Ethiop. J. Agric. Sci. 28(1) 51- 69 (2018)

Agro-Climate Based Pedogenetic Assessment of Soils in Kulumsa Subwatershed, Arsi, Ethiopia

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አህፅርኦት

ማንኛውም አፈር የአካባቢ ሁኔታዎች በአለት ላይ በሚፈጥሩት መጠኑ-ሰፊ የተቀናጀ ተፅዕኖ ውጠት በመሆኑ በዓለማችን ላይ በሺህ የሚቆጠሩ የአፈር ዓይነቶች ይኖራሉ፡፡ የአፈር አፈጣጠር ጥናት ደግሞ ይኼንን እጅግ ሰፋት ያለውን መረጃ አቀናጅቶ ሥርዓት በማስያዝ ለአፈር ጥናትና ስያሜ አሰጣጥ ያግዛል፡፡ በዚህም መሰረት በቁሉምሳ ወንዝ ተፋሰስ ላይ በባለ 1፡50000 ሚዛን የአካባቢውን የገፀ-ምድር ካርታን መነሻ በማድረግ በተደረገው የመስክ ጥናት 19 የአፈር ጥናት ናሙና መውሰጃ ሥፍራዎች ተለይተውና የጥናት ጉድጓዶች ተቆፍረው የአፈር ናሙናዎችን በመውሰድና በላቦራቶሪ በመመርመር የአፈር አፈጣጠር ጥናት ተካሂዶ 10 የአፈር ዓይነቶችን በመለየት ከመሬት የከፍታ ልዩነትና ከባህላዊ የአየር ሁኔታ አመዳደብ ጋር ያላቸው ተፈጥሯዊ ግንኙነት ተጠንቷል፡፡ የጥናቱ ዉጤት እንደሚያመለክተዉ የአፈር ዕድገት፣ የመታጠብ ደረጃ እና አሲዳማነት ከመሬት ከፍታ ጋር የሚጨምሩ ከመሆናቸው አንፃር በጣም ዝቅተኛ የመታጠብ ደረጃና በጣም ከፍተኛ አልካሊንነት ያላቸዉ ካስተኖዘምስ የሚባሉ የአፈር ዓይነቶች በዝቅተኛ ወይናደጋ የአየር ሁኔታ አካባቢ በስምጥ ሸለቆ ውስጥና በድምበሩ አካባቢ እንደሚገኙና በተቃራኒው በጣም ከፍተኛ የመታጠብ ደረጃና በጣም ከፍተኛ አሲዳማነት ያላቸው ኡምብሪዞል የሚባሉ የአፈር ዓይነቶች በከፍተኛ ውርጭ አካባቢ በጭላሎ ተራራ ላይ መኖራቸው ታውቋል፡፡ በጣም ከፍተኛ የመታጠብ ደረጃና በጣም ከፍተኛ አሲዳማነት (pH ≈5.15) ያላቸው የአፈር ዓይነቶች በከፍተኛ የጭላሎ ተራራ አካባቢዎች ቢኖሩም የእነዚህ ከፍተኛ ቦታዎች የአፈር አፈጣጠር ሂደት ግን ከፍተኛ የአፈር ማዕድናት መብላላትን ማስከተል ባለመቻሉ ዝቅተኛ የአሲዳማነት ደረጃ ባላቸው አፈሮች ውስጥ በብዛት የሚገኙ የአፈር ማዕድናት በብዛት የሚገኙባቸው መሆኑ ታውቋል፡፡ ይኼውም ለማዕድናት መብላላት ከፍተኛ አስተዋፅዖ የሚያደርገው ሙቀት ከመሬት ከፍታ መጨመር ጋር የሚቀንስ ከመሆኑ አንፃር የተከሰተ መሆኑ ይገመታል፡፡ በሁለቱ ተቃራኒ የመሬት ከፍታ ስፍራዎች (ዝቅተኛ ወይናደጋና ከፍተኛ ውርጭ) መካከል በሚገኙ አካባቢዎች፣ በመካከለኛ ወይናደጋ ቸርኖዘምና ሉቪዞል፣ በከፍተኛ ወይናደጋ ፕላኖዞልና ቨርቲዞል፣ በዝቅተኛ ደጋ ቨርቲዞልና ሉቪዞል፣ በመሃከለኛ ደጋ ሬቲዞልስ እና በከፍተኛ ደጋ ደግሞ አሊዞል የተባሉ የአፈር ዓይነቶች በቅደም ተከተል ከዝቅተኛ ወደ ከፍተኛ አካባቢ ተገኝተዋል፡፡ በአጠቃላይ፣ ከዚህ ጥናት ለመረዳት እንደተቻለው በE.2.03 ዓይነት የዝናብ ስብጥር ክልል ውስጥ የአፈር አፈጣጠርና ዕድገት ሁኔታ ከባህላዊው የኢትዮጵያ አርሶአደሮች የአየር ሁኔታ አመዳደብ ጋር የሚጣጣም ሆኖ ተገኝቷል፡፡ ቢሆንም፣ የበለጠ አስተማማኝ መደምደሚያ ላይ ለመድረስ ሌሎች የዝናብ ስብጥር ክልሎችን አቀፍ የሆነ ጠለቅ ያለ ጥናት ሊካሄድ ይገባል፡፡

