface layers could be due to OM content, as there exists strong correlation between TN and OC.

The available phosphorus content of the soils ranged from 1.98 mg/kg of soil, in the BC2 horizon of the upper pedon to 13.76 mg/kg soil in the A horizon of the lower pedon (Table 7). The available phosphorus content of the soils decreased down the profiles. This is attributed to the increase in clay content. Although it was not significant, available phosphorus correlated negatively (r = -0.32) with clay content and positively(r = 0.21) with organic carbon content (Appendix Table 1). Phosphorus fixation tends to be more pronounced and ease of phosphorus release tends to be lowest in those soils with higher clay content (Havlin et al., 1999; Brady and Weil, 2002).

Higher available P values in surface horizon as compared to subsurface horizons could be attributed to the difference in organic matter contents and application of P-containing fertilizer. According to Havlin et al. (1999), the available P contents of the soils ranged from very low to high (Table 7). The authors rated Olsen P as < 3 mg/kg as very low, 4 - 7 mg/kg as low, 8 - 11 mg/kg as medium, and > 12 mg/kg as high.

The available micronutrient content (Fe, Mn, Zn, and Cu) in all pedons decreased with increasing soil depth except Fe in the surface horizons of the lower and toe slope pedons (Table 8). The concentration of available micronutrients were found to be Mn> Fe> Zn> Cu in the upper and middle pedons and Fe>Mn>Zn>Cu in the lower and toe slope pedons.

The micro nutrient content of soils is influenced by several factors among which soil organic matter content, soil reaction and clay content are the major ones (Fisseha, 1992).

The amounts of Fe, Mn, Zn, and Cu in the surface soils ranged from 20.6 (in the Ap horizon of the lower pedon) to 57.2 in the A horizon of the lower pedon, 13.9 (in A horizon of the lower pedon) to 113.4 (in the A horizon of upper pedon), 13.5 (in A2 horizon of the toe slope pedon) to 15.7 (in A1 horizon of the middle slope pedon) and 0.26 (in Ap horizon of the lower pedon) to 1.03 cmol (+)/kg soil (in the A horizon of the upper pedon), respectively.

According to critical values of available micronutrients set by Havlin et al. (1999) (Table 9), the amounts of Fe, Mn and Zn in the surface soils may not be deficient for crop production. However, the amount of Cu is sufficient in the upper, deficient in the lower and marginal in the middle and toe slope pedons. This is in agreement with various works which stated that Cu is most likely deficient, Zn contents are variable and, Fe and Mn contents usually at an adequate level in Ethiopian soils (Desta, 1982; Fisseha, 1992; Abayneh, 2005; Alemayehu, 2007).

Classification according to soil taxonomy

The surface horizons of the lower and toe slope pedons qualify for mollic epepedon while the upper and middle pedons for umbric epepedon. In the subsurface horizons, all pedons had thick B horizons (> 7.5 cm). The upper and middle pedons had distinct clay increment in the B horizons, which met all the requirements of an argillic horizon. Although few to many distinct clay coatings exist in the lower and toe slope pedons, due to slight clay increment in the profiles they did not meet the clay increase requirement of argillic horizon. Rather they showed evidence of color alteration in their B-horizons, and as a result they are recognized to have a cambic horizon.

Two of the pedons (upper and middle slope) with argilic subsurface horizons were classified as Ultisols based on the presence of umbric epepedon, which has a base saturation less than 50% (by NH_4OAC) (Soil Survey Staff, 1999). Whereas the lower and toe slope pedons with mollic epepedon, cambic subsurface horizon and at pH 7

Table 8. Available micronutrients content of soils at Delbo Wegene watershed.

Horizons	Depth (cm)	Fe	Cu	Zn	Mn
		Mg/kg soil			
		Upper slope			
A	0-34	50.73	1.03	14.01	113.39
B	34-73	22.95	0.73	12.43	46.70
Bt1	73-99	21.85	0.66	11.66	44.42
Bt2	99-136	20.45	0.75	13.18	38.24
Bt3	136-163	20.01	0.70	7.79	28.42
BC1	163-188	17.56	0.73	11.90	25.59
BC2	188-205	15.40	0.46	3.37	63.10
		Middle slope			
A	0- 18	49.41	0.51	15.74	77.48
A2	18-45	49.35	0.48	14.90	44.95
Bt1	45-62	39.18	0.35	14.70	15.14
Bt2	62- 93	2.00	0.18	1.19	6.53
Bt3	93-127	2.29	0.13	0.42	5.26
BC1	127-154	2.13	0.09	0.09	14.04
BC2	154-200	2.97	0.07	0.22	17.12
		Lower slope			
Ap	0- 22	20.61	0.26	15.29	35.02
A	22-50	57.20	0.37	14.52	13.88
Bt	50-106	49.30	0.29	10.54	12.65
C	106- 180	13.13	0.15	4.09	11.13
		Toe slope			
Ap	0- 22	32.49	0.48	13.77	41.34
A	22-66	47.50	0.51	13.53	33.31
AB	66-102	47.72	0.51	12.01	29.04
Bt	102- 127	15.07	0.40	4.47	19.43
BC	127- 180+	13.02	0.31	1.67	21.32

