CHARACTERIZATION AND CLASSIFICATION OF SOILS ALONG A TOPOSEQUENCE AT DHENGEGO SUBWATERSHED, EAST HARARGHE ZONE, ETHIOPIA

MSc THESIS

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JUNE 2023
HARAMAYA UNIVERSITY, HARAMAYA

Characterization and Classification of Soils along a Toposequence at Dhengego Subwatershed, East Hararghe Zone, Ethiopia

A Thesis Submitted to the School of Natural Resources Management and
Environmental Sciences, Post Graduate Program Directorate
HARAMAYA UNIVERSITY

In Partial Fulfillment of the Requirements for the Degree of
MASTER OF SCIENCE IN AGRICULTURE (SOIL SCIENCE)

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June 2023
Haramaya University, Haramaya

HARAMAYA UNIVERSITY
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We hereby certify that we have read and evaluated this Thesis entitled **“Characterization and Classification of Soils along a Toposequence at Dhengego Subwatershed, East Hararghe Zone, Ethiopia”** prepared under our guidance by **Mekonnen Keneni Gameda**. We recommend that it be submitted as fulfilling the Thesis requiremen

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DEDICATION

I dedicate this Thesis manuscript to my wife Ayantu Feyissa and my children Meti Mekonnen and Geda Mekonnen for nursing me with affection, love and for their dedicated partnership to the success of my work.

STATEMENT OF THE AUTHOR

By my signature below, I declare and affirm that this Thesis is the result of my work and I have followed all ethical and technical principles of scholarship in the preparation, data collection, data analysis and compilation of this Thesis. Any scholarly matter that is included in the Thesis has been given recognition through citation.

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BIOGRAPHICAL SKETCH

The author, Mr. Mekonnen Keneni Gameda was born in Meta Walkite, West Shoa Zone, Oromia Regional State, Ethiopia, on July 18, 1984. He attended his junior and elementary education from 1993 to 1999 at Mugher Mokoda Elementary School. Then he attended his Senior Secondary Education from 2000 to 2003 at Holeta Comprehensive Secondary and Preparatory School. After completing his secondary education, he joined Nedjo Agricultural Technical Vocational Educational and Training College from 2004 to 2006 and graduated with a Diploma in Natural Resource in 2006. After graduation, he was employed by the zonal agricultural office of West Shoa Zone and served in Jeldu and Meta Robi *Woreda*s until 2013. In 2013, he was employed by Haramaya University as Technical Assistant and served for two years. Then, he upgraded his study and graduated with a Bachelor of Science degree in Natural Resources Management in 2018. Soon after graduation he was promoted to the rank of Assitant Lecturer and worked in the School of Natural Resources Management and Environmental Sciences until he joined the postgraduate program at Haramaya University in 2020 to pursue his MSc studies in Soil Science.

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ACKNOWLEDGEMENTS

Heartfelt gratitude goes to my major advisor, Dr. Samuel Feyissa for his unreserved support and encouragement which I enjoyed throughout the course of the study. His thorough review and constructive criticisms and suggestions on the manuscript were among the most important factors that enabled me to shape this Thesis in its final form. In addition, I would like to express my heartfelt and special gratitude to my co-advisor Dr. Alemu Kebede, for his profound and genuine guidance in all directions especially during the field survey.

I would like to acknowledge the Ministry of Education and Haramaya University, for financing all the expenses required for the study. I am also grateful to Haramaya University Soil Chemistry Laboratory technicians for their invaluable support and continuous encouragement in many ways during laboratory analysis work.

My sincere gratitude goes to Mr. Sisay Kasahun and Matios Ware for their unconditional help during sample collection. Finally, I am also pleased to express profuse thanks to all my family members for their prayers, moral support, encouragement and valuable advice during my study.

ACRONYMS AND ABBREVIATIONS

AAS	Atomic Absorption Spectrometer
AWC	Available Water Content
AD	Awudawit
BG	Biftu Geda
Pb	Bulk Density
CEC	Cation Exchange Capacity
EH	East Haraghe
EC	Electrical Conductivity
ESP	Exchangeable Sodium Percentage
FAO	Food and Agriculture Organization of the United Nations
GB	Genda Bukusho
GH	Genda Hassan
GE	Gende Erga
GIS	Geographical Information System
HW	Haramaya *Woreda*
IUSS	International Union of Soil Science
Masl	Meter above sea level
OC	Organic Carbon
OM	Organic Matter
Ps	Particle Density
PBS	Percentage Base Saturation
PWP	Permanent Wilting Point
RSG	Reference Soil Group
SOM	Soil Organic Matter
TN	Total Nitrogen
USDA	United States Department of Agriculture
WRB	World Reference Base for Soil Resources

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ABSTRACT

Characterization and classification of soil is the main source of information for precision agriculture, land use planning and management. For an efficient use of the limited land resources, site specific management recommendations based on site specific information are much required. Undulating topography, altitudinal differences and large variations in slope were characteristic features of the present study area (*Dhengego subwatershed*)*. The purpose of the present study was to characterize, classify and map soils of Dhengego subwatershed along the hill-slope to generate baseline information. Four representative pedons were opened and described at four topographic positions (summit, upper, middle and lower slope). One pedon was opened for each topographic position and described in the field and sampled basd on standard description sheet. A total of 30 soil samples 15 diturbed and 15 undistarbed were collected from the genetic horizons of each pedon for laboratory analysis of the selected physicochemical properties of the soils. The morphological description of the pedons showed that the effective soil depth of the study area was greater than 200 cm for pedon 3 and 4, but was less than 200 cm for pedon 1 and 2. The soil description and analysis results revealed also variations in the other morphological physical and chemical properties of the soils along different topographic positions. The soil structure of all pedons at the upper horizons was moderate to moderately strong granular that gradually changed to moderately sub-angular to angular blocky aggregates with increasing soil depth. Sand sized fraction dominated the texture of soils in the study area and loose to friable moist consistence was observed at the surface horizons of almost all pedons, which changed to firm consistence with increasing depth only in pedon 4. The soils had a neutral to slightly alkaline reaction (6.74-7.74) throughout their profile. The organic carbon content of the study area ranged from low to hihg (0.71 to 3.07%). Total nitrogen, available phosphorus, cation exchange capacity and percent base saturation of the soils were in the range of (0.13-0.22%), (6.7-25.90 mgkg^{-1}), (24-51 cmol(+)kg^{-1}) and (60-99.6%), respectively, which were rated as moderate, high, high to very high and also high to very high, respectively. The concentration of micronutrients in the soils were high for Fe, medium to very high for Mn, very low to low for Zn and medium to high for Cu. The soils were classified into different Reference Soil Groups following the FAO-WRB of 2015 by detecting diagnostic characteristics (horizons, properties and materials). The soil classification revealed that three Reference Soil Groups, namely, Regosols, Phaeozems and Luvisols; the second level detailed naming of which would be Eutric Epileptic Regosol (Humic, Loamic, Mollic) for pedon 1, Cambic Phaeozem (Hypereutric, Profundihumic, Pantoloamic) for pedon 2, Calcaric Phaeozem （Humic, Pantoloamic) for pedon 3 and Endocalcaric Luvisol (Humic, Katoloamic) for pedon 4. The equivalent names of the USDA-Soil Taxonomy were: Lithic Ustorthents for pedon 1, Typic hapludolls for pedon 2 and 3 and Udic haplustalfs for pedon 4. Since almost all the soils identified were of ample fertility status especially in terms of their base saturation but prone to topographically exacerbated soil degradation, special emphasis should be given to soil OM and integrated soil fertility management coupled with soil and water conservation measures to optimize and sustain crop production in Dhengego subwatershed.*

Keywords*: Pedon, diagnostic characteristics, genetic horizons, reference soil groups, topographic position.*

1. INTRODUCTION

Soil represents the most important component of the lithosphere (earth's crust), being involved in environmental changes through direct interaction with the atmosphere, hydrosphere and living organisms (Osman, 2012). It consists of mineral particles, organic matter (OM), water, air and living organisms, and is an extremely complex and variable medium (Nicolaescu *et al*., 2009).

Soil is a slowly renewable dynamic natural resource that determines the ultimate sustainability of any agricultural system. Soils provide food, fodder and fuel for meeting the basic human and animal needs (Schoonover and Crim, 2015). However, due to the steadily increasing population with inappropriate land management practices prevalent in developing countries, the nutrients have been depleted and the productive capacity of soils has diminished through changes in soil characteristics (Bot and Benites, 2005). This demands systematic evaluation of soil resources with respect to their extent, distribution, characteristics and use potential, which is very important for developing an effective land use system for precision agricultural production on a sustainable basis (Pulakeshi *et al*., 2014). Soil is an ecosystem that can be managed to provide nutrients for plant growth, absorb and hold rainwater for use during dry periods, filter and buffer potential pollutants and provide habitat for soil microbes to flourish and diversify in order to keep the ecosystem running smoothly (Blanco and Lal, 2008).

Soil is a valuable resource and a critical component in many of the environmental and economic issues facing today's society (Vanlauwe and Giller, 2006). The inherent ability of soils to supply nutrients for crop growth and maintenance of soil physical conditions to optimize crop yields is the most important component of soil fertility that virtually determines the productivity of agricultural system (Vanlauwe and Giller, 2006).

Soils have diverse morphological, physical, chemical and biological properties. As a result, they differ in their responses to management practices, their inherent ability to deliver ecosystem services as well as their resilience to disturbance and vulnerability to degradation (Bruinsma, 2017). A thorough and proper understanding of morphological, physical and chemical characteristics and classification of soils (Basavaraju *et al*., 2005) gives greater insight into the dynamics of the soil and also aids land use plan to protect our finite soil resources to achieve sustainable crop production. Characterization and classification of soils is therefore of paramount importance in using them based on their capability and to manage them in a sustainable manner. Soil information obtained through systematic identification and grouping of soils eases effective planning of different land uses, as it provides information related to potentials and constraints of the land (Lufega and Msanya, 2017).

Detailed soil survey is useful in selecting sustainable agricultural land use options. It also provides adequate information in terms of landform, slope, land use and on the characteristics of soils such as texture, depth, structure, stoniness and drainage, which can be utilized for the planning and development (Pinki *et al*., 2017). Soil characterization studies are major building blocks for understanding the soil, classifying it and for the understanding of the soil's environment (Certini and Scalenghe, 2007). Soil characterization provides the information for our understanding of the physical, chemical, mineralogical and microbiological properties of a soil (Certini and Scalenghe, 2007). It also helps to organize our knowledge, facilitates the transferring of experience and technology from one place to another (Chekol and Mnalku, 2012). In Ethiopia, the soil characterization studies made so far were mostly at small scale, which could not be applicable for site specific land use and soil management (Elias, 2017). Therefore, adequate knowledge on soil characteristics at large scale or watershed or farm level is essential in tackling specific and local problems of agricultural production.

Soil properties such as clay content and its distribution with depth, sand content and pH have been shown to be highly correlated with slope position (Mulugeta and Sheleme, 2010), and the same true for organic matter (Miller *et al*., 1990). Research reports indicated, that the depth of A-horizon decreases with increasing slope gradient, whereby the soils at the shoulder are shallow due to erosion while those at foot slopes are thicker due to deposition (Mulugeta and Sheleme, 2010). Soil formation in most pedons is characterized by clay illuviation from the surface to the subsurface soil horizons (Fekadu *et al*., 2018).

Topography influences the soil formation along the toposequence, whereby the soils on upper slope positions may develop from *in situ* weathering of the parent material, whereas continuous removal of materials from the upper slope positions and hilly locations and their deposition in depressions may result in development of soils of different geological origin causing lithological discontinuities (Sheleme 2017). Topography gives rise to toposequence of related soils from the same parent materials, about the same age under similar climatic conditions that may have differences in their characteristics due to changes in slope (Brady and Weil, 2004). As a general rule, soil profiles on the convex upper slopes are shallower and have less distinct subsurface horizons than soils at lower slope (Mulugeta and Sheleme, 2010). Topography plays a major role as one of the factors that influence pedogenesis and in the process that dictates the distribution and use of soils in the landscape (Esu *et al.*, 2008). Topography also strongly affects geomorphic processes such as water erosion and sedimentation, creep and land sliding due to the effect of topography on the distribution of energy and water (Certini and Scalenghe, 2007).

Undulating topography, altitudinal differences and large variations in slope are characteristic features of the present study area, namely, Dhengego subwatershed that may in turn result in large variations in soil types. However, soils of this area, where agricultural activities are underway for many decades, have not yet been characterized in terms of their morphological, physical and chemical characteristics and classified for sound land management alternatives. On the other hand, farmers continued to use the land with limited input and the prevailing land use systems and management interventions are not supported by information that shows the potentials and constraints of soil resources. Meanwhile, land degradation due to the use of incompatible land management practices has continued, as a consequence of which the production and productivity of the smallholder farmers' subsistence farming is declining from time to time (Barbier and Hochard 2018). This decline in production and productivity has been threatening the food and nutrition security of the community in the study area (Barbier and Hochard 2018).