Abstract

Any particular soil results from the integrated action of soil-forming factors that occur in different kinds and degrees of expression that can be combined in many different ways; so that each combination produces a different soil with its unique properties resulting in the existence of thousands of different soils on earth. Soil genesis brings order to this overwhelming variety of soils aiding their classification. Soils of Kulumsa sub-watershed were surveyed and 19 representative profile locations identified, described, and sampled based on observable site and soil characteristics such as slope, topographic position, vegetation, topsoil color, texture, etc. using a topographic map of 1:50,000 scale as a base map through free survey along altitudinal and latitudinal transects. The sampled 19 pedons were categorized into 10 Reference Soil Groups through pedogenetic assessment; and the relationship of the overall pedogenesis and spatial distribution of the soil groups to altitude and the traditional agro-climates were examined. The pedogenetic assessment of the soils revealed that the degree of weathering and leaching increased with increasing altitude. Accordingly, the least leached and most alkaline Kastanozems in the Lower-Woina-Dega (1800-2100 masl) within the "rift valley" and its border escarpment areas, and the most leached and most acidic Umbrisol in the High-Wurch (>3700 masl) agro-climatic belt on Mount Chillallo, were identified. Even though there were acidic soils with pH as low as 5.15 and very strongly leached profile, the chemical weathering processes appeared to be not *so intensive when evaluated in terms of their clay mineralogy. The acidic soil profile condition of these high altitude areas seemed not to be in a position to cause an advanced weathering of the high-activity clay minerals, so that they still dominated the clay fraction of the soils. In relation to the traditional agro-climates, from the lowest towards the highest elevation within the study area, the least leached Kastanozems in the Lower-Woina-Dega, Chernozems and Luvisols in the Proper-Woina-Dega (2100-2250 masl), Planosols and Vertisols in the Upper-Woina-Dega (2250-2400) to Lower-Dega (2400-2550 masl),Vertisols and Luvisols in Lower-Dega, Retisols in the Dega-Proper (2550-3000 masl), Umbric Alisols in the Upper-Dega (3000-3200 masl) and Hyperdystric Umbrisols in the High-Wurch (>3700 masl) agro-climatic belt, were the dominant soil groups. In inference, the results of the pedogenetic assessment denoted that the trend in pedogenesis and the spatial distribution of the soil groups was generally in concurrence with the traditional agro-climatic classification used by the Ethiopian farmers in the E.2.03-type Rainfall Pattern Region of the Arsi-Highlands. However, this needs more detailed investigations that include the other Rainfall Pattern Regions of Arsi and of the country as well for more reliable conclusion.*

Introduction

Soil genesis as a natural phenomenon, is the process of forming a soil from a parent material through a combined effect of the soil forming factors. This includes reducing the size of the parent material particles and rearranging them, alteration and decomposition of the minerals of the parent material, synthesis of newer minerals and other substances from the decomposition products and their translocation, incorporation and humification of organic matter and eventually forming the soil horizons (Singer and Munns, 2002). A particular combination of the soil-forming factors gives rise to a set of certain soil forming processes that lead to the development of a particular soil. Any soil results from the integrated action of these factors that occur in different kinds and degrees of expression that can be combined in many different ways; whereby each combination produces a different soil with its unique properties resulting in the existence of thousands of different soils on earth (Van Breemen and Buurman, 1998; Brady and Weil, 2014). Dealing with soil genesis brings order to this overwhelming variety of soils and aids their classification thereby linking the field of soil science to other scientific disciplines (Van Breemen and Buurman, 1998; SSS, 1999; SSDS, 2000). Varied combinations of the soil forming factors lead to specific sets of soil forming processes that bring about change in soil properties and hence soils are found to be the same wherever all the elements of the soil forming factors and the respective soil forming processes are the same. Hence, scientific predictions of the locations of different kinds of soils and their use potentials on earth is possible, though it is rarely likely to find groups of soils in which all factors are similar (SSDS, 2000).

Regarding the Ethiopian conditions, coupled with great variations in the age and character of the parent materials, the diverse physiography and climate have led to extremely varied vegetation and land-use; and as a consequence of the variability in terms of place and time, a wide diversity of soils have been developed (Mesfin, 1998). According to Mishra *et al*. (2004), regarding the genesis, classification, potential fertility, and productivity, the soils of Ethiopia are generally unique in their characteristics and Ethiopia can be considered as the land of "Soil Museum" where different soil orders except the Gelisols of the US Soil Taxonomy in varying frequencies occur, depending upon the existing physiographic and agro-ecological differences. According to Hurni *et al*. (2007) climatic, geologic and topographic variabilities under Ethiopian conditions encourage the formation of different soil types as these factors trigger the abundance and intensity of soil building processes. Due to the heterogeneity of the soil forming factors and processes, different types of soils in different stages of development exist; and this holds true for the present study area (Kulumsa Subwatershed) that has also great environmental diversity.

In developing countries like Ethiopia with strong environmental diversity and where agriculture is the mainstay of their economy, the future productivity and sustainability of the agricultural production depends on a comprehensive study based wise use of the natural resources that include the mosaic of soils. Moreover, in the Ethiopian context, agricultural land resource management can be better addressed by tackling the problems at the watershed or subwatershed level, since each has its own specific physical and socio-economic dimensions (Mohammed, 2003). According to Klaij and Abiye (2001) and Lakew *et al*. (2005), a watershed is a geographical unit of a stream system from which runoff is discharged through a common confluence, being separated from its neighboring areas by a ridge called *divide*. It has a hierarchical relationship with its smaller watershed units and hence can be divided into smaller and smaller sub-watersheds drained by natural streams or artificial drains; which could be observed also by the Arsi highlands dissected through many large and small streams including Kulumsa River. The Arsi highlands by virtue of their agriculturally favorable environmental conditions have been the center of attraction for several agricultural development organizations that need site-specific comprehensive information on the natural resources, especially on the soils. However, not so much attention has been paid in the past particularly to detailed soil genesis studies, despite the fact that a research into these aspects would create the opportunity to understand and solve site-specific problems pertaining to the use and management of the major land resource, the soil (Mitiku, 1987; Mesfin, 2006). Moreover, it seems to be crucial to review the efforts made by the Ethiopian farmers since long to classify their altitudinally varied production environments in terms of elevation and temperature relationship as traditional agro-climates, in relation to pedogenetic aspects since a scientific progress made in this direction may enhance the efficiency of agricultural extension and research. Dealing with the genesis of the soils of the study area as part of the Arsi highlands, was found to be of paramount importance to have a detailed knowledge on their intrinsic properties related to agricultural production potentials, limitations and the respective management options. It was in line with this premise that a soil genesis study was initiated and carried out in the physiographically and climatically diversified Kulumsa sub-watershed as part of the Arsi highlands within the southeastern highlands of Ethiopia, with due consideration to the traditional agro-climatic classification of Ethiopian farmers.