Table 9. DTPA-extractable Fe, Zn, Cu, and Mn for deficient, marginal and sufficient soils.

Category	Fe	Zn	Mn	Cu
		Mg/kg soil		
Low(deficient)	0 - 2.5	0 - 0.5	< 1.0	0 - 0.4
Marginal	2.6 - 4.5	0.6 - 1.0	-	0.4 - 0.6
High(sufficient)	> 4.5	> 1.0	> 1.0	> 0.6

Source: Havlin et al. (1999).

base saturation less than 50% between the mollic epepedon and a depth of 180 cm were classified as Inceptisols. Although the soil moisture and temperature regimes of the pedons were not measured, using the mean annual and monthly temperature and moisture distributions of the region as recommended by Van Wambeke (1992), the study area was characterized by isotermic temperature and ustic moisture regimes,

Table 10. Diagnostic horizons and family names of the soils of Delbo Wegene watershed according to soil taxonomy (1999).

Pedon	Diagnostic horizons		Soil type
	Surface	Subsurface	
DB1	Umbric	Argilic	Typic Paleustults
DB2	Umbric	Argilic	Typic Paleustults
DB3	Mollic	Cambic	Typic Haplustepts
DB4	Mollic	Cambic	Typic Haplustepts

Table 11. Diagnostic horizons and soil unit names of the soils at Delbo Wegene watershed according to WRB (2006).

Pedon	Diagnostic horizons		Soil unit
	Surface	Subsurface	
DB1	Umbric	Argic	Cutanic Luvisols
DB2	Umbric	Argic	Cutanic Luvisols (Abruptic, Endoclayic)
DB3	Mollic	Cambic	Haplic Cambisols (Epieutric)
DB4	Mollic	Cambic	Haplic Cambisols (Epieutric,Clayic)

respectively. At suborder level, the Ultisols (the upper and middle pedons) were differentiated as Ustults on the basis of the ustic moisture regime. Further, the pedons did not have a densic, lithic, paralithic, or petroferric contact within 150 cm of the mineral soil surface; and within 150 cm of the mineral soil surface, with increasing depth, do not have a clay decrease of 20 percent or more (relative) from the maximum clay content. Hence, they were classified as Paleustlts and Typic Paleustults great groups and subgroups, respectively.

The lower and toe slope pedons, which were classified as Inceptisols order of Soil Taxonomy, were differentiated as Ustepts and Haplustepts at suborder and great group levels respectively. At sub group level, the two pedons were classified as Typic Haplustepts. The list of diagnostic horizons (epipedon and subsurface) of the soils and their classification at sub group level are given in Table 10. The occurrence of Ultisols and Inceptisols in the study area is in agreement with the findings of Mulugeta (2006) and Alemayehu (2007).

Classification according to WRB legend

The surface horizons of the upper and middle Pedons fulfill all the requirements of an umbric epipedon. Whereas the surface horizons of the lower and toe slope pedons qualify for mollic epipedon.

The upper and middle pedons were identified to have argic subsurface horizons (equivalent to argilic subsurface horizon of Soil Taxonomy). While the lower and toe slope pedons showed color alteration, (redder hue) in their subsurface horizon than the overlying horizons. Therefore, these two pedons had been identified as having cambic sub surface horizon.

The upper and middle pedons have an argic horizon with a cation exchange capacity (by 1 M NH_4OAc) greater than 24 cmolc kg^{-1} clay throughout the horizon. Hence the two pedons were grouped under Luvisols. These pedons had clay coatings in some parts of an argic horizon starting from 100 cm. Therefore, at the unit level the two pedons were classified as Cutanic Luvisols. The lower and toe slope pedons qualify for cambic subsurface horizon and are classified as Cambisols. The list of diagnostic horizons (epipedon and subsurface) of the soils and their classification at unit level are given in Table 11.