In order to use the limited land resources more efficiently, site specific management recommendations based on site specific information are very much required. The purpose of the present study was to characterize, classify and map soils of Dhengego subwatershed along the toposequence to generate baseline information, which may be helpful to formulate appropriate management alternatives for different soil types. Accordingly, the specific objectives of the study were :

- To characterize the soils, along different topographic positions, based on their morphological, physical and chemical properties.
- To classify and map the soils according to the FAO-World Reference Base of soil classification system and USDA-Soil Taxonomy.

2. LITERATURE REVIEW

2.1. Soil Forming Factors

Soils vary from place to place due to differences in the distribution of soil forming factors and processes. Factors such as parent materials, topography, biota and climate in combination with various forms of anthropogenic activities affect soil properties in a given locality. Dokuchaev and his coworkers were the first to develop the concept of soil as an independent natural body with unique properties that result from the influence of a unique combination of soil-forming factors (climate, organisms, parent material and time). These Russian workers stated that properties of soils reflect the combined effects of the particular set of genetic factors responsible for their formation (Baldwin. *et al*., 1938). According to Jenny (1994), soil-forming factors are not formers (creators), but are state factors that define the state of the soil system as they lead to the action of a particular set of soil-forming processes that bring about change in soil properties. Hence, soils are found to be the same whenever all the elements of the soil-forming factors and the respective soil-forming processes are the same, so that under similar environments in geographically different places, soils are similar (Baldwin. *et al.*, 1938).

Topography or relief is the most important factor for soil formation and affects how water and energy were added to and lost from soil. Likewise, topography is central to the catena concept of soil development (Hook and Burke, 2000), which is characterized by leaching and redistribution of soil material downhill slope. Topography is an intrinsic factor in soil formation that also influences potential land use, though land use-land cover also has the potential to modify soil properties such as soil organic matter and nutrient levels (Baskan and Gunturk. 2016). (Nahusenay *et al*., 2014), revealed that the lower topographic pedons were deeper, high in clay accumulation and gently sloping (2-4%). According to these authors, 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.

Any particular combination of soil forming factors will give rise to certain soil-forming process, which are a set of physical, chemical and biological processes that create a particular soil (Van Breemen and Buurman, 2002). Any soil property should then depend on the resultant of the interactions of these factors (Osman, 2012), so that similar soils will develop under similar set of factors. On the other hand, under similar sets of organisms, parent material, relief and time, differences in properties between two soils would be brought about by climate alone (Osman, 2012).

2.2. Soil Forming Process

Genesis (origin) of soil describes in details the formation of soil from rocks under the influence of pedogenic (soil forming) factors (Hartemink and Bockheim, 2013). Soil formation is a global biospheric process, and as a result of its manifestation a soil attains a number of characteristics, which are absent in soil forming rock and those distinguish soil from other components of the biosphere (Vladychenskiy, 2004). Soil forming process takes place due to the interaction of five major factors, according to (Jenny, 1994), which are time (T), climate (C), parent material (P), topography or relief (R), and organisms (O). The formation of a soil from raw parent material or from a pre-existing soil encompasses the concept of soil genesis, or pedogenesis. The link between soil genesis and classification is envisioned as follows: soil-forming factors → soil-forming processes → diagnostic characteristics → soil taxonomic system (Bockheim & Gennadiyev, 2000).

Addition of materials and energy in soil generally takes place from the atmosphere, organism, rocks and minrals, and graund water. Atmosphere provides the inputs of solar energy ,moisture, gases, dusts and sometimes pollutants (Pierzynski *et al*., 2005). The amount solar energy received by a soil depends on geographical location, topography, mineralogical composition, degree of moisture saturation, etc (Osman, 2012). Ammount, intensity and distribution of rainfall determinats of water receipt depend on climatic conditions of rain water may couse transformation and removal (Osman K.T 2013). Matrials are removed from soil by volatilization and evaporation to the athmosphere in solution and suspension in water downward, upward and in lateral directions and outside the soil by biomass harvest (Osman K.T 2013).

Aggregation is affected by colloids, clay, humus, cementing agents, lime, Ca^{2+} ions and microbial products and binding agents, plant roots, fungal hyphae, etc (Osman, 2012). Flocculation of colloidal which is physicochemical transformation is the intial step of aggregation. Formation of clay humus complex is also important for aggregation. Chemical transformations includes solution, hydration, hydrolysis, oxidation, reduction, carbonation and othr acid readctions (Chadwick and Chorover, 2001). Translocation of materials occurs in all directions of the soil lateral, upward, and downward. This may take place in solution and suspension or as mass movement along cracks and channels (Osman, K.T., 2013).

When soil materials move downward with water and are lost from the soil body, it is called leaching. If movement takes place from an upper horizon to a lower horizon, it is known as eluviation (Mirsal and Mirsal, 2008). Eluviation occurs usually from the surface horizons. However, under prolonged weathering in humid conditions, eluviation of bases, humus, clay minerals, and sesquioxides may create a bleached gray horizon enriched with silica (denoted by E) below the A horizon. E horizons are common in Alfisols and Spodosols (Lavelle and Spain, 2001). Translocation of clay-sized particles in suspension is called lessivage or argilluviation (L. *argilla*, white clay; *luv*, washed). Although most lessivage occurs from the upper profile to the lower (from A and E horizons to B horizon), the process does occur laterally as well. Eluvial materials are deposited in the B horizon either by coagulation, precipitation, or by mechanical impedance.

Removal of calcium by decalcification in the upland removed calcium with percolating subsurface and surface water and deposited calcium rich water in the low lying topographic position (Abdena *et al*,. 2018). Upon drainage of percolation water, calcification process formed calcium carbonate in the subsurface horizons (Abdena *et al.*, 2018). This formed a calcic horizon. Pedoturbation (vertization) process formed Vertisols with wedge shaped, massive, and polished aggregates with tapering edge, shrink swell properties and gilgai micro-relief formation at low lying topographic position at foot slope position with imperfect drainage (Abdena *et al.*, 2018; Kebeney *et al.*, 2014) describes the similar central concept of Vertisol as a clayey shrinking-swelling soil that has cracks that open and close periodically, and a layer 25 cm thick or more 42 with either slickensides or wedge-shaped peds within 100 cm of the mineral surface.

As indicated by (Abayneh *et al.*, 2006), the relative difference in Si concentration between surface and B horizons is more discernible in the soils derived from ignimbrite. This is due to the relatively higher quartz content in these soils and its residual accumulation in the surface soils as a result of differential runoff of finer particles and eluviations of colloidal constituents

(Abayneh *et al*., 2006). The trend of Fe and Al concentrations up the profile is the opposite of the other elements (Abayneh *et al*., 2006). The increase in their concentrations between saprolitic layers and B horizons indicates their relative stability and accumulation as a result of leaching losses of other constituents. The relative decline in their concentrations in the surface horizons is attributed to translocations (as colloidal particle) into the subsurface horizons, relative increase in concentration of other cations, and possibly runoff losses (Abayneh *et al*., 2006).

2.3. Selected Morphological Characteristics of Soils

Morphological characteristics of soils such structure, color, depth and drainage, vary with changes in slope position. Morphological description of a soil is one of the most important tools of soil classification, since it is performed under natural soil condition. In order to place a soil in its correct position in the classification system, tangible information on the morphological characteristics is necessary; whereby the following morphological parameters are considered as the most important for the review.

2.3.1. Soil Depth

The original definition of the solum was the topsoil (‘A’ horizons) and subsoil that includes ‘E’ and ‘B’ horizons; where the ‘C’ horizons were defined as substrata with little evidence of pedogenesis (Prathibha et al., 2018). The “effective” soil depth then was considered as the solum thickness (Prathibha *et al*., 2018). However, roots and biological activity occurs often in the C horizon and effective soil depth should hence include this layer (Prathibha *et al*., 2018). In practice soil surveys use arbitrary limits of depth (*e.g* 200 cm) to study soils (MacDicken, 2015). For any given soil, the greater the rooting depth, the larger will be the quantity of soil water available to the crop Bodner *et al.,* 2015). This is particularly important for annual crops as they have less time to develop deep and extensive rooting systems than perennial crops (Bodner *et al*., 2015).

Solum depth reflects the balance between soil formation and soil loss by erosion in any area which in turn are governed by topography and slope (Prathibha *et al*., 2018). Generally, shallow soils above bedrocks develop on sloping surfaces. Usually a thin A horizon develops over the thin C horizon (Osman, 2012). Such thin soils were earlier known as Lithosols (Osman, 2012);

whereas on gentler slopes, well-developed B horizon may be found. The depth of soil thus depends on the degree of slope. Sometimes erosion removes the entire A horizon exposing the B horizon. If the degree of slope is very high and the soils are not stabilized by vegetation or if the vegetation is removed by deforestation, such soils may be completely removed exposing the underlying rock (Osman, 2012).

2.3.2. Soil Color

Soil color reflects the composition as well as the past and present oxidation reduction conditions of the soil (Retallack 2008). It is generally determined by coatings of very fine particles of humified organic matter (dark), iron oxides (yellow, brown, orange and red), manganese oxides (black) and others, or it may be due to the color of the parent material (Retallack 2008).

The dark color in surface horizons might be attributed to the effect of higher organic matter 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 organic matter content (Nahusenay *et al.,* 2014). In line with this result, several authors reported that the surface horizons have darker color than the corresponding subsurface horizons as a result of relatively higher soil organic matter contents (Dessalegn *et al*., 2014; Ali *et al*., 2010; Demis and Sheleme, 2010). The findings by Ringer *et al*. (2021) proved that soil color could be related to organic matter, water logging, carbonate accumulations and redoximorphic features. Similarly, this gradation in soil color is ascribed to varied chemical and mineralogical composition, topographic position, textural make up and moisture regimes of the soils.

2.3.3. Soil Structure

Soil structure refers to the natural organization of soil particles into discrete soil units (aggregates or peds) that result from pedogenic processes (Sitanggang *et al.,* 2006), whereby the clumping of the soil textural components of sand, silt and clay forms aggregates and the further association of those aggregates into larger units forms soil structures called peds. The aggregates are separated from each other by pores or voids. Weak structural development is ascribed to low clay and low organic carbon content (Sitanggang *et al*., 2006). The soil structure affects aeration, water movement, conduction of heat, plant root growth and resistance to erosion. (Rengasamy *et al*., 2022)

As reported by Usman *et al.* (2018) the structure of the soil at the summit areas was fine to medium crumb, while that of the soil at the toe slope was fine to very coarse blocky at the surface. Such structure in the horizons might be due to the relatively high OM and low clay content of the soils, which are suitable for agriculture because they are easy for plowing (Foth 195). In the subsurface horizons, soil structure changed to blocky with subangular variants with variations in grade and size (Mulugeta, 2010). The strong structure in the soils could be attributed to the high clay content. According to (Ozsoy and Aksoy, 2012) the high clay content in soils brings out excessive shrink-swell actions during drying and wetting cycles.

2.3.4. Soil Consistence

Consistence refers to the degree of cohesion or adhesion of the soil mass. It includes soil properties such as friability, plasticity, stickiness and resistance to compression (Bell, 2013). It depends greatly on the amount and type of clay, organic matter and moisture content of the soil (Bell, 2013). Most of the time consistence is described for three moisture levels; wet, moist, and dry (Buol *et al*., 2003). It is a term used to describe the action of physical forces of cohesion and adhesion on the attributes of soil material at these moisture contents that determines the resistance of soil material to crushing or rupture and its ability to change the shape or to be molded. According to Endalkachew *et al* (2018), soil friability indicates that soils are workable at appropriate moisture contents and lack of very sticky and very plastic consistency.

Consistence is an inherent soil characteristic which can be changed by the presence of high organic matter in the surface horizon (Heluf and Wakene, 2006). As indicated by (Mulugeta *et al*., 2018), differences in soil consistence can be explained by the differences in particle size distribution, particularly clay content, OM and nature of the clay particles. As reported by (Moradi, 2013), soil consistence varied with soil texture. (Demis and Sheleme 2010) also pointed out that the friable consistence observed in the surface soils of the pedons could be attributed to the higher soil OM content. The soil became harder, more firm, sticky and plastic with increasing depth owing to progressive increase in clay content with depth (Demis and

Sheleme, 2010). The land attribute and relief are reported to have significant bearing on soil consistency (Mahapatra *et al*., 2000).

As indicated by (Abdenna *et al*., 2018), at upper and middle landscape positions, soils were workable at moist and wet conditions, whereas at lowland position, workability becomes difficult due to firm soils and very plastic and very sticky soil conditions. Change in soil consistence from higher to lower topographic positions could be due to change in clay minerals as suggested by (Velde & Meunier, 2008).