Materials and Methods

Description of the study area

The study area, Kulumsa sub-watershed (as part of Ketar River watershed), is located in Oromia Regional State in Arsi Administrative Zone at about 168 km southeast of Addis Ababa and at about 6 km north of Assela town (the capital of Arsi Zone). Its geographical extent is from 07° 54'16.0" to 08° 02' 17.1" N and from 039° 07' 29.7" to 039° 15' 54.0" E (Figure 1) with an altitude ranging from 1810 to 4005 masl and has the total area of 70025.16 ha. The sub-watershed starts at the eastern summit of Mount Chillallo and ends in the "Main Ethiopian Rift Valley", where the *Gonde* river joins Kulumsa river to form the *Deneba* river (after the junction) that joins the Ketar River (the largest river in Arsi Zone) within the "rift valley". Kulumsa sub-watershed encompasses areas of four woredas, namely Tiyo, Hetosa, Lode-Hetosa and Digelu and Tijo, though its major part is found in Tiyo woreda that includes Assela town and Kulumsa Agricultural *Research Center*.

The soils pedogenetically assessed

The soils pedogenetically assessed were those pedons identified through the soil survey conducted within Kulumsa sub-watershed, in order to produce basic data as a basis for an interpretation for various kinds of present and future uses including some which may not be anticipated now. The soils were surveyed, described and sampled for the subsequent laboratory analysis based on the topographic map of 1:50,000 scale as a base map using free survey along two transects (altitudinal and latitudinal). The altitudinal transect was from northwest towards southeast from the lowest to the highest elevation (1810-4000 masl), and the latitudinal transect was from north towards the south that had also altitudinal variation that increased southwards, so that the spatial variations that may result from the physiographic diversity could be assessed in all direction. Based on the observable and measureable surface expressions of the environmental factors such as topographic position, slope, vegetation and topsoil characteristics like color, texture, consistence, *etc*. and laboratory analysis results, about 19 pedons and 10 Reference Soil Groups of the FAO/IUSS-WRB (2015), which were presumed to be representative for the respective landscape portions were identified and sampled (Table 1).

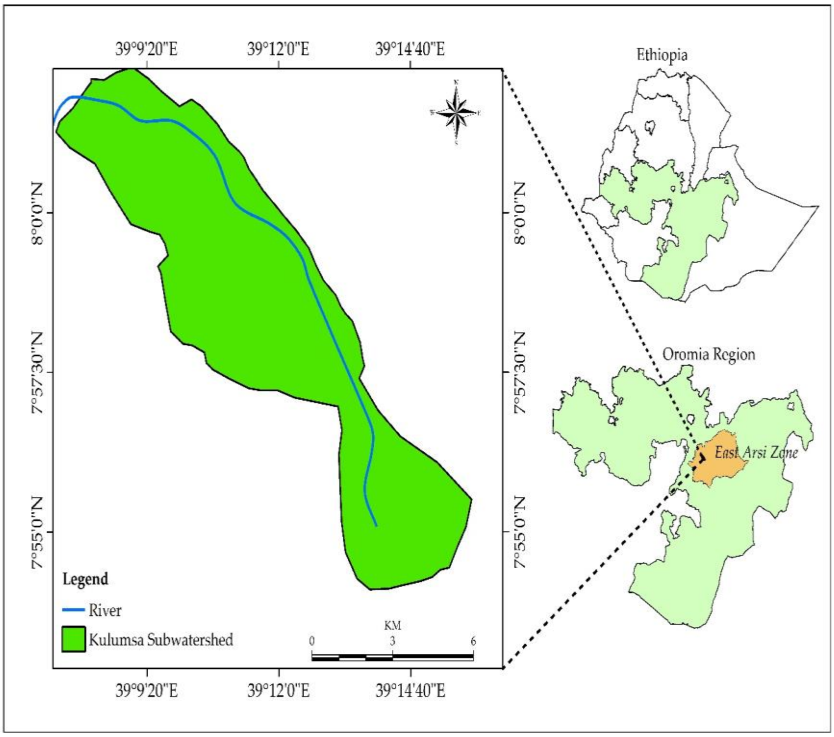


Figure 1. Location of the study area in Arsi Zone, Oromia Region and Ethiopia

Table 1. Master horizons, their vertical subdivisions (sub-horizons) sampled and total profile depth

Profile no	Altitude (m)	Master horizons	Transition horizons	Vertical Sub-divisions	Average profiles depth (m)	Total sub-horizons
KS 01	2290	A, B	BA, BC	Ah, A1, A2, BA, Bss1, Bkss2, BCkss	200+	7
KS 02	2050	A, B, C	BC	Ah, A1, BAt, Btk1, Btk2, BCtk, Ck	200+	7
KS 03	2110	A, B	BA	Ah, A1, A2, BAk, Bwk1, Bw2	200+	6
KS 04	2345	A, B, R	AE, BA	Ah, AE, BAt, Btss1, Btss2, BCr	200+	6+Rs
KS 05	2050	A, B, R	BA, BC	Ah, A1, Bt1, Bt2, BCr	123+	5+Rs
KS 06	2110	A, B, R	BA, BC	Ah, A1, BAt, Bt1, Bt2, BCtrk	126+	6+Rs
KS 07	2150	A, B, C, R	B/C	Ap, A1, Bt, B/Ctk, Cr	200+	5+Rs
KS 08	2080	A, B, C, R	BA, BC	Ap, A1, BAt, Bt1, B2, BCk, Crk	172+	7+Rs
KS 09	2190	A, B, C	BA, BC	Ah, A1, BAt, Bt1, B2, BCk, Ck	200+	7
KS 10	1950	A, B, C, R	BA, BC	Ah, A1, BAt, Bt1, Bk2, BCk, Crk	200+	7+Rs
KS 11	1980	A, C, R	AC	Ah, AC, Cr	62	3+Rs
KS 12	2345	A, B	EA, B/E	Ah, EA, B/Et, Btss1 Btss2	200+	5
KS 13	2470	A, B, R	A/E, BC	Ah, A/E, Btss1, Btssg2, B/Ctrg	181+	5+Rs
KS 14	2340	A, B, C	BC	Ap, A1, Bw1, Bw2, BC, C	200+	6
KS 15	2650	A, B	BE, BC	Ah, A1, BEt, Bt1, Bt2, BC	200+	6
KS 16	2965	A, R	A/C	Ah, A1, A/Ctr	83+	3
KS 17	2790	A, B	BE	Ah, A1, BEt, Bt1, B2	200+	5
KS 18	3100	A, B, R	B/C	Ah, A1, Bt1, B/Ctr	113+	4
KS 19	3800	A, R	AC	Ah, A1, ACr	55	3
_____	________	__________	___________	Total number of horizons sampled	____	103

Rs = Rock sample taken for petrographic analysis.