Conclusions

The soils of the study area are developed from one parent material group namely ignimbrite. Topography had influence on the characteristics of the soils in the studied site. Hence, much of the soil properties varied along the toposequence. The soils are generally dark reddish brown to very dark brown, very deep (> 150 cm). There is discernable difference in amount and distribution of clay content with depth along the toposequence. The over all friable consistency, low bulk density (1.00 - 1.26 gm/cm^{-3}), sub angular to angular blocky structure, high total porosity (53 to 61%) indicate that the soils have good physical condition for plant growth.

The soils are moderately to slightly acidic with pH values between 5.8 - 6.4. Surface soils in the upper and middle pedons have lower pH than subsurface soils. However, the lower and toe slope pedons have uniform pH distribution with depth. In general, Organic carbon content, micronutrient cations and cation exchangeable capacity of the soils decreased with soil depth. However, exchangeable cations (except K in the middle, lower and toe slope pedons) increased with increasing soils depth.

Available P content of the soils ranged from very low to high. Low available P content of the soils could be due to high P retention. Whereas high available P content of the soils could be due to application of P containing fertilizers. Available Fe, Zn and Mn contents of the soils may not be deficient for crop production. Available Cu content of the soils (except in the upper pedon) is marginal to deficient.

Macromorphological observations have shown that clay translocation and accumulation has taken place in the soils. In the upper and middle pedons, there was a marked increase in clay content with depth and common to many distinct clay coatings were observed. Hence, in those pedons the clay increase requirement of argillic horizon was met.

The upper and middle pedons with argilic subsurface horizons were classified as Typic Paleustults. These soils correlate with Cutanic Luvisols (WRB, 2006). Whereas the lower and toe slope pedons were classified as Typic Haplustepts. These soils correlate with Haplic Cambisols (WRB, 2006).

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Appendix Table 1. Correlation analysis among soil properties.

	Na	K	Mg	Ca	CEC	pH- H_2O	pH-KCl	EC	AV.P	OC	TN	AWC	BD	Sand	Silt	Clay	Fe	Cu	Zn	Mn
Na	1.00	-0.67	-0.31	0.50	-0.53	0.62	0.08	-0.57	-0.01	-0.12	-0.47	0.08	0.21	0.24	-0.24	-0.01	0.41	-0.14	0.18	-0.50
K		1.00	0.13	-0.30	0.50	-0.55	-0.21	0.57	-0.01	0.35	0.59	0.09	-0.33	-0.03	0.51	-0.28	-0.24	0.48	0.22	0.63
Mg			1.00	0.44	0.78	-0.17	0.30	0.20	-0.22	-0.31	0.05	-0.29	0.09	-0.45	-0.40	0.52	-0.63	-0.07	-0.62	-0.15
Ca				1.00	0.11	0.43	0.69	0.07	0.25	-0.04	-0.15	-0.49	-0.02	0.04	-0.25	0.12	-0.27	-0.09	0.00	-0.36
CEC					1.00	-0.65	-0.12	0.41	-0.41	0.11	0.53	-0.14	-0.23	-0.21	0.03	0.12	-0.35	0.36	-0.24	0.31
pH -H20						1.00	0.54	-0.48	0.34	-0.49	-0.80	-0.13	0.49	-0.21	-0.26	0.29	-0.22	-0.45	-0.15	-0.70
pH-KCl							1.00	0.35	0.61	-0.09	-0.26	-0.63	-0.06	-0.01	-0.20	0.12	-0.48	-0.25	-0.10	-0.23
EC								1.00	0.36	0.58	0.65	-0.30	-0.75	0.38	0.38	-0.47	-0.13	0.42	0.25	0.72
AV.P									1.00	0.21	-0.03	-0.12	-0.08	0.26	0.26	-0.32	-0.11	-0.34	0.30	-0.05
OC										1.00	0.79***	0.03	-0.61*	0.52	0.50	-0.63	0.58*	0.40	0.85***	0.65*
TN											1.00	0.08	-0.64	0.34	0.48	-0.50	0.28	0.54	0.53	0.76
AWC												1.00	0.20	-0.04	0.05	-0.01	0.35	0.04	0.05	0.07
BD													1.00	-0.77	-0.40	0.73**	-0.31	-0.75	-0.40	-0.85
Sand														1.00	0.32	-0.83	0.60	0.49	0.55	0.54
Silt															1.00	-0.79	0.22	0.29	0.54	0.40
Clay																1.00	-0.52	-0.48	-0.67	-0.59
Fe																	1.00	0.15	0.60	0.26
Cu																		1.00	0.33	0.79
Zn																			1.00	0.42
Mn																				1.00

Numbers are correlation coefficients (r). Number of observation (n) = 23
*Significant at the $p \leq 0.05$. **$p \leq 0.01$ and ***$p \leq 0.001$