2.3.5. Coatings and Mineral Concretions

According to Abdenna *et al*. (2018), differences in the abundances of coatings and concretions were connected to slope positions and land uses (plantation and tillage), which would have affected lateral and horizontal movements of solutions and plasma; whereas 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 (Ali *et al*., 2010). Coatings denote clay or mixed-clay illuviation features, coatings of other composition (such as calcium carbonate, manganese, OM or silt), reorientations (such as slickensides and pressure faces), and concentrations associated with surfaces but occurring as stains in the matrix “hypodermic coatings” (Liu and Chen 2004). All these features are described according to their abundance, contrast, nature, form and location (Liu and Chen, 2004).

2.3.6. Horizon Designation and Boundary

The soil horizon designation summarizes many observations of the soil description and gives an impression about the genetic processes that have formed the soil under observation. Soil morphological and other characteristics are presented as they are described by horizon (Camino-Serrano et al., 2014). The differences in nature of the horizon boundaries may indicate the existence of variations in the processes of soil formation and may partly reflect anthropogenic impacts (Camino-Serrano *et al*., 2014). Under special circumstances such as variation in color, texture and structure, by close examination of the soil profile, the B and C horizons often need to be subdivided even after using the subordinate distinctions (Osman, 2012). These subdivisions are denoted by Arabic numerals such as B2t. However, a soil profile may contain all the master horizons or may lack one or more of them. There are ample examples of A–C, A–B–C, A–E–B–C, and B–C profiles (Osman, 2012). In some very steep slopes, all the genetic horizons may be removed by erosion exposing the C or R to the surface (Osman, 2012).

2.4. Selected Physical Properties of Soils

2.4.1. Soil Texture

Soil texture, which is defined as the relative proportions of the primary soil particles or soil separates (sand, silt and clay) influences the suitability of soils for most agricultural uses and hence its knowledge and investigations are crucial as these allow to make inferences about use related important soil characteristics (Coyne *et al*., 2006). Textural variation is ascribed to differences in composition of parent material, topography, in-situ weathering and translocation of clay by eluviation and age of soils (Geetha Sireesha and Naidu, 2013). Maniyunda *et al*., (2014), indicated that silt and clay soil fractional contents increased while sand decreased along the toposequence with moisture and other soil materials. The sand content was found to be higher in surface horizons, whereas higher clay content was found in the sub-surface horizons because of the eluviation of fine fractions from the surface layers (Amara *et al.*, 2022). Heavy clay texture of the lower topographic positions 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 pedon (Daniel and Tefera, 2016). Lack of definite trend in soil separates along the topographic position might be due to the dominance of erosion and accumulation in influencing the pedogenic processes (Hailu *et al*., 2015), whereas irregular trend with depth, might be due to variation in weathering of parent material (Sekhar *et al*., 2014).

2.4.2. Bulk and Particle Density

Bulk density is an indicator of soil compaction. It is calculated as the oven dry weight of soil divided by its volume and expressed in g/cm^3. This volume includes the volume of soil particles and the volume of pores among soil particles. Particle density is the density of the solid particles that collectively make up a soil sample, the value of which is commonly expressed in grams per cubic centimeter. Bulk density increased with depth primarily because of the decrease in soil OM content as was indicated by the significant negative correlation between the two properties (Damis and Sheleme, 2010). Soils that are loose, porous or well aggregated usually have lower bulk densities than soils that are compacted or non-aggregated as the air within pore spaces weighs less than the solid soil particles (Damis and Sheleme, 2010). According to (Landon, 2014), soil bulk density has a major impact on the dynamics of water and air in the soil and crop root development which ultimately affects crop growth and yield. The bulk density in soils, irrespective of landforms, increased with depth which might be due to weight of the overlying soil and the relatively low amount of OM in the subsurface soil layers. Similarly, (Chaudhari *et al*., 2013) reported increase in bulk density with pedon depth, due to changes in OM content, porosity, and compaction.

Particle density is the average density of the soil particles, not including fluid or pore space, and is usually expressed in grams per cubic centimeter. For many mineral soils, the particle density ranges from 2.60 to 2.75 g/cm3 (Hillel, 2012). The presence of iron oxides and various heavy minerals increases the average value of particle density, whereas the presence of organic matter lowers it (Philippe and Schaumann 2014). Accordingly , the surface soil layers possessed lower particle density values than the subsoil horizons, and the highest particle density (2.93 g/cm^3) was obtained at the subsoil horizon (57–95 cm depth) in grazing land soils of the middle elevation. The value cited for clay soils is 1.4 g/cm3 (Hazelton and Murphy, 2016).

2.4.3. Total Porosity

Soil porosity is an indication of the total volume of voids which is measured and recorded as the percentage of the volume occupied by pores. According to (Shah *et al*., 2017), total porosity decreases with soil depth as a result of increasing compaction, decreasing of rooting effect and organic matter content with depth. (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 %. The pore spaces exist because of the particle and the disturbance including those due to roots, soil animals, swelling, cracking on shrinking and tillage that alter the spacing of aggregates or particles (Ghezzehei, 2012). Total porosity decreasing with an increase in depth is apparently due to increasing bulk density with depth (Pietola *et al*., 2005) and ranges to affect soil properties and root growth depends on texture.

2.5. Selected Chemical Properties of Soils

Soil chemical properties are those soil attributes that are responsible for and take part in the chemical reactions and processes of the soil and are the results of weathering of their mineral components, decomposition of organic materials and the activity of plants and animals residing in the soil (Bohn *et al*., 2015). Among the many soil chemical characteristics, the following are selected for the purpose of soil classification.

2.5.1. Soil pH and Cation Exchange Capacity

Soils with high percent base saturation have a higher pH; therefore, they are more buffered against acid cations from plant roots and soil processes that acidify the soil. Lower pH value was recorded in steep slope position as compared to the gently sloping landscapes, perhaps due to the removal of bases from the higher slope areas and their accumulation on gentle and moderate slopes corroborating the findings of (Damis and Sheleme, 2010). The lowest and highest values of total exchangeable bases were noticed at the highest slope position and depression respectively, indicating the removal of exchangeable bases from steep slopes and their accumulation in flat areas (Sheleme, 2017).

According to Landon (2014), cation exchange capacity (CEC) values less than 5 are rated as very low, 5 - 15 as low; 15 - 25 as medium, 25 - 40 as high and > 40 as very high. The higher CEC values in surface layers of the pedons along with the upslope positions as compared to their subsurface counterparts could be attributed to the effect of the relatively higher organic matter content of the surface layers, since organic matter is strongly associated with CEC as was also discussed by (Sheleme, 2017). Cation exchange capacity is the measure of a soil to retain readily exchangeable cations which neutralize the negative charge of soils. The negatively charged sites make up the CEC as the ability to hold the cations such as H^+, $Ca^{2+,}$ Mg^{2+}, Na^+, and $NH_{4+,}$ etc., and the positively charged sites, which hold OH^-, SO_4=, NO_{3-}, PO_4=, etc., make up the anion exchange capacity (Mukhopadhyay *et al.*, 2019). Ions held at these sites can be exchanged with others of similar charge. Cation exchange capacity is an important index of nutrient status because exchangeable cations are the most important source of immediately available plant nutrients (Mukhopadhyay *et al*., 2019).

2.5.2. Carbonates, Base Saturation and Electrical Conductivity

Total exchangeable bases and base saturation of the soils were influenced by slope classes, whereby lower slope and depression had higher exchangeable bases and base saturation as compared to those on upslope positions (Sheleme, 2017). This could be attributed to the transport of soil materials from upslope positions and their deposition on the lower slope and depression as proved by (Sheleme, 2017). Higher exchangeable bases and base saturation values were recorded in the B horizons owing to the very high smectite clay content and eluviation from the upper horizons, which contributes higher CEC/kg clay (Abayneh *et al*., 2006).

Percent Base saturation (PBS) is an important soil chemical property which has implications both for soil taxonomic classification and soil fertility. PBS is defined as the sum of four basic cations (Ca, Mg, K, and Na) relative to total soil cation exchange capacity (CEC) at pH 7.0 or 8.2 (Bohn *et al*., 1979). Furthermore, PBS is a dynamic soil property affected by climatic, geochemical, and environmental conditions (Osman, 2012). Increases in BSP can elevate plant availability of Ca^{+2}, Mg^{+2}, and K^+ (Rawal *et al*., 2019).

Soil salinity indicates the concentration in the soil pore water of major dissolved ions, mainly Na^+, Mg^{2+}, Ca^{2+}, Cl^-, $SO4_{2-}$, HCO_{3-} and in some instances also CO_{32-} (Visconti *et al*., 2016). In agricultural lands, K^+ and NO_{3-} also may become major ions and thus significantly contribute to salinity. All these ions build up in soils as a consequence of both evaporation and plant transpiration, which extracts almost pure water from soils while leaving its salts behind, and also as a consequence of fertilization practices (Visconti, and de Paz, 2016).

Soil electrical conductivity (EC) is a measure of the amount of salts in soil (salinity of soil). It is an important indicator of soil health (Pourrut *et al*., 2011). It affects crop yields, crop suitability, plant nutrient availability, and activity of soil microorganisms which influence key soil processes including the emission of greenhouse gases such as nitrogen oxides, methane, and carbon dioxide (Pourrut *et al*., 2011).

Carbonates in soils are either residues of the parent material or the result of neo-formation (secondary carbonates) (Jahn *et al*., 2006). The latter are concentrated mainly in the form of soft powdery lime, coatings on peds, concretions, surface or subsoil crusts, or hard banks. The presence of calcium carbonate ($CaCO_3$) is established by adding some drops of 10-percent HCl to the soil (Jahn *et al*., 2006). A calcic horizon is a horizon in which secondary calcium carbonate ($CaCO_3$) has accumulated in a diffuse form (calcium carbonate occurs as impregnation of the matrix or in the form of fine calcite particles of < 1 mm, dispersed in the matrix) or as discontinuous concentrations (Sarmast *et al*., 2016).

2.5.3. Organic Carbon and Total Nitrogen

Soil organic carbon and total nitrogen are the key indicators for estimating soil quality and act as important carbon and nitrogen reservoirs (Watson *et al.,* 2000). The chemical composition of soil organic matter influences carbon and nutrient dynamics through the rapid degradation of its constituent substances (Lehmann and Kleber, 2015). Plant's nutrient content is therefore the main factor responsible for differentiating the chemical properties of organic matter in soils (Banville, 2009). As indicated by (Daniel and Tefera 2016), lower slope positions have relatively low SOM contents than the upper ones, which may be due to the continuous cultivation, burning of farm lands and removal of crop harvest for many purposes.

Intensive and continuous cultivation aggravates OC oxidation resulting in reduction of TN as compared to virgin land according to (Assai and Heluf, 2003); (Abera and Kafyalew, 2017), who reported that intensive and continuous cultivation forced oxidation of OC and thus resulted in reduction of TN. Continuous cultivation, burning farm and grasslands and clearing of forests for annual crop production invariably resulted in loss of soil organic matter and reduction in the quantity and quality of organic inputs added to the soil because of the removal of large quantities of biomass (Daniel and Tefera, 2016). Total nitrogen levels of less than 0.2% and organic carbon values below 0.6% are considered low for agricultural activities (Landon, 2014). The OM level in the soil is strongly correlated with the soil's CEC, and is a source of many plant nutrients, particularly nitrogen (Brady *et al*., 2008). Low organic matter can be a cause of poor soil structure and low supply of plant nutrients such as nitrogen, phosphorus, and potassium (Nandi and Luffman, 2012).

2.5.4. Available Phosphorus

Phosphorus (P) is an important plant nutrient necessary for root development, nodulation which is important for nitrogen fixation process, pod formation and filling in legumes (Marschner, 1995). Low available phosphorus in the subsurface layers of soils may be attributed to low soil pH (5.5) since P may react with iron (Fe) and Aluminium (Al) to produce insoluble Fe and Al phosphates that are not readily available for plant uptake (Karuma *et al*., 2014).

The available phosphorus content of the soils decreases down the profile, which may be 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 (Ali *et al*., 2010). According to (Ahmed *et al*., 2018) the level of available P showed increasing pattern first from the surface towards the sub-surface horizons and a decreasing trend again towards the C horizon, which may be attributed first to the increase and then decrease in clay content.

2.5.5. Micronutrients

Soil micronutrients are important elements for plant growth despite being required in small quantities. Deficiency of micronutrients can result in severe crop failure while excess levels can lead to health hazards (Hodges. 2010). Major sources of soil micronutrients are parent materials for the inorganic forms and humus for organic forms, though deficiency or toxicity can mostly be attributed to the parent material (Hodges. 2010). At low pH values, the solubility of the micronutrient cations is at a maximum and as the pH is raised their solubility and availability to plants decrease (McCauley *et al*., 2005).

Micronutrients play a critical role in soil fertility and can affect soil properties along a toposquence (a sequence of soils that differ in their properties along a slope). The availability and distribution of micronutrients in soil are influenced by various factors such as soil depth, soil texture, pH, and organic matter content (Guckland *et al*., 2009). In general, nutrient levels in soils tend to decrease with increasing elevation due to factors such as lower temperatures, more rainfall, and higher weathering rates. However, the effects of micronutrients on soil properties along a toposquence are complex and may vary depending on the specific micronutrient and soil conditions (Dessalegn *et al*., 2014). For example, iron and manganese are important micronutrients that can influence soil color, structure, and nutrient availability. In areas with high rainfall, iron and manganese can become more available in the soil due to the leaching of other nutrients (Gupta *et al*., 2008). As a result, soils along a toposquence may have different colors at different elevations due to variations in iron and manganese content.