Site selection, environmental, profile description, and soil sampling

In order to determine the soil sampling sites that represent relatively homogeneous environmental conditions (landscape topography, vegetation, land use and surface soil characteristics such as color, texture, consistence, *etc*.), a field survey was conducted using a combination of free (traverse) and transect survey methods through visual observation, probing with auger and measuring with equipment such as clinometer or Jallo, altimeter and GPS (Geographic Positioning System). The description of the environmental conditions (physiography, climate, parent materials, vegetation, and land use) and the profile micromorphology was performed based on the FAO (2006) Guidelines for Soil Description.

The soil profiles of freshly opened pits were described and the horizons to be sampled designated according to the FAO (2006); and the color identification of the soil materials of the sampled genetic horizons was conducted using the Munsell Soil Color Charts (2000). Two types of soil samples, namely bulk and core samples were collected from each genetic horizon designated for the purpose from freshly dug soil pits of 1m width, 2 m length and 2 m depth (1x2x2 m), unless otherwise the depth is limited by the specific profile site condition. Additionally, rock samples were procured from the profiles with hard rock or similar material exposure after the stipulated depth (200 cm) of their regolith or after any pedon specifically limited depth of the respective regolith (Table 1).

Soil sample processing and laboratory analysis

The bulk soil samples collected were air-dried, ground and sieved to pass through a 2 mm sieve before the analysis except for those for soil organic carbon and total nitrogen which were sieved by 0.5 mm sieve. The chemical and physical laboratory analysis of the soil samples was carried out generally according to the standard analytical methods and procedures used in Jije Analytical Testing Service Laboratory, which is owned by the Jije Laboglass Pvt. Limited Company, in Addis Ababa.

The petrographic analysis of the rock samples collected from the bottom of the soil pits (profiles) was conducted in the Central Geological Laboratory of *Geological Survey of Ethiopia* and in the Geological Laboratory of the *Department of Earth Sciences* of Addis Ababa University according to the standard petrographic analysis methods and procedures used in the respective laboratory. Regarding soil mineralogy, due to lack of mineralogical laboratory that uses apposite soil mineralogy analysis methods, it was attempted to estimate only the dominant clay mineral types according, to Van Reeuwijk (2002) and Brady and Weil (2014) using the formulas (2.1) and (2.2) as elucidated below, through estimation of the CEC of the mineral clay fraction in the soil. The respective cation activity class was also estimated through the ratio of CEC_7 to % clay of the soil (apparent CEC) based on the clay percent determined by the texture analysis (Formula 2.3 below) for each horizon (Buol *et al.*, 2011). Moreover, the percentage proportion (magnitude) of the variable negative charge to CEC_7 was also used as additional discriminating factor based on the fact that each clay mineral type (group) has specific proportion of a variable negative charge to its CEC_7 (Table 4). The variable negative charges were estimated by subtracting the ECEC value from that of the CEC_7 for the acidic soils, and by subtracting the value of the sum of exchangeable bases from that of the CEC_7 for neutral and alkaline soils. Since the calculations performed using both approaches resulted in most cases in almost identical or similar values, the formula from Van Reeuwijk (2002) was preferred in order to minimize the errors of estimating the ECEC of SOM from a graph prepared for the purpose.

- $CEC_{clay} = \dfrac{CEC_7 - (\%\ SOM \times ECEC\ of\ SOM)}{\%clay/100}$, **according to Brady and Weil (2014)** **(2.1)**

- $CEC_{clay} = \dfrac{CEC_7 - (350 \times \%OC)}{\%clay/100}$, **according to Van Reeuwijk (2002)** **(2.2)**

- $CEC_7 : \%clay\text{-}ratio = \dfrac{CEC_7}{\%clay}$, **according to Buol *et al.* (2011)** **(2.3)**

Where: ECEC = Effective cation exchange capacity; CEC = Cation exchange capacity; CEC_7 = CEC
determined by ammonium acetate method at pH7; CEC_{clay} = CEC of the mineral clay fraction;
OC = Organic carbon; SOM = Soil organic matter.

Data analysis and interpretation

The data obtained from field survey activities and laboratory soil sample analysis was examined mainly using descriptive statistics. Moreover, simple linear regression and correlation was used with descriptive statistics particularly to assess the trends of the relationships observed between some soil characteristics and environmental factors (mainly altitude), and the results were interpreted based on the hitherto existing research findings and previously established scientific facts. The field survey data was mapped using GIS-Software version ArcGIS-10.3.

Results and Discussion

General environmental description

The study area belongs to the E.2.03 Rainfall Pattern Region of the Arsi highlands and is located partially in the "rift valley" (below 2000 masl) and its border areas, and extends up to the eastern (3910 masl) and southeastern (about 4000 masl) summit of Mount Chillallo. By the E.2-type rainfall pattern, the main rains in summer (*Kiremt*) are preceded by a small rainfall peak in spring (*Belg*) or by a prolonged period of moderate rainfall in both cases (FAO/UNDP, 1984). According to FAO (2006), in the study area, there exist landforms that vary from level land (land with less than 10% slope and less than 50 m/km relative relief) to steep land (areas with more than 30% slope and relative relief of 150-300 m/km or more), and landscape topography ranging from almost flat (0.5-2.0% slope) to mountainous (above 30% slope).