2.6. Soil Classification and Mapping

Soil Classification concerns the grouping of soils with a similar range of properties (chemical, physical and biological) into units that can be geo-referenced and mapped (Oldeman and Van Engelen 1993). It provides a structured conceptual framework for describing and understanding soil properties and soil formation, and helps to organize soil knowledge, often through national soil survey (Isbell, R. 2016). The two most widely used international soil classification systems are the World Reference Base (WRB) for Soil Resources (IUSS Working Group WRB, 2015) and Soil Taxonomy (Soil Survey Staff, 2014). The WRB is an international system for soil classification and developed under the direction of the Food and Agriculture Organization of the United Nations (FAO). However, many countries also have their own national classifications.

Soil maps show the spatial distribution of soils across the land and were originally produced by field surveyors who walked over the landscape, looking at the soils and other features such as vegetation and topography, drawing boundaries between the different soil types (Omuto *et al*., 2013). Mapping methods have evolved over time, and now techniques such as aerial photography and satellite-based Global Positioning Systems (GPS) are used and are linked with analytical databases. Soil maps are produced at a range of scales from those covering large areas (countries and regions; 1:100000 or smaller scale) to detailed areas such as farms or parklands (1:10000 or larger scale) (Bastian *et al*., 2002). Each soil has its own characteristics which can be described by the soil scientist. These classifications allow us to narrow down areas in search operations, such as through the comparison of analytical attributes of a questioned soil with the attributes of samples held within the spatially referenced databases (Burrough *et al*., 2015).

3. MATERIALS AND METHODS

3.1. Description of the Study Area

3.1.1. Study Area Location

This study was conducted at Dhengego Subwatershed in Biftu Geda *kebele*, Haramaya *Woreda*, East Hararghe Zone of Oromia National Regional State, Ethiopia. It is located at about in the direction 488 km southeast from Addis Ababa and 36 km from Dire Dawa city. Geographically, the subwatershed is located at 9°27’0’’ to 9^{o}28’30’’N latitude and 41°55’30’’ to 41^{o}56’0’’ E longitude and within subwatershad an altitudinal range of 2037 to 2251 meters above sea leve(Figure 1). The total area of the study area is about 2.2 Km^{2}.

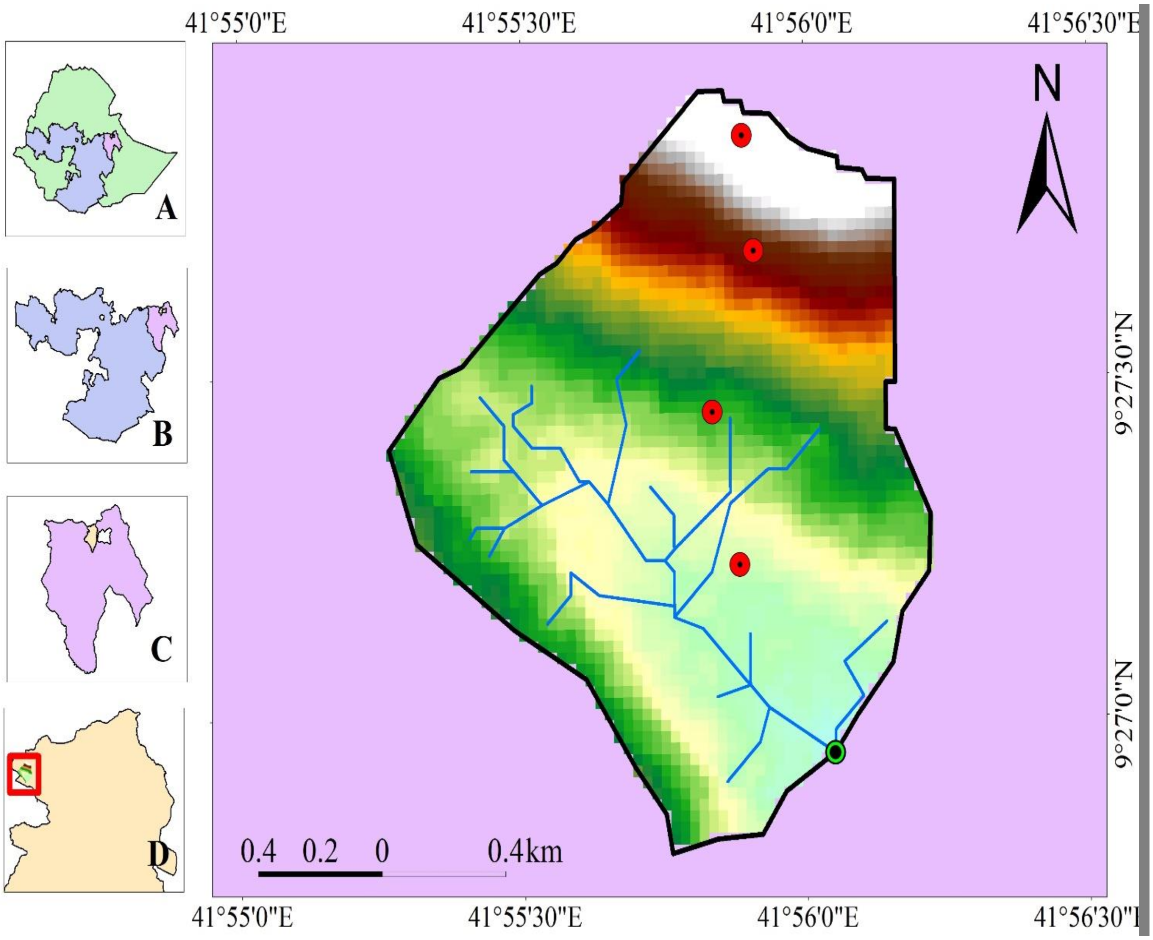

Figure 1. Location map of the study area: (A) Ethiopia, (B) Oromia, (C) East Haraghe Zone, (D) Haramaya Woreda.

3.1.2. Climate

Agro-ecologically the area is classified as a semi-arid tropical belt of eastern Ethiopia and is characterized by a sub-humid type of climate with 26 years (1994-2020) of an average annual rainfall of about 701 mm. As indicated by the Ethiopian National Meteorological Agency (NMA) minimum and maximum average annual temperatures are 12.8 and 28 °C respectively (Figure 2).The study area is characterized by a bimodal rainfall distribution pattern.The short rainy season, locally called *Badheessa*, usually starts in March and extends to May, while the long rainy season, called *Ganna*, stretches from end of June to September.

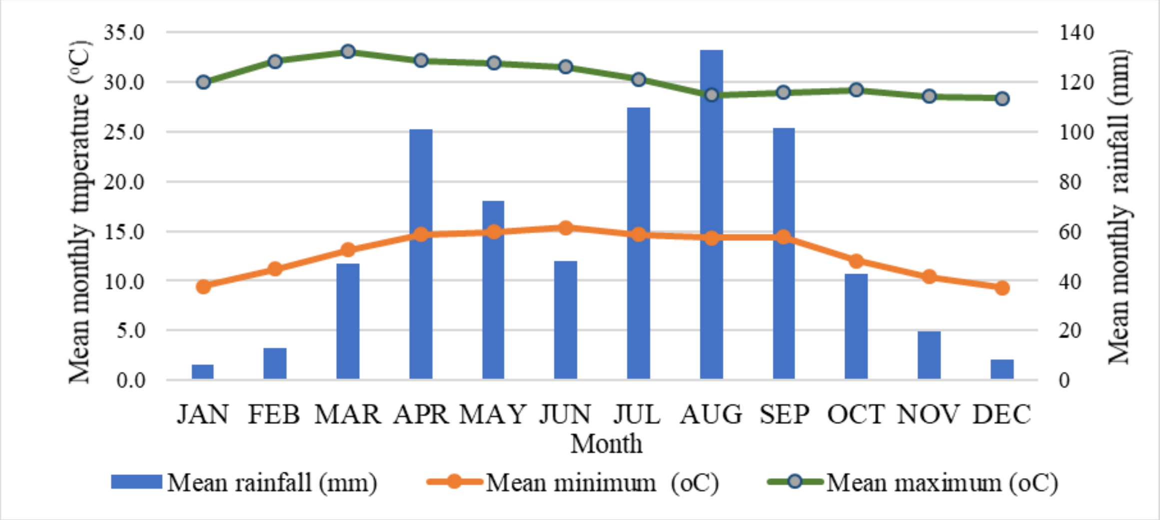

Figure 2. Mean monthly rainfall, maximum and minimum temperature of the study area

3.1.3. Topography

Dhengago subwatershed varies from nearly level land, which represents the plains and plateau areas, to moderately steep and undulating land that characterizes the medium to high gradient hills highly subject to water erosion (Figure 3). The study area is normally extensively cultivated but partially protected by soil conservation structures and practices such as grass strips, alley cropping and bench terraces. In these areas, land scarcity has led the farmers to destroy the few remaining forests in order to cultivate on steep slopes, resulting in additional erosion.

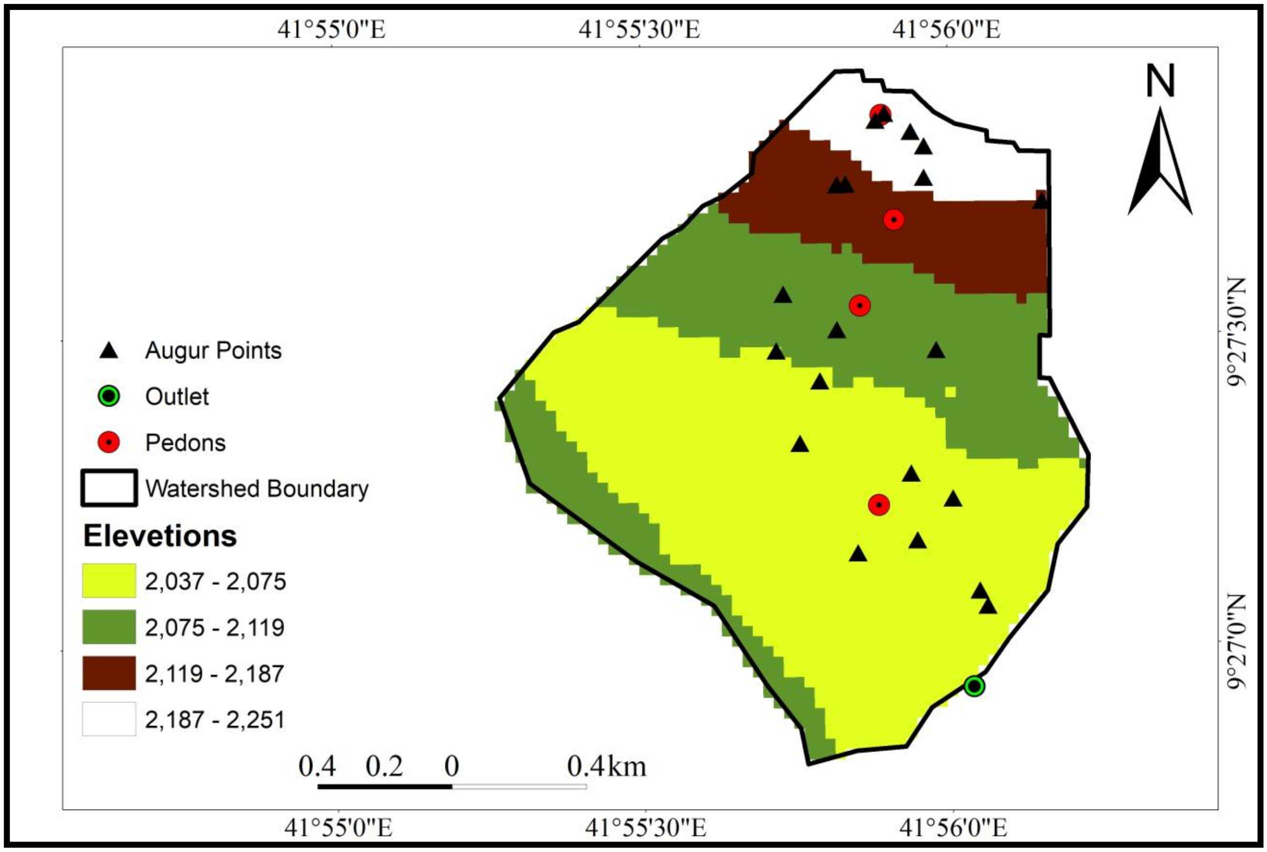

Figure 3. Altitudinal range, distribution of augers points and pedon sites in Dhengego subwatershad.

3.1.4. Geology and Soil

According to the geological map of Ethiopia, first published in 1973 and edited in 1996 at a scale of 1:2,000,000, the geology of the *Woreda* is dominantly covered by Adigrat formation that constituted sandstones and the Hamanlei formation that contains Oxfordian limestone and shale formed during the early Triassic to middle Jurassic periods.

The carbonate deposits used to extend from Tigray to Dire Dawa/ Harar area are truncated by an erosional surface due to an Early Cretaceous tectonic event marked by faulting and tilting (Bosellini *et al*., 2001). The abruptly overlying Amba Aradam Sandstones are fluviatile and commonly associated with lenses of quartz conglomerates and red shale. They often exhibit laterites at their base. Their maximum thickness is 200 m, and their age determined on the base of Orbitolina findings in the Harari region is Aptian to Albian (Bosellini *et al*., 1999).

Mohr (1964), on the other hand, indicates that the Hararghe highlands, where Haramaya *Woreda* forms a part, lie over the crystalline bedrock of the pre-historic Gondwana continent which became fractured at a much later time. The hard rocks of this Continent were granite and gneiss, which were formed during the Pre-Cambrian period (Mohr, 1964). These rocks lay as peneplains below sea level for a long period, which then resulted in the deposits of very ancient sedimentary rocks (Mohr,1964).

The Pre-Cambrian rocks, such as granite, and to a lesser extent gneiss and mica schists, are particularly exposed throughout Haramaya and many other places (Mohr, 1964; Tamirie, 1974). On some of the lower and higher elevations where both limestone and sandstone are completely eroded, granite rock is exposed on the surface. The location of the site, as was observed during the fieldwork and also described by Tamirie (1986), is the site of numerous sink-hole lakes reviving (Lake Adele) and represents some of the typical examples of Karst topography regions in Ethiopia.The dominant rock of Dhengago subwatershed was sandstone and the dominant reference soil group of the study area was Luvisol according to (FAO-WRB (IUSS Working Group WRB 2006).

3.1.5. Land Use and Land Cover

Different land use types that include cultivation, grazing and settlements as the major land use types. Most of the steep slopes are slightly degraded and covered by shrubs, bushes. The vegetation in most places is dominantly *Lanthana camara*, *Cactu*s, and small stature *Acacia abyssinica*. At few places, remnants of *Junipperus procera*, and *Olea europaea* are present on the slopes and border areas. Around homesteads, eucalyptus trees, such as *Eucalyptus globules* and *Eucalyptus camaldulensis* are found. Some agroforestry tree species, such as *Acacia abyssinica*, and *Croton macrostachyus*, were also observed on some farms. Lake Adele located at the outlate of Dhengego subwatershade which is currently showing some signs of rehabilitation.

3.1.6. Farming System

Farmers grow crops twice a year, one during the dry season by using irrigation from groundwater and regularly during the summer season using rainfall. The major cereals grown are sorghum (*Sorghum bicolor*) and maize (*Zea mays*) often intercropped with legumes, such as haricot bean (*Phaseolus vulgaris*). Khat (*Catha edulis*) is the main cash non-food crop grown in the study area. Some vegetable crops, such as potato, onion (*Alluim cepa* L.), and hot pepper (*Capsicum annuum* L.) are grown in the dry season at the lower valley of the watershed where underground water is available for irrigation. Livestock are integral part of the farming system that supply food and income to households. According to the report, by Haramaya *Woreda* agricultural office the irrigation water source is dominantly traditional hand-dug well developed by the farmers themselves.

3.2. Site Selection, Soil Sampling and Sample Preparation

A reconnaissance survey was carried out within the selected subwatershed to identify the major landforms in the area using Google Earth image and digital elevation model (DEM of 30 x 30 m) and to define the preliminary boundary of the subwatershed and select temporary pedon sampling sites before the actual field survey. The free soil survey (traverse survey) method was employed to identify auger sampling sites. Augers were opened up to 120 cm depth (unless limited by impervious layer) and described in the field to observe the variations in site and soil surface characteristics so as to determine the final pedon opening sites along toposequence within the study area. The study area was categorized into four land units after inspecting 20 auger point samples and four representative pedons were identified and opened along the toposequence, namely: Pedon 1(at Summit), Pedon 2 (at Upper slope), Pedon 3 (at Middle slope) and Pedon 4 (at Lower slope) having the dimension (150 width x 150 cm length x 2 m depth) (Figure 3). Selected morphological properties were described *in situ* in the field as per the FAO guidelines for soil description (FAO, 2006). The classification of soils is based on soil properties defined in terms of diagnostic horizons, properties and materials, which were to the greatest extent possible was measurable and observable in the field. According to the World Reference Group definitions and descriptions reflect variations in soil characteristics that occur both vertically and laterally in the landscape the Pedons were assigned and opened along the toposequence.

Disturbed soil samples were collected from each genetic horizon of each pedon, for laboratory analysis of selected physicochemical properties of soils. Moreover, undisturbed soil samples were taken from each horizon using the core sampler to determine soil bulk density. Soil color was measured both under dry and moist conditions using the Munsell Soil Color Chart (Post *et al*., 2000). Soil structures was studied in terms of grade, size and type (shape) of aggregates whereas horizon boundaries were described in terms of distinctness and topography. The soil consistence was identified at dry, moist and wet moisture conditions. About one kg soil sample was taken from each genetic horizon of a pedon. A total of 30 disturbed and undisturbed soil samples were collected. 15 soil samples for chemical analysis were collected, properly labeled and packed in polyethylene bag, and transported to Haramaya University Laboratory and 15 undisturbed samples were taken using core sampler for bulk density determination. Standard laboratory proceduere were followed for soil sample analysis.

The geographic coordinates, elevation and slope gradient of auger and pedon sampling sites were recorded using a global positioning system (GPS), altimeter and clinometer, respectively. Soil samples were air-dried at room temperature, ground, and passed through a 2 mm sieve for laboratory analysis of selected physicochemical properties of soil except soil organic carbon and total nitrogen by which the soil was sieved using 0.5 mm mesh.

3.3. Laboratory Analysis

Determination of particle size distribution was carried out by the Bouyoucos hydrometer method (Bouyoucos, 1962). Bulk density was determined using the core-sampling method as described by Black and Hartge (1986). The average soil particle density (*P*s) (2.65 g cm^{-3}) was used for estimating total porosity (Timm *et al*., 2005). The moisture contents at field capacity (FC) and permanent wilting point (PWP) were measured at the soil water potentials of -1/3 bar (33 kPa) and -15 bars (1500 kPa) respectively, using the pressure plate apparatus technique

(Gupta, 2004). The results were converted into volume percent (Vol %) by multiplying the gravimetric water content with the ratio of soil bulk density to the density of water. The available water content (AWC) was obtained by subtracting water content at PWP from FC and finally converted to mm/ m of soil depth by multiplying it by 1000.

The soil pH (pH-H_2O) was determined in a 1: 2.5 soil to water solution ratio using a pH meter as described by Topp *et al* (2008). The electrical conductivity was measured by a conductivity meter in a soil-water extract 1: 2.5 soil to water (Okalebo *et al*., 2002). Calcium carbonate was determined by acid neutralization method Jackson (1970). Organic carbon was determined following the Walkley and Black wet oxidation method (Walkley and Black, 1934). Total N of the soils was determined through digestion, distillation and titration procedures of the Micro-Kjeldahl method as described by Bremner and Hauck (1982). Available phosphorus in the soil was determined using the sodium bicarbonate extraction solution (pH 8.5) method and the amount was measured by a spectrophotometer as described by Olsen (1954)

Exchangeable bases and cation exchange capacity (CEC) of the soils were determined by the 1M ammonium acetate (pH =7) method (Reeuwijk *et al*., 1993). Exchangeable Ca^{2+} and Mg^{2+} in the extracts were measured by Atomic Absorption Spectrophotometer (AAS), while a flame photometer was used to determine the concentration of exchangeable K^+ and Na^+. Micronutrients (Fe, Mn, Zn and Cu) contents of the soils were extracted by the diethylene triaminepenta-acetic acid (DTPA) method (Houba *et al*., 1989) and the contents in the extract were measured by AAS. The following equations were used to estimate the values of some parameters of the soil.

$$\rho_b(\mathrm{gcm}^{-3}) = \frac{\text{Mass of oven dry soil}}{\text{Total volume}} \tag{1}$$

$$\mathrm{f}\,(\%) = \left(1 - \frac{\rho_b}{\rho_s}\right) \mathrm{x}100 \tag{2}$$

$$\mathrm{CEC_{clay}} = \left(\frac{\mathrm{CEC_{soil}} - (\%\mathrm{OM\ x\ 200})}{\%\,\mathrm{Clay}}\right) \tag{3}$$

$$\text{PBS } (\%) = \left(\frac{\sum (\text{Ca}^{2+} + \text{Mg}^{2+} + \text{Na}^{+} + \text{K}^{+})}{\text{CEC}} \right) \text{x} 100 \quad (4)$$

$$\text{ESP} (\%) = \left(\frac{\text{Exchangeable Na}^{+}}{\text{CEC}} \right) \text{x} 100 \quad (5)$$

Where: CEC = Cation exchange capacity, PBS = Percentage base saturation, OM = Organic matter, *p*b = Bulk density, *p*s = Particle density, ESP = Exchangeable sodium percentage, f (%) = Total porosity.

fractions coarser than clay does not have a significant CEC. OM and Clay were used in decimal form in the formula.

3.4. Soil Classification and Mapping

The soils were classified into different Reference Soil Groups following the classification system of the World Reference Base for Soil Resources of FAO-WRB (IUSS Working Group WRB, 2015) and USDA soil taxonomy (2014). USDA soil taxonomy was used for the purpose of correlation with FAO-WRB. The presence or absence of specific diagnostic horizons, properties and materials were employed to distinguish soil classification. The geographic coordinates of each soil profile location and the boundaries of each soil mapping unit were recorded in the field using GPS. Based on soil-landscape relations and soil surface characteristics such as soil color, structure, texture, consistency, vegetation, etc., soil boundaries were identified at each topographic position. The auger points and soil mapping units’ boundary coordinates were recorded in an excel spread sheet and later displayed in the Arc map as polygons. A soil map was prepared by employing Arc GIS 10.8 (Geographic Information System) and the respective soil mapping units were sketched and the relative area of each polygon determined and labeled.

4. RESULTS AND DISCUSSION

4.1. Site Characteristics of the Pedons

The site characteristics of the pedons indicated differences in slope and extent of water erosion. The slope gradient of the study area was categorized on the basis of FAO (2006a) slope gradient classes.The site slope gradient classes are categorized as very gently sloping (0-2%), strongly sloping (10-15%), sloping (5-10%) and gently slopping (1-5%) at the summit, shulder, back slope and foot slope positions, respectively (Table 1). The estimated parent rocks as the source of the soils' parent materials were sandstone at the summit and upper slope position ; whereas an colluvial and alluvial material was estimated to exist as the soil parent material at the middle and lower slope position (Table 1). Parent material determines certain soil properties and drainage condition, which is among other factors that also determine the type of soil (Kalev and Toor 2018).

Table 1. Selected site characteristics of representative soil pedons at Dhengego subwatershed

Pedon	Location		Altitude (masl)	Slope (%)	Slope position	Drainage	Parent materials
	Latitude	Longitude					
P1	9.46424	41.93152	2251	2%	CR	WD	Sandstone
P2	9.46142	41.93185	2152	15%	UP	WD	Sandstone
P3	9.45748	41.93061	2081	8%	MS	WD	Colluvial
P4	9.45375	41.93139	2037	3 %	LS	MD	Alluvial

CR = Crest, UP = Upper slope, MS = Middle slope, LS = Lower slope, WD = Well drained, MD = Moderate

4.2. Selected Morphological Characteristics of the Soils

The effective soil depth of the soils of study area is observed to be greater than 200 cm for pedon 3 and 4, but the depth of pedons 1 and 2 is less than 200 cm (Table 2). The soil was very shallow at the summit slope position and very deep at the lower slope position according to FAO (1990) rating of soil depth. The depth of the soil increased downslope probably due to the removal of soil materials from the upper slope and deposition at the lower slope position. Although the identified genetic horizons had a variable thickness, pedon 1 with its very shallow profile which was opened at the summit slope position had a 14 cm thick Ap horizon. Below this horizon, a 20 cm (14 -34 cm) thick subsoil horizon was observed and designated as ACr that had a continuous rock beneath.

Pedon 2 was opened on the upper slope position. The surface horizon Ah had about 18 cm thickness. Next to Ah, Bw had a thickness of 25 cm and was similar in soil structure and consistence. The last horizon of Pedon 2, was designated as C with a thickness of 67cm and was different from the above two horizons.

Pedons3 and 4 were opened at the middle and lower slope positions, respectively. The effective depth of both pedons was very deep (200+ cm). The surface horizon of pedon 3 was designated as Ap horizon with a thickness of 23 cm, and the next horizon was A1 that had a thickness of 37 cm. The third layer was designated as AB and had a thickness of 30 cm. The fourth and fifth horizons were designated as B1 and Bt with the thickness of 40 cm and 70 cm, respectively . The surface horizons in pedon 4 were designated as Ap and had a thichness of 18 cm, whereby the Ak, Bt1, Bt2 and Bt3 had a thichness of 32, 60, 40, 50 cm respectively.