Generally, the study area is characterized by a strong physiographic diversity, whereby areas with a rugged topography and sloping to steep major landforms comprise altogether about 75% of the total area. The proportion of level land is only about 21% and 4% is occupied by a mixture of dissected plain and depression with certain ruggedness. The level land portion itself is dissected by the Kulumsa river gorge and by several other non-permanent small streams. From the "rift valley escarpment" up to the "main body" (where the typical mountainous topography starts) of Mount Chillallo, there existed a repeating pattern of terrace type topography (stairs) within a certain interval of rather irregular spacing. This stair-like topography divides the sub-watershed into five major landform units that have been the basis for the subdivisions of the major traditional agro-climatic belts and identification of the soil-mapping units. These five major landforms have altitudinal ranges that fall within defined elevation-ranges of the major traditional agro-climates. Hence, subdividing the major traditional agro-climates was inevitable to ease the assessment of the pedogenetic trend observed within the study area (Table 2). The variations within the altitudinal ranges of the landforms were also clearly observable from the natural vegetation, the cultivated crop types, the identified soil groups, and different agricultural activities of the local farming community.

Table 2. Description of agro-climatic belts in relation to soil temperature and soil moisture regimes

Name of the major traditional agro-climatic belts and their subdivisions	Altitude range in masl	Mean annual rainfall (mm)	MAAT range* in °C	Adjusted (MAST) range* in °C	Name of the corresponding MAST	Normal MAST range* in °C	Estimated soil moisture regime**	Equivalent world's major climate type
Kola and below it	< 1800	≤ 700	> 27.5	> 30.0	Isohyperthermic	≥ 22.0	Aridic	Desert/Tropical
Entire *Woina-Dega*	1800-2400	700-1200	20.0-16.0	22.5-18.5	Isothermic	15.0≤V<22.0	________	Subtropical
Lower-Woina-Dega	1800-2100	700-1200	______	______	Isothermic	_________	Ustic	"
Proper-Woina-Dega	2100-2250	700-1200	______	______	Isothermic		Ustic/Udic	"
Upper-Woina-Dega	2250-2400	700-1200	______	______	Isothermic		Udic	"
Entire *Dega*	2400-3200	1200-2200	16.0-11.5	18.5-14.0	________	_________	Udic	Temperate
Lower-Dega	2400-2550	1200-2200	11.5<X≤ 16.0	14.0<X≤ 18.5	Isothermic	15.0≤V<22.0	Udic	"
Proper-Dega	2550-3000	1200-2200	16.0>Y<11.5	18.5>Y<14.0	Isomesic	8.0≤S<15.0	Udic	"
Upper-Dega	3000-3200	1200-2200	16.0>P ≤11.5	16.0>P ≤14.0	Isomesic	8.0≤S<15.0	Udic	"
Wurch	3200-3700	≥1500	7.5-11.5	10.0-14.0	Isomesic	8.0≤S<15.0	Udic	Alpine
High-Wurch	> 3700	≥1500	< 7.5	< 10.0	Isofrigid	0-8.0	Udic	Frost limit

** The capital letters P, S, V, X and Y are used to indicate the respective specific ranges of temperature; MAAT = Mean annual air temperature.*

*** The aquic soil moisture regime is not included since it was restricted to land surfaces that had subsurfaces with lower permeability. MAST = Mean annual soil temperature.*

Thus, the use of terms such as *Lower-Dega*, *Upper-Dega, Lower Woina-Dega, etc*. was necessary to describe the transitional type environmental conditions within the major traditional agro-climatic belts of the study area. On the other hand, linking the agro-climatic divisions to the soil temperature and soil moisture regimes was indispensable for the assessment of pedogenetic trend in relation to the traditional agro-climatic belts. According to Miller and Gardiner (2001), FAO (2006) and Buol *et al.* (2011), the major traditional agro-climatic belts and their subdivisions were categorized in terms of soil temperature regime by adding 2.5^{o}C to mean annual air temperature for adjustment and using the prefix "Iso", thereby including the estimated soil moisture regimes as elucidated in Table 2.The subdivisions of the major traditional agro-climatic belts were based on the divisions of MOA (1998) and Lakew *et al*. (2005).

General pedogenetic trend

The integrated effect of the environmental factors (soil-forming factors) can be seen in the morphology of a soil, since soil morphology as expressed by the vertical section of a soil (profile) through the differing horizons reflects the combined impacts of a particular set of the genetic factors and processes responsible for its development. Hence, soil properties are the outcomes of a variety of soil forming processes acting on a parent material; the marks of which can be seen in a soil profile that enable an inference on the details of the processes. Since the marks of the set of pedogenic processes are facts that can be observed and measured, they can be used as the basis for the distinction between different kind of soils and their stage of development (SSS, 1999).

Climatic, geologic and topographic variabilities under Ethiopian conditions encourage the formation of different soil types as these factors trigger the abundance and intensity of soil building processes, so that due to the heterogeneity of soil forming factors and processes, different types of soils in different stages of development exist (Hurni *et al*., 2007); and this holds true for the present study area. As Kulumsa sub-watershed is characterized by strong physiographic and climatic diversity that in turn induced strong variation in the natural vegetation, the land use and thereby the soil development, about ten Reference Soil Groups according to FAO/IUSS-WRB (2015) have been identified within the small land area of Kulumsa sub-watershed. Accordingly, several soil characteristics such as profile horizonation, effective soil depth, solum thickness, occurrence and sequence of genetic horizons and various other morphological, physical and chemical characteristics of the sampled pedons appeared to be strongly linked to these environmental conditions. Thus, five types of subsurface horizons (argic, calcic, cambic, vertic and protovertic), six types of diagnostic properties (abrupt textural difference, albeluvic glossae, gleyic properties, protocalcic properties, retic properties and stagnic properties), four types of diagnostic materials (albic, calcaric, colluvic and mineral) and three types of surface horizons (chernic, mollic and umbric) were identified to be used for the pedogenetic interpretations. Mollic epipedons were encountered in the areas with elevation range of 1800 to about 3000 masl under ustic, udic and aquic soil moisture and isothermic and isomesic soil temperature regimes leaving the way for umbric epipedons in areas above 3000 masl. Except the abrupt textural difference and protocalcic properties, all the diagnostic properties identified were found under aquic soil moisture regime and isothermic and isomesic soil temperature regimes in lower slopes and other flat topographic positions. Albic materials and related subsurface horizons were encountered also at similar topographic positions under aquic soil moisture and isothermic to isomesic soil temperature regimes mainly on grass dominated land surfaces. Calcaric materials were encountered mainly in the lower elevation areas below the *Lower-Dega* agro-climatic belt, primarily in ustic soil moisture and isothermic soil temperature regimes. Colluvial materials were found at the upper foot slope (pediment) of steep slopes in mountainous landscape topography. Under otherwise similar topographic and agro-climatic conditions, more woody areas appeared to be predominated by soils with argic (argillic) subsurface horizons (excluding areas with steep slopes); and grass dominated areas were occupied mainly by soils with vertic or cambic subsurface horizons.