The variation of solum thickness along the different slope positions in the study area could be attributed to removal of soil via runoff erosion from upper and middle slopes and subsequent deposition at the lower slope position, so that the soil at the lower topographic position is deeper than that at the upper topographic position. This observation is supported by (Dessalegn *et al,*. 2014), who pointed out that topography was the major factor in soil development. Considering horizon boundaries, distinctness and topography of both pedons 1 and 2 were clear and smooth respectively, except for surface horizon irregular topography. Pedon 3 was described by clear to gradual distinctness with wavy topography while pedon 4 was characterized by gradual to clear wavy wavy horizon boundary topography at the surface and smooth at the subsurface of the soil horizon (Table 2).

The pedons showed variability in relation to soil color patterns (Table 2). Pedon 3 and 4 had relatively darker surface horizons as compared to their subsurface horizons probably owing to the relatively higher organic matter contents in the surface horizons (Table 5). The results showed that soil color is highly influenced by organic matter content, whereby the color got darker with an increase in organic matter content (Akalu *et al*., 2016). Even though not so pronounced, similar trend was also observed in P1 ans P2. Soils on the upper topographic positions had more reddish subsoil colors, which may be indicative of more well drained conditions at these topographic positions.

Table 2. Selected morphological characteristics of the pedons

Pedon	Horizon	Depth (cm)	Horizon boundary		Munsell color		Structure			Consistency		
			Disc.	Topo.	Moist	Dry	Grade	Size	Type	Dry	Moist	Wet
P1	Ap	0-14	C	I	2.5YR3/2	2.5 YR4/3	MO	FI	GR	SHA	FR	SST, SPL
	ACr	14-34	C	S	2.5 YR3/2	2.5YR3/3	MO	FI	GR	SHA	VFR	SST, SPL
P2	Ah	0-18	C	S	7.5YR3/2	7.5YR4/3	WE	ME	GR	LO	VFR	SST, SPL
	Bw	18-43	C	S	7.5YR3/3	7.5YR3/4	WE	ME	GR	LO	VFR	SST, SPL
	C	43-110	C	S	5YR4/4	5YR4/6	WE	FI	GR	LO	LO	NST, NPL
P3	Ap	0-23	C	W	5YR3/2	5YR3/3	WE	FI	GR	SHA	LO	ST, PL
	A1	23-60	C	W	5YR2.5/2	5YR3/1	MO	ME	AB	HA	FR	SST, PL
	AB	60-90	G	W	5YR3/2	5YR3/3	ST	CO	SB	VHA	FR	SST, SPL
	B1	90-130	G	W	5YR4/2	5YR4/4	MO	CO	SB	HA	FR	ST, PL
	Bt	130-200+	C	W	5YR3/1	5YR2.5/1	MO	FI	SB	HA	FR	VST, PL
P4	Ap	0-18	G	W	5YR4/1	5YR3/2	WE	FI	SB	SO	FR	SST, SPL
	Ak	18-50	G	S	5YR2.5/1	5YR4/2	MO	CO	SB	HA	VFI	ST, SP
	Bt1	50-110	C	S	5YR4/2	5YR3/1	MO	CO	AB	HA	VFI	ST, PL
	Bt2	110-150	C	S	5YR3/4	5YR3/4	MO	ME	SB	SO	FR	SST, SPL
	Bt3	150-200+	C	S	5YR3/1	5YR4/2	ST	CO	SB	HA	VFI	VST, PL

Disc. = Distinctness; Topo. = Topography; C = Clear G=Gradual; I= Irregular;W= Wavy; S = Smooth; MO= Moderate; WE = Weak; ST= Strong; FI= Fine; ME= Medium; CO = Columnar (coarse); GR= Granular; AB= Angular blocky; SB = Sub angular blocky; SHA= Slightly hard; LO= Loose; , HA=Hard; SO= Soft; FR= Friable; VFR=Very feriable;VFI= Very firm; SST = Slightly sticky; ST= Sticky; NST= Non sticky; VST= Very stick; SPL= Slightly plastic;NPL=Non plastic; PL= Plastic; SPL= Sligtly plastic (FAO,2006).

There were variations in the grade, size and shape of the soil structure among pedons (Table 2). In the surface soil layers, it ranged from moderate fine (pedon 1) and weak medium (pedon 2) fine (pedon 3) granular to weak fine subangular blocky structure (pedon 4). Regarding subsurface layers, soils at the summit and shoulder of the landscape (pedons 1 and 2, respectively) were composed of granular structure throughout the depth. It varied from angular to subangular blocky in subsurface layers of pedon 3 opened at the back slope whereas it changed inconsistently from subangular to angular blocky, and agin to subangular blocky in the soil of foot slope (pedon 4). The differences in soil structure within a pedon could be attributed to differences in organic matter and clay content (Ali *et al*., 2010; Tobiašová *et al*., 2013), root distribution, biological activities, type and amount of cations. In line with the current result Yitbarek *et al*. (2016) detected granular soil structure in the surface horizons that changed to angular and subangular structure in the subsurface horizons.

The presence of OM in the surface soil might be attributed to the formation of a granular type of soil structure. Soil consistence of surface soil layers varied at different mioisture status among the pedons. The surface soils across the subwatershed seemed to be suitable for ease of workability and hence also for plant root penetration. These could be ascribed to relatively high organic matter that enhanced aggregate formation and stability and modified the soil consistence. This is in harmony with Obour *et al*. (2017) who reported that the friable consistence of soils shows good workability of the soils at appropriate moisture content. Moreover, the observed differences in soil consistence could probably be evidenced by the differences in particle size distribution, particularly type and amount of clay.

4.3. Selected Physical Properties of the Soils

4.3.1. Particle Size Distribution, Bulk Density and Total Porosity

The field, as well as laboratory textural class determinations, revealed that the soils are dominated by sand fraction followed by clay (Table 3). Regarding to surface soils, Pedons 1, 2 and 3 have sandy clay loam texture whereas Pedon 4 has sandy clay textural class. On the other hand, the soil texture is sandy clay loam throughout the subsurface layers of Pedons 1, 2 and 3 except the sandy clay textural class at the deepest layer of Pedon 3 (130-200+ cm), but it varied from sandy loam and sandy clay loam to sandy clay within Pedon 4. Deposition of percentage clay materials by water may contribute to higher clay content at the surface of Pedon 4. Relatively higher clay contents recorded in most of the subsurface layers could be attributed to clay migration into the lower horizons through eluviation and illuviation processes. The content of clay in the subsurface horizon of the middle and lower slope pedons is high. Demis and Sheleme (2010) also suggested that the percentage of clay in the profile increases with depth, indicating pedogenic eluviation illuviation processes. The removal of finer particles by selective erosion or transfer of finer particles into the subsurface soil could be responsible for the highest sand content at the surface soil of the study area.

The surface ρ_b (1.56 g cm^{-3}) was recorded in Pedon 2 opened at the shoulder slope followed by 1.36 g cm^{-3} in Pedon 3 opened at the back slope of the surface soil layers across the Subwatershed. The higher bulk density at the surface of Pedon 2 could be attributed to compaction by animal trampling during animal grazing (Appendix table 2). Relatively the highest ρ_b (1.59 g cm^{-3}) was recorded in the subsurface of Pedon 3 layer (90-130 cm) of back slope topographic position and the highest mean value of bulk density was recorded at the same topographic position of Pedon 3. This could be attributed to a decrease in organic matter accumulation with depth, less root penetration and compaction caused by the weight of the overlying layers (Brady and Weil, 2004). On the other hand, it varied inconsistently with increasing depth in the subsurface soil layers. Overall, the bulk density could not be a limiting factor for the root penetration. Soil bulk density values ranged between low to moderate as per the rating suggested by Hazelton and Murphy (2007) (Table 3).

The soil total porosity was varied inconsiyently along the toposequence and with icreasing depth in a pedon (Table 3). It ranged between 41 and 57% in the surface layers and 40 and 53% in the subsurface layers.

The total porosity of surface soil was ranged from 41% of Pedon 2 to 57% in Pedon 4. It also ranged from in subsurface of Pedon 3, 40% (90-130 cm) to (53%) (18-43) at Pedon 2. This variation did not exhibit any consistent trend except Pedon 1. It was found to decrease with the depth of profile and it is closely related to organic matter content, clay accumulation and the activities of earthworms and other macro animals in the soil system (Table 3). The decrease of total porosity with soil depth could be attributed to the effect of compaction due to the overlaying layers, limited penetration of crop roots into subsurface layers as well as to the relatively low OM contents in the surface horizons. This finding is in agreement with Shah *et al*. (2017) who reported that decrease in total porosity with soil depth is the result of increasing compaction, decrease in rooting effect and OM content with depth.

The value of the silt to clay ratio was higher than 0.15 (Table 3). Older parent materials are reported to have silt:clay ratio below 0.15 while silt:clay ratios above 0.15 are indicative of younger parent materials (Wambeke, 1962). The results of this study along the toposequence had a silt:clay ratio above 0.15 indicating that the soils were relatively young with a high degree of weathering potential. Silt clay ratios are relatively higher in the surface horizons and decrease with increased depth in the pedons and decrease along the toposequence at Pedon 1 and 4 but increase at Pedon 2 and 3. The decrease in silt clay ratio with an increase in soil depth is an indication that subsoil horizons are more weathered than top soils.

Table 3. Selected physical characteristics of soils

Pedon	Horizon	Depth (cm)	Particle size distribution (%)			Textural Class	*Pb* (gcm^{-3})	*f* (%)	Silt: Clay	FC (%v/v)	PWP (%v/v)	AWC (mm m-^{1})
			Sand	Silt	Clay							
P1	Ap	0-13	62	14	24	SCL	1.28	52	0.58	26.60	11.59	150
	ACr	14-34	66	12	22	SCL	1.21	44	0.54	29.45	14.66	147
P2	Ah	0-18	64	7	29	SCL	1.56	41	0.24	15.52	7.92	76.0
	Bw	18-43	60	8	32	SCL	1.25	53	0.25	23.88	10.29	135
	C	43-110	76	4	20	SCL	1.39	47	0.20	16.14	6.44	97.0
P3	Ap	0-23	74	6	20	SCL	1.36	48	0.30	17.82	7.66	101.6
	A1	23-60	60	14	26	SCL	1.53	42	0.53	22.88	9.39	134.9
	AB	60-90	62	10	28	SCL	1.50	43	0.35	22.29	9.17	150
	B1	90-130	68	6	26	SCL	1.59	40	0.23	20.32	8.60	117.2
	Bt	130-200+	58	6	36	SC	1.48	44	0.16	28.86	15.92	129.4
P4	Ap	0-18	50	12	38	SC	1.13	57	0.31	30.85	15.17	156.8
	Ak	18-50	78	4	18	SL	1.41	46	0.22	27.80	13.13	146.7
	Bt1	50-110	58	8	34	SCL	1.49	43	0.23	27.61	13.75	138.6
	Bt2	110-150	62	8	30	SCL	1.52	42	0.26	23.91	13.75	101.6
	Bt3	150-200+	58	6	36	SC	1.35	49	0.16	34.18	19.48	146.9

SCL = Sandy clay loam; SC = Sandy clay; SL = Sandy loam; *Pb* = Bulk density; *f* = Total porosity;; FC = Field capacity; PWP = Permanent wilting point; AWC = Available water holding capacity.

4.3.2. Soil Water Retention Capacity

The water retaention capacity of soils inconsistently varied with increasing depth and along toposequence (Table 3). The soil water content retained at field capacity (FC at 33 kPa) ranged from 15.52% to 34.18 % in P2 (0-18 cm) and P4 (150-200+ cm), respectively. At permanent wilting point (PWP at 1500 kPa), it ranged between 6.44% at 43-110 cm depth in P2 and 19.48% at 150-200+ cm in P4, with sandy clay loam and sandy clay textural classes, respectively. The available water content (AWC) varied from 76 mm m^{-1} to 156 mm m^{-1} both in the surface horizons of P2 and P 4, in this order. The available water content (AWC) of the soil varied from 76 mm m^{-1} to 156 mm m^{-1} on horizon basis and could be rated as very low to medium in accordance with Beernaert (1990), who rated available water content values <8, 8-12, 12-19, 19-21 and >21 volume percentage as very low, low, medium, high and very high, respectively. Overall such variation in AWC with increasing depth within a pedon could be ascribed to the clay contents within the horizons. The work done by Nahusenay *et al*. (2014) implied that the presence of appreciable amount of finer fraction in the subsurface soil could increase the water holding capacity of the soil and facilitate a longer period of soil water retention for crop utilization.

4.4. Selected Chemical Properties of Soils

4.4.1 Soil pH, Electrical Conductivity and Calcium Carbonate

The pH-H_2O values varied from 6.74 to 7.32 in the surface layers of Pedon 2 and Pedon 3, respectively, and 6.78 to 7.74 in the subsurface horizons at 18-43 cm depth in Pedon 2 and 110-200+ cm in Pedon 4 with generally increasing trend along the toposequence and from surface to the subsurface of the horizon in all pedons except in Pedon 3 (90-130 cm) and Pedon 4 (150-200 cm) (Table 4). The ΔpH in the surface horizon was 0.53 to 1.19 and 0.09 to 1.88 for the sub-surface in the study site. The values were positive and it was an inconsistent trend along toposequence. The higher the ΔpH values indicate the presence of appreciable amount of negatively charged clay colloids (Tombácz, 2006).

Increased soil pH in pedons with soil depth may indicate the presence of vertical movements of exchangeable bases due to leaching and fewer H^+ ions released from the decomposition of organic matter, which is caused by decreased organic matter content with depth (Abay *et al*., 2012). In all of the identified horizons of the representative soil pedons, soil pH-H_2O values were consistently greater than the pH-KCl ones, indicating the existence of net negative charges on the exchange complex in accordance with findings reported by (Heluf and Mishra 2005); Kibebew (2014), Yacob *et al.* (2014), and Samuel (2017). This helps the soil retain more nutrient cations (Samuel, 2017). The pH value was rated neutral to slightly alkaline which was the pH requirement for optimum plant growth according to the rating (Tekalign 1991).

Table 4. Soil pH, electrical conductivity (EC) and calcium carbonate ($CaCO_3$)

Pedon	Horizon	Depth (cm)	pH 1:2.5			EC dSm^{-1}	$CaCO_3$ (%)
			H_2O	KCl	ΔpH		
P1	Ap	0-13	6.91	6.38	0.53	0.08	1.5
	ACr	13-33	6.94	6.24	0.70	0.15	1.2
P2	Ah	0-18	6.74	5.90	0.84	0.08	1.3
	Bw	18-43	6.78	6.69	0.09	0.07	0.4
	C	43-110	6.97	6.32	0.65	0.03	0.3
P3	Ap	0-23	7.32	6.22	1.1	0.10	2.9
	A1	23-60	7.41	6.54	0.87	0.08	2.4
	AB	60-90	7.53	6.87	0.66	0.04	1.1
	B1	90-130	7.32	5.44	1.88	0.05	1.2
	Bt	130-200+	7.59	5.88	1.71	0.08	1.8
P4	Ap	0-18	6.87	5.68	1.19	0.10	0.4
	Ak	18-50	7.10	5.84	1.26	0.06	6.9
	Bt1	50-110	7.35	6.71	0.92	0.08	2.52
	Bt2	110-150	7.74	6.6	1.14	0.20	3.4
	Bt3	150-200+	7.40	6.35	1.05	0.15	1.7

Electrical conductivity (EC) of the soils showed very low values that ranged from 0.08 to 0.10 dSm^{-1} in the surface horizon of Pedon 1 and Pedon 2, and Pedon 3 and Pedon 4, respectively (Table 4). It varied from 0.03 to 0.20 dSm^{-1} in sub-surface horizon of Pedon 2 (at 43-110 cm) and Pedon 4 (at 110-150 cm), this sequence indicating that the soils were not saline (FAO, 1988). Based on the salinity rating classified by Horneck *et al.* (2011), the EC results obtained in soils of the study area indicated that the concentration of soluble salts in soils of the study area was below the levels at which most crop cultivation are affected. Hence, they were not regarded as a class of problem soils that require special remedial measures and management practices. Similarly, the calcium carbonate ($CaCO_3$) content within the pedons varied from 0.4

to 2.9% at the surface layers of Pedons 4 and 3 and 0.3 to 6.9% in subsurface layers of Pedon 2 (at 43-110 cm) and Pedon 4 (at 18-50 cm), correspondingly (Table 4). The relatively higher concentration of $CaCO_3$ at the subsurface than at the surface horizons might be ascribed to the effects of leaching and parent material; similar findings were reported by Özsoy and Aksoy (2007), in which case the $CaCO_3$ contents increased with depth. Thus, the soils in the study watershed were low to modrate in calcium carbonate (Landon, 2014). The EC and CaCO3 contents showed an irregular pattern in most of the pedons with increasing depth, indicating low degree of leaching process in the area.

4.4.2. Organic Carbon, Total Nitrogen, C:N-Ratio and Available Phosphorus

The organic carbon (OC) content of the surface soil layers ranged from 2.3 % in Pedon 2 to 3.07% in Pedon 3 (Table 5). Considering the subsurface layers, it varied from 0.71% at 110-150 cm depth in Pedon 4 to 2.80 % at 23-60 cm in Pedon 3. It showed irregular variation along toposequence. In contrast it decreased invariably with increasing depth in each pedon except Pedon 2 and beyond 110 cm depth of Pedon 4 which varied inconsistently. The surface layers had higher OC concentrations than the deeper layers. This might be attributed to the presence of plant material, as well as root and biological activity, on the surface layers as opposed to the subsurface layers. Similarly, prior research found that the topsoil had a greater OC than the subsurface (Fang *et al*., 2015). As per rating suggested by Tekalign (1991), the organic carbon (OC) contents of the soils across the study subwatershed was within the range of low to high.

The total N content of the surface soil layers ranged from 0.21 to 0.22%, and 0.13 to 0.19% in the subsurface horizons which could be rated as moderate as suggested by Tekalign *et al*. (1991) throughout the subwatershed. According to Ju *et al*. (2007), the low levels of TN in the soils may also be due to intensive cropping practices without measures to build up soil nutrient reserves. Total N content decreased with depth in all pedons along topographic position except Pedon 3 in which it varied inconsistently (Table 5). Soils with less than 0.07% TN have limited N mineralization potential, while those having greater than 0.15% TN would be expected to mineralize a significant amount of N during the succeeding crop cycle showing that most of the soils have good potential of N mineralization (Tadesse *et al*., 1991).

The carbon to nitrogen ratio (C: N) of the surface soils along the toposequence in the study area ranged from 10.95 (Pedon 2) to 14.62 (Pedon 3) (Table 5). In subsoil horizons, it ranged from 4.4 at deepest depth of 110-150 cm of Pedon 4 to 20.0 in Pedon 3 (at 23-60 cm) and it showed an inconsistent trend with depth in all pedons except Pedon 1 probably suggesting the existence of different conditions of mineralization within the depth of the profiles. The C:N ratio of all horizons in the study area showed more than 10 except Pedon 4 the last two subsurface layers which indicates a slightly low level of mineralization. According to Yifru and Belachew (2010), the optimum C:N ratio is about 10:1 to 12:1 that provides N in excess of microbial needs. Accordingly, the C:N ratio of the surface soils across the study area may be considered to be within the optimum range. In general, a CN ratio of about 10 suggest relatively better decomposition rate and indicate improved availability of N to plants and there will be possibilities to incorporate crop residues to the soil without adverse effect of N immobilization (Yifru and Belachew, 2010).

Table. 5. Organic carbon, total nitrogen, C:N ratio and available phosphorous

Pedon	Horizon	Depth (cm)	OC %	TN %	C: N	AvP (mgkg^{-1})
P1	Ap	0-13	2.63	0.22	11.95	13.10
	ACr	14-34	2.08	0.18	11.56	12.24
P2	Ah	0-18	2.30	0.21	10.95	11.15
	Bw	18-43	2.36	0.19	12.42	8.73
	C	43-110	1.52	0.14	10.86	10.13
P3	Ap	0-23	3.07	0.21	14.62	25.90
	A1	23-60	2.80	0.14	20.00	9.27
	AB	60-90	1.91	0.19	10.05	9.90
	B1	90-130	1.82	0.15	12.13	10.44
	Bt	130-200+	1.58	0.13	12.15	6.70
P4	Ap	0-18	2.63	0.21	12.52	25.11
	Ak	18-50	2.47	0.18	13.72	11.30
	Bt1	50-110	2.19	0.15	14.60	6.70
	Bt2	110-150	0.71	0.16	4.44	9.23
	Bt3	150-200+	1.32	0.14	9.43	14.35

OC = Organic carbon; TN = Total nitrogen; AvP = Available phosphorus

Available P content of soils in the surface horizon ranged from 11.15 mg kg^{-1} in Pedon 2 to 25.11mg kg^{-1} in pedon 4 while in the subsurface horizon it varied from 6.70 mg kg^{-1} in Pedons 3 and 4 at 130-200 cm and 50-110 cm, respectively to 14.35 mg kg^{-1} at 150-200 cm in Pedon 4 with inconsistent trend in all pedons except Pedon 1 (Table 5). According to this author, the Av. P extracted by Cottenie (1980) method is rated for Av. P < 3 mg kg^{-1} as very low, 4-7 mg kg^{-1} as low, 8-11 mg kg^{-1} as medium, and > 12 mg kg^{-1} as high. Accordingly, the study area was rated as high in Av. P. The higher Av. P recorded in the surface compared to the subsurface horizons could be attributed to the relatively higher OC contents in the surface layers, and the application of P containing fertilizer and compost by farmers. Awdenegest *et al*. (2013) also argued that the higher Av. P in the topsoil layer of farmland might be related to the application of animal manure, compost, household wastes like ashes and fertilizer for soil fertility management. The decrease in Av. P down the profile in these pedons could also be attributed to the increase in clay contents of lower horizons that fix P (Sheleme, 2011; Tigest and Fisseha, 2018). Phosphorus fixation tends to be more pronounced and P release could be lowest in soils with higher clay content (Lehmann and Schroth, 2002).

4.4.3. Exchangeable Bases

The exchange complex was predominantly occupied by exchangeable Ca^{2+} followed by Mg^{2+}, Na^{+}, and K^{+} (Table 6). Exchangeable Ca^{2+} and Mg^{2+}, consistently increased while exchangeable K^{+} and Na^{+} showed increasing trend with slight variation downslope along toposequence. This could be result from surface soil erosion at the upperslope and subsequent deposition at the lower slope. On the other hand, attributable to leaching, they irregularly increased except exchangeable Na^{+} which invariably increased with depth. Accordingly, the concentration of exchangeable Ca^{2+} at surface layers varied from 16.45 at Pedon 1 to 28.87 cmol$_{(+)}$/kg at Pedon 4. Exchangeable Mg^{2+} varied 3.93 in Pedon 1 to 6.74 cmol$_{(+)}$/kg in Pedon 4. Exchangeable K^{+} ranged 0.02 Pedon 2 to 0.19 cmol$_{(+)}$/kg Pedon 4 and exchangeabl Na^{+}, and 0.03 Pedon 1 to 0.75 cmol$_{(+)}$/kg Pedon 3. Similarly, their concentrations (cmol$_{(+)}$/kg) in varied from 14.43 Pedon 2 to 41.53 Pedon 4 for Ca^{2+}, 4.10 Pedon 1 to 8.57 Pedon 3 for Mg^{2+}, 0.04 Pedon Pedon 1 to 0.61 Pedon 2 for K^{+} and 0.04 Pedon 1 to 0.98 Pedon 4 for Na^{+} in subsurface horizons.

The contents of exchangeable bases increased with increasing soil depth, perhaps due to the leaching of exchangeable cations in the study area. Supporting this finding, other authors Ali *et al*. (2010); Nahusenay *et al*. (2014) indicated that the accumulation of exchangeable Ca^{2+} with depth could be due to translocation from the overlying horizons. In accordance with the ratings of FAO (2006), the soils of Dhengego subwatershed are categorized under high to very high in exchangeable Ca^{2+} and Mg^{2+} concentrations, medium to high in exchangeable K^+ except Pedon 1 which was rated as very low and low in exchangeable Na^+.

The Ca:Mg ratio of the soils was in the range of 3.52-4.28 at the surface and1.22-5.12 in the subsurface layers (Table 6). As per Eckert (1987) ratings, soils having Ca:Mg ratio of <4:1 are suspected to have Mg induced Ca deficiency; Ca:Mg >8:1 ratio Ca induced deficiency of Mg; and 4-8 ratio is as optimum. Accordingly, the results indicate Mg induced Ca deficiency in Pedon 2 and subsurface of layers of Pedon 3. The rest were rated in the normal range in the soils. On the other hand, the values of K: Mg ratio ranged at the surface 0.01-0.03 and in subsurface 0.01-0.12, and in accordance with the ratings by Loide (2004), Mg induced K deficiency is also expected for crop production on the soils. The results suggest the need for soil management to balance the cations for optimum crop production, although their absolute values are above the critical levels.