Accordingly, the main soil forming processes that have been operating by the soil development of the lower altitude areas with *Woina-Dega* up to *Lower-Dega* agro-climates (below 2550 masl) seemed to be calcification accompanied by OM accumulation and humification (melanization), braunification, eluviation versus illuviation and lessivage, that led to the development of soils with brown carbonatic argic (argillic) and cambic subsurface horizons and mollic surface horizons (epipedons) such as Kastanozems, Chernozems and Luvisols. On the other hand, pedogenic processes such as ferrolysis and gleization were limited to hydromorphic sites irrespective of altitudinal variation (agro-climates). By the soils of the higher altitude (above 2550 masl) areas with *Proper-Dega* up to *High-Wurch* agro-climates, the dominant pedogenetic processes appeared to be intensive leaching (soluvation) accompanied by decalcification, lessivage, braunification, melanization, faunal pedoturbation and mass-wasting (solifluction), that led to the formation of soils such as Retisols and Alisols with non-carbonatic brown argic subsurface horizons and mainly umbric surface horizons. Depending on the topographic position, slope gradient and moisture condition that limit their intensity, erosion and deposition, *elutriation*, lessivage, ferrolysis and gleization, melanization and braunification were probably the main pedogenetic processes common to soils of both areas.

The occurrence of secondary carbonates within the profile appeared to be related to altitude. The depth of the free carbonate occurrence increased with altitude until they totally disappeared out of the profile in areas above 2550 masl (Table

3). Thus, free carbonates could not be observed in the profiles of the *Proper-Dega* (2550-3000 masl) and above agro-climatic belts indicating the existence of more intensive leaching (soluvation) in these areas than in the *Woina-Dega* and *Lower-Dega*. Mohammed (2003) had reported also that content of free carbonates, exchangeable Ca and Mg and soil pH values decreased with a rise in altitude in the Jelo Catchment of Chercher highlands. Additionally, secondary carbonates in the form of nodules were encountered only in areas below 2300 masl in the *Proper-Woina-Dega* (2100-2250 masl) and in the *Lower-Woina-Dega* (1800-2100 masl) agro-climatic belts mainly in an ustic and partially lower udic soil moisture and isothermic soil temperature regimes (Table 3). If the degree of profile leaching is evaluated in terms of the subsoil base saturation according to Hazelton and Murphy (2007), there existed an increasing tendency with increasing altitude which could be also testified by the simple linear regression and correlation analysis (Figure 2B). Thus, soils below 2550 masl showed on average a very weak (70-100%) to weak (50-70%) degree of leaching and those above 2550 masl showed a very strong (0-15%) to weak degree of leaching. The most leached profile (KS19) was located at 3800 masl (*High-Wurch*) agro-climatic belt and the least leached one in the *Lower-Woina-Dega* (1800-2100 masl) belt at 2050 masl (KS02). The trend in soil pH was in conformity with that of the secondary carbonates and base saturation, whereby the most alkaline soils (Kastenozems) were encountered in the lowest altitude areas and the most acidic soils (Umbrisols and Alisols) in the highest elevation areas (Figure 2A).

The soil development within the study area under the E.2.03-type Rainfall Pattern Region of the Arsi Highlands seemed generally to be influenced more by the climatic and topographic factors than by the parent material (Table 3). In the *Lower-Woina-Dega* or in the lowest elevation areas of Kulumsa Subwatershed (below 2100 masl), soils with strongly calcareous subsoils (more than 10% $CaCO_3$ equivalent) such as Kastanozems that had high to very high base saturations (higher than 65%) throughout their profiles have been encountered. The only profile (KS10) with a calcic horizon and highest sodium saturation (9%) was also encountered in this area. In the *Proper-Woina-Dega* agro-climatic belt, Luvisols and Chernozems with base saturations above 60% throughout their profiles and moderately calcareous subsoils (2-10% $CaCO_3$), which were characterized as weakly to very weakly leached soils according to Hazelton and Murphy (2007), have been identified.

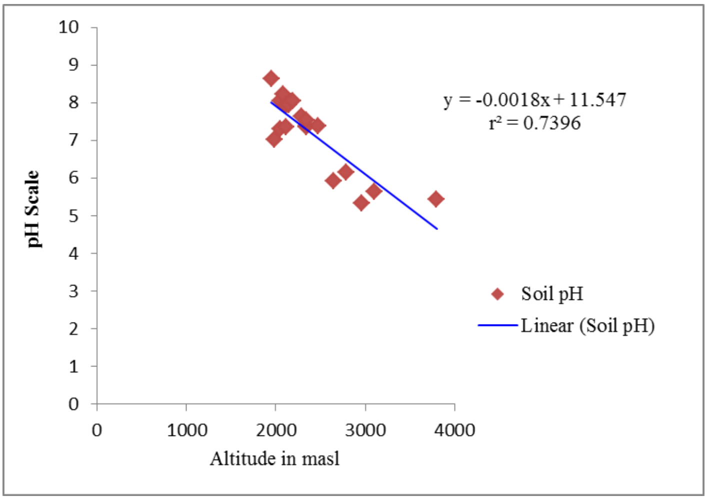
Table 3. Occurrence of the identified Reference Soil Groups in relation to some environmental features

Agro-climatic belt	Altitude (m)	Major landscape topography	Dominant parent materials	Type of soil temperature regime	Major soil moisture regime	Dominant vegetation type	Identified dominant RSGs	Carbonate occurrence	
								Level	Form
Lower-Woina-Dega (L.W.D)	1800-2100	Rolling to hilly	Pyroclastic rocks and deposits	Isothermic	Ustic	Short and medium grass admixture and acacia trees	Kastanozems, Hypereutric Regosols	Str. Car.	Nod., Dis.
Proper-Woina-Dega (P.W.D)	2100-2250	Gently undulating to undulating	Pyroclastic rocks and deposits	Isothermic	Ustic	Medium and tall grass with short grass admixture and acacia trees	Chernozems, Hypereutric Luvisols, Vertisols	Mod.Car.	Nod., Dis.
Upper-Woina-Dega (U.W.D)	2250-2400	Undulating to rolling	Pyroclastic deposits and extrusive volcanic rocks	Isothermic	Udic/Ustic Aquic	Short, medium and tall grasses, acacia and montane forest	Vertisols, Planosols, Cambisols, (Luvisols)**	Sl.Car. to Mod.Car.	Nod., Dis.
Lower-Dega (L.D)	2400-2550	Undulating, rolling and hilly	Extrusive volcanic rocks	Isothermic	Udic, Aquic	Short and medium grasses, montane forest	Vertisols, (Luvisols)**	Sl.Car. to Mod.Car	Dis.
Proper-Dega (P.D)	2550-3000	Rolling, hilly and mountainous	Extrusive volcanic rocks and colluvial materials	Isomesic	Udic, Aquic	Short and medium grasses, montane forest and subafro-alpine vegetation	Retisols, Orthodystric Regosols	None	None
Uper-Dega (U.D)	3000-3200	Hilly to mountainous	Extrusive volcanic rocks and colluvial materials	Isomesic	Udic, Aquic	Montane forest, subafro-alpine and afro-alpine vegetation	Umbric Alisols, Umbrisols**	None	None
Wurch	3200-3700	Mountainous	Colluvial materials*	Isomesic	Udic, Aquic	Afro-alpine vegetation	(Umbrisols)**	None	None
High-Wurch (H.W)	> 3700	Mountainous	Colluvial materials*	Isofrigid	Udic	Afro-alpine vegetation	Umbrisols	None	None

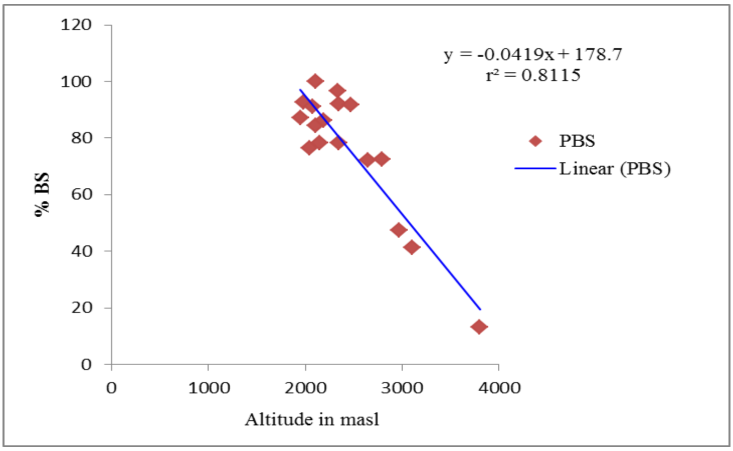
Str.Car. = Strongly carbonatic; Nod. =Nodules; Dis. = Dispersed lime; Mod. Car. = Moderately carbonatic; Sl.Car. = Slightly carbonatic; Car. = Carbonatic (Calcareous).
** Represents only areas with marked pedogenetic development, since most areas with extrusive volcanic rocks were soilless bare rock surfaces; ** Note sampled during the soil survey, but presumed to exist based on the field observations and ABRDP (2004).*

Although the *Upper-Woina-Dega* and *Lower-Dega* soils were somewhat similar with the *Proper-Woina-Dega* soils in terms of their base saturation and free carbonate content (without free carbonates in form of nodules however), soils such as Planosols, Vertisols and Vertic Cambisols with less free carbonates and lower base saturation, namely a base saturation somewhat higher than 50% (weakly leached) were identified in these agro-climatic belts. The *Proper-Dega* (2550-3000 masl) agro-climatic belt was dominated by soils with profiles devoid of free carbonates that had strongly to moderately medium acidic (pH of 5.15-6.0) soil reaction (Benton, 2003), and a base saturation somewhat higher than 45% (moderately leached) throughout their profile.The soil groups identified as dominant in this area include Retisols and Orthodystric Regosol. In the *Upper-Dega* (3000-3200 masl), strongly to moderately leached (base saturation less than 45%) and moderately acidic Alisol (with pH of 5.6-5.8) according to Benton (2003) and Hazelton and Murphy (2007), the profile of which was also devoid of free carbonates, was encountered. In the *High-Wurch* belt, a strongly to moderately acidic (pH 5.4-5.6) and strongly to very strongly leached (base saturation 13-26%) Umbrisol was identified as a prevalent soil group, though this area was covered also by remarkable proportions of bare rock surfaces and very shallow soils (Leptosols).On average, the Umbrisol profile (KS19) on the eastern summit of Mount Chillallo, was the most leached and most acidic.

Generally, the degree of leaching and weathering of the soils increased with increasing altitude. This might have been most likely due to increasing annual rainfall amount and decreasing temperature and evapotranspiration that enabled the existence of sufficient water for leaching and chemical weathering within the soil profile, though the chemical weathering processes appeared to be less intensive when evaluated in terms of clay mineral composition (Table 4). Even though there were acidic soils with pH as low as 5.15 and very strongly leached profile, the chemical weathering processes appeared to be not so intensive. The acidic profile condition seemed not to be in a position to cause an advanced weathering of the high-activity clay minerals, so that the 2:1-layer minerals (smectites) dominated still the clay fraction of the soils (Table 4).