Table 6. Exchangeable bases, base saturation, CEC-soil and CEC-clay

Pedon	Horizon	Depth (cm)	Exchangeable bases (cmol$_{(+)}$/kg)					Ca:Mg	K:Mg	CEC$_{soil}$ (cmol(+)/kg	CEC$_{clay}$ (cmol$_{(+)}$/kg	PBS (%)	ESP (%)
			Ca	Mg	K	Na	SEB						
P1	Ap	0-14	16.45	3.93	0.08	0.03	20.49	4.19	0.02	34	104	60.26	0.09
	ACr	14-34	17.41	4.10	0.04	0.04	21.59	4.25	0.01	32	113	67.47	0.13
P2	Ah	0-18	17.83	5.07	0.02	0.24	23.16	3.52	0.01	26	62	89.08	0.92
	Bw	18-43	14.43	5.24	0.61	0.46	20.74	2.75	0.12	24	50	86.42	1.92
	C	43-110	15.37	5.78	0.06	0.55	21.76	1.62	0.01	36	145	60.03	1.53
P3	Ap	0-23	22.6	5.59	0.15	0.75	29.09	4.04	0.03	30	97	96.97	2.50
	A1	23-60	25.6	7.01	0.09	0.68	33.38	3.65	0.01	35	98	95.37	1.94
	AB	60-90	18.42	4.51	0.06	0.69	23.68	1.22	0.01	39	111	60.71	1.77
	B1	90-130	27.6	7.16	0.12	0.71	35.59	3.85	0.02	47	147	75.72	1.51
	Bt	130-200+	34.59	8.57	0.19	0.75	44.1	4.04	0.02	45	100	98.00	1.67
P4	Ap	0-18	28.87	6.74	0.19	0.65	36.45	4.28	0.03	51	110	71.47	1.27
	Ak	18-50	33.94	7.31	0.27	0.87	42.39	4.64	0.04	43	192	98.58	2.02
	Bt1	50-110	36.07	8.57	0.12	0.95	45.71	4.21	0.01	46	113	99.37	2.07
	Bt2	110-150	25.29	6.73	0.08	0.97	35.00	4.04	0.01	35	109	94.50	2.77
	Bt3	150-200+	41.53	8.11	0.19	0.98	50.81	5.12	0.02	51	118	99.63	1.92

SEB = Sum of exchangeable bases; CEC = Cation exchange capacity; PBS = Percent of base saturation; ESP = Exchangeable sodium Percentage.

4.4.4. Cation Exchange Capacity, Base Saturation and Exchangeable Sodium Percentage

The value of cation exchange capacity of soil ranged from 26 to 51 cmol (+) kg^{-1} at the surface and 24 to 51 cmol (+) kg^{-1} at the subsurface horizon (Table 6) which was rated as high to very high according to a rating by London (1991). The amount of CEC inconsistently increased from surface horizon to subsurface horizon and along the toposequence except Pedon 2 due to the amount and type of clay, and organic carbon content in the soil. The CEC can determine appropriate fertilizer applications and the amount of nutrients needed to correct imbalances. High CEC values indicate that soil has a greater capacity to hold cations and requires higher rates of fertilizer that can increase its cation level to provide adequate crop nutrition. Where as, low CEC soils hold fewer nutrients, and are likely subject to leaching of mobile "anion" nutrients that leads to the requirement for split applications of several nutrients (Hamza, 2008). A single application of large quantities of fertilizers to sandy soils with low CEC can cause loss of nutrients via leaching Sonon and Zhang (2014). CEC is a very important soil property influencing soil structure stability, nutrient availability, soil pH, and the soil's reaction to fertilizers and other ameliorants (Hazelton and Murphy, 2007). Generally, the soils of the study area had good nutrient retention and buffering capacity due to the high status of the CEC of clay.

On the other hand, the CEC clay varied from 50 to 192 cmolc kg^{-1} suggesting greater proportions of 2:1 clay mineral, most probably montmorillonite and/or Vermiculite with more nutrient reserves. There was an inconsistent trend with depth except pedon 1 which was found at the summit topographic position. Higher CEC clay values were found at Pedon 3 and Pedon 4. Soils with low CEC are more likely to develop deficiencies in potassium (K^+), magnesium (Mg^{2+}), and other cations while high CEC soils are less susceptible to leaching of these cations (Nawaz *et al*., 2012.).

Total exchangeable bases and base saturation of the soils were influenced by slope classes (Sheleme 2017) whereby the pedons at lower slope and depression had higher exchangeable bases and base saturation as compared to those on upslope positions. This could be attributed to the transport of soil materials from upslope positions and their deposition on the lower slope and depression. Following the high concentration of exchangeable bases, the percentage of base saturation (PBS) was also high. The PBS of the soils in the subwatershed varied inconsistently along with the topographic position. It also showed irregularly increasing trend with soil depth within the pedons except for Pedon 1. Increasing with soil depth might be due to the leaching of bases from the overlying layers and subsequent accumulation in the subsurface horizons. The PBS in the soils of the area was within a high to very high range Hazelton and Murphy (2016). Idoga and Azagaku (2005); Atofarati *et al*. (2012) and Nahusenay *et al.* (2016) also reported higher base saturation of subsurface horizons which was attributed to the contribution of clay colloids which increases with depth. In general, the occurrence of the higher percentage of the base saturation in almost all soil profiles could be used as an indication of soil fertility and the presence of high weather-able minerals in the soil (FAO-WRB, 2006). The exchangeable Na content of the soils was low and the exchangeable sodium percentage (ESP) of the soils was also less than 15% (Table 6). 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.

4.4.5. Extractable Micronutrients

The concentrations of all available micronutrients varied inconsistently in the soils both along toposequence and with increasing depth within each pedon except decreasing invariably for extractable Fe, Mn and Cu in Pedon 1 and Fe in Pedon 2 with increasing depth (Table 7). The values of extractable micronutrients were in the decreasing order of Fe > Mn > Cu > Zn. According to the rating described by Lindsay and Norvell (1978), the overall concentrations of micronutrients in the soils of the study area were found to be high to very high in Fe (6.32 to 21.51 mg kg^{-1}), medium to very high in Mn (2.67 to 9.67 mg kg^{-1}), very low to low in Zn (0.02 to 0.52 mg kg^{-1}), and medium to high in Cu (0.36 to 1.07 mg kg^{-1}) contents (Table 7). This finding is in line with that of Abayneh (2005) which showed Fe and Mn are at an adequate level across Ethiopian soils. According to Mesfin *et al*. (2017) soil micronutrients are influenced by several factors among which soil OM content, soil reaction and clay contents are the major ones. Fertilizer response is unlikely for values greater than 10.0, 3.0, 1.5, and 1.0 for Fe, Mn, Zn, and Cu, respectively (Hartz, 2007). Consequently, the soils of the study area can supply adequate amount of available Fe, Mn, and Cu for the growing plants, whereas the lower values of available Zn in all of the pedons indicate the potential deficiency of this nutrient and, hence, urgently requires addition of Zn containing fertilizer.

Table 7. DTPA extractable micronutrients in Dhengago subwatershad

Pedon	Horizon	Depth (cm)	Extractable micronutrients (mg kg^{-1})			
			Fe	Mn	Cu	Zn
P1	Ap	0-14	10.50	4.35	0.54	0.21
	ACr	14-34	7.84	3.73	0.36	0.26
P2	Ah	0-18	10.63	3.02	0.43	0.12
	Bw	18-43	10.00	7.30	0.46	0.02
	C	43-110	7.97	5.46	0.44	0.16
P3	Ap	0-23	8.60	5.12	0.61	0.91
	A1	23-60	21.51	4.62	1.02	0.04
	AB	60-90	19.62	2.67	1.01	0.03
	B1	90-130	15.31	6.45	0.77	0.03
	Bt	130-200+	11.39	9.67	0.87	0.07
P4	AP	0-18	13.79	3.68	0.99	0.52
	Ak	18-50	14.93	4.73	1.07	0.17
	Bt1	50-110	10.00	6.25	0.66	0.14
	Bt2	110-150	6.32	7.58	0.44	0.06
	Bt3	150-200+	6.32	6.27	0.84	0.22

4.5. Soil Classification and Mapping

The soils were classified based on both morphological and physicochemical properties of soils following the FAO-WRB for soil resources (IUSS Working Group WRB, 2015) and USDA-Soil Taxonomy (2014). The identification of the diagnostic soil characteristics (diagnostic horizons, properties and materials) was performed based on *in situ* description of morphological properties of pedons and laboratory analysis results of selected physicochemical properties of soils. Accordingly, the soils were assigned to their corresponding Reference Soil Groups (RSGs) together with associated principal and supplementary qualifiers.

Pedon 1 was shallow with an underlying continuous rock starting at 34 cm and had no diagnostic diagnostic subsurface horizon, and hence was classified as Regosol. Besides, it was characterized by high base saturation ≥ 60% (by 1 M NH4OAc pH 7) which enables to use Eutric principal qualifier; had more than 1% weighted average of soil organic carbon starting from the mineral soil surface and sandy clay loam textural class throughout, so that Humic and Loamic supplementary qualifiers can be used. Furthermore, the Munsell color notation (both moist and dry), the OC% and the PBS of the two horizons of the pedon fulfill the diagnostic criteria of a mollic surface horizon, eventhough a mollic supplementary qualifier does not exist in the respective list of qualifiers of the IUSS Working Group WRB (2015) . Accordingly, P1 was further classified as Eutric Regosol (Humic, Loamic, Mollic).

Regarding pedon 2, in addition to its cambic subsurface horizon at the depth of 18 – 43 cm, the Munsell color notation (both moist and dry), the OC% and the PBS of the two upper horizons of the pedon fulfill the diagnostic criteria of a mollic surface horizon. The secondary carbonate distribution within the profile indicated that this pedon is relatively more leached or the parent material might be less carbonate bearing when compared to pedon 3 and 4. All these attributes give a strong clue to the existence of a taxonomic unit that belongs to the Mollisols order of the US-Soil Taxonomy. Accordingly, pedon 2 was classified as Cambic Phaeozem. Furthermore, its relatively highe OC content >1.4% starting from the mineral soil surface to more than 100 cm depth enable to use the profundihumic subqualifier; and the sandy clay textural class throughout its depth starting at the soil surface permits the use of pantoloamic subqualifier and its base saturation above 80% in the depth range upto 43 cm from the soil surface enables to use a hypereutric subqualifier. Accordingly, this pedon is classified as Cambic Phaeozem (Hypereutric, Profundihumic, Pantoloamic).

Pedon 3 consisted of granular structure in its surface horizon, neither massive nor hard when dry, high organic matter content (3.07% OC, humic), dark-color with Munsell color value 3 both in moist and dry, and chroma 2 moist, high base saturation (96.97% by *1M* NaH_4OAc, pH 7) throughout a depth of 200 cm; whereby all indicate the presence of a mollic surface diagnostic horizon.. The sandy clay loam textural class throughout the depth of 130 cm starting from the mineral soil surface met the requirement of pantoloamic subqualifier. Furthermore, a calcaric material (≥2% carbonate) throughout between 20 and 100 cm from the soil surface and a PBS above 80% between 20 and 100 cm depth, enable the use of calcaric, humic and hypereutric qualifiers. Hence, pedon 3 was classified as Calcaric Phaeozem（Humic, Pantoloamic) leaving out the hypereutric qualifier to avoid redundancy with the calcaric qualifier.

Pedon 4 had an argic horizon characterized by sandy clay loam with remarkably higher clay content (at the ratio of 1.89 clay) than the overlying horizon that does not form part of both natric and spodic horizons. Moreover, this pedon had high base saturation of above 50% (by 1 M NH_4OAc at pH 7) throughout and > 80% PBS between 20 and 100 cm depth (hypereutric) and was calcaric throughout the depth range between 20 and 150 cm; contained more than 1% soil organic carbon within 50 cm depth starting from the mineral soil surface (humic) and sandy loam to sandy clay loam textural class throughout the depth of 18-110 cm (katoloamic), which enable to use the calcaric, humic and katoloamic qualifiers. Hence, pedon 4 was classified as Endocalcaric Luvisol (Humic, Katoloamic).

Generally, the soil classification revealed that three Reference Soil Groups, namely, Regosols, Phaeozems and Luvisols; the second level detailed naming of which would be Eutric Epileptic Regosol (Humic, Loamic, Mollic) for pedon 1, Cambic Phaeozem (Hypereutric, Profundihumic, Pantoloamic) for pedon 2, Calcaric Phaeozem（Humic, Pantoloamic) for pedon 3 and Endocalcaric Luvisol (Humic, Katoloamic) for pedon 4. The equivalent names of the USDA-Soil Taxonomy were: Lithic Ustorthents for pedon 1, Typic hapludolls for pedon 2 and 3, and Udic haplustalfs for pedon 4. Lithic Ustorthents of the US-Soil Taxonomy are Orthents with ustic soil moisture regime that have a lithic contact within 50 cm from the mineral soil surface and a soil temperature regime warmer than cyic. Typic Hapludolls of the US-Soil Taxonomy are Hapludolls that do no have aquic condition for sometime in normal years and not saturated with water in any layer within 100 cm depth from the mineral soil surface; and do not have a lithic contact within 50 cm and a calcic horizon within 100 cm from the mineral soil surface. Udic haplustalfs of the US-Soil Taxonomy are Halustalfs with an argllic diagnostic subsurface horizon, but do not have a kandic or natric horizon and do not have duripan, petrocalcic horizon and much plinthite