A) Altitude and soil pH relationship



B) Altitude and percent base saturation (PBS) relationship

Figure 2. Altitudinal trends of soil pH (A) and percent base saturation (B)

Table 4. Computed CEC_{clay}, V.N.C, C.E.A.C and estimated dominant clay mineral types of the representative pedons

Profile No. and altitude (masl)	Part of the profile	SEB (cmol/kg)	ECEC (cmol/kg)	% OC	% Clay	CEC_7 $cmol_c/kg$	V.N.C		C.E.A.C		Clay mineral estimation	
							In $cmol_c/kg$	In % of CEC_7	CEC_7 / % Clay	Activity class	CEC_{clay} in $cmol_c/kg$	Anticipated dominant clay mineral type (group)**
KS10 1950, *L.W.D*	Topsoil	29.11	------	4.21	39	45.20	16.09	35.60	1.16	S. active	78.12	Smectites
	Subsoil	46.21	------	1.32	50.50	52.53	6.32	12.03	1.04	S. active	94.87	Smectites
KS09 2190, *P.W.D*	Topsoil	29.43	------	3.55	41	45.35	15.92	35.10	1.11	S. active	80.31	Smectites
	Subsoil	40.28	------	1.28	56.50	49.63	9.35	18.84	0.88	S. active	79.91	Smectites
KS12 2345, *U.W.D*	Topsoil	19.24		3.86	27.50	32.55	13.31	40.89	1.18	S. active	69.24	Smectites
	Subsoil	38.21		0.84	66.67	41.60	3.39	8.15	0.62	S. active	57.99	Smectites, chlorites
KS13 2470, *L.D*	Topsoil	23.02	------	3.65	37	37.54	14.52	38.68	1.02	S. active	66.93	Smectites
	Subsoil	48.51	------	0.40	70.67	52.73	4.22	8.00	0.75	S. active	72.63	Smectites
KS15 2650, *P.D*	Topsoil	23.14	23.38	5.86	30.50	37.48	14.10	37.62	1.23	S. active	55.64	Smectite, chlorites, L.A.C
	Subsoil	14.72	15.61	0.93	56.50	22.14	6.53	29.49	0.39	Se. active	33.43	Smectites, L.A.C
KS18 3100, *U.D*	Topsoil	14.12	16.35	9.85	32.50	44.55	28.20	63.30	1.37	S.active	31.00	Smectites, L.A.C
	Subsoil	8.44	12.27	1.14	51.50	20.64	8.37	40.55	0.40	Active	32.33	Smectites, L.A.C
KS19 3800, *H.W*	Topsoil	9.24	10.06	8.78	30	41.05	30.99	75.49	1.37	S. active	34.40	Smectites, L.A.C
	Subsoil	2.96	3.63	2.35	38	22.81	19.18	84.09	0.60	S. active	38.38	Smectites, L.A.C

* = Average; C.E.A.C = Cation activity class; V.N.C = Variable negative charge; L.A.C = Low-activity clay; S. = Supper; Se. = Semi; L.W.D = Lower-Woina-Dega;*
*** The order of the estimated clay mineral groups as written from left to right denotes their degree of importance; P.W.D = Proper-Woina-Dega; U.W.D = Upper-Woina-Dega; L.D = Lower-Dega; P.D = Proper-Dega; U.D = Upper-Dega; H.W = High-Wurch.*

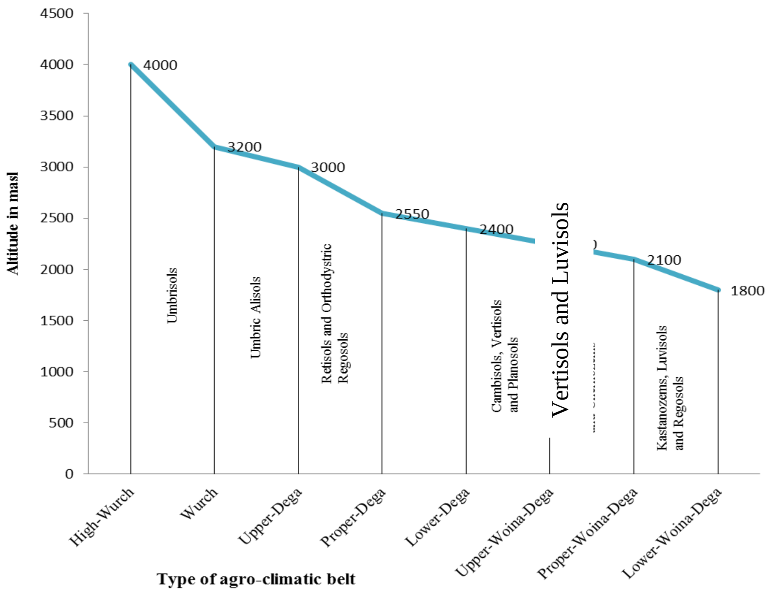


Figure 3. Sequential soil-agro-climate relationship of the identified soil groups (as adapted from MOA (1998) and Lakew *et al.* (2005)

This may occur as a result of lower temperatures that slow down the chemical reactions (chemical weathering) when compared to the warm humid tropical areas where there is both high rate of chemical weathering and leaching that causes the predominance of the low-activity clays in soils such as Ferralsols of the FAO/IUSS-WRB (2015) classification system.

Agro-climatically, the occurrence of the Reference Soil Groups (Figure 3) was in the order of *Lower-Woina-Dega* (Kastanozems and Hypereutric Regosols), *Proper-Woina-Dega* (Chernozems and Vertic Luvisols), *Upper-Woina-Dega* to *Lower-Dega* (Planosols, Cambisols, Luvisols and Vertisols), *Proper-Dega* (Retisols and Regosols (Orthodystric)), *Upper-Dega* (Umbric Alisols) and *High-Wurch* (Umbrisols). On the other hand, the occurrence of Regosols and Leptosols appeared not to be linked to the agro-climatic variation within the study area, but rather seemed to be related to the slope gradient of the land surface since they were found on any steep land surface irrespective of the agro-climatic belts or the altitudinal variations.

In summary, the strong variations observed in several morphological, chemical and physical soil properties and in the diagnostic soil characteristics (diagnostic horizons, properties and materials) and thereby also in the occurrence of the identified Reference Soil Groups were found to be mainly the results of strong physiographic and climatic diversity of the study area. Thus, in the E.2.03-type

Rainfall Pattern Region of the Arsi highlands, the general relationship observed between the traditional agro-climatic belts and the trend of pedogenesis (soil development), indicated that the elevation related differences perceived by the Ethiopian farmers in relation to their agricultural activities, is also valid for the trends in pedogenesis observed in this study within Kulumsa Subwatershed. However, for more reliable conclusion and holistic understanding of the pedogenesis under the physiographically and climatically diversified similar Ethiopian environments, this needs more detailed study that includes the other Rainfall Pattern Regions of Arsi and of the country as well.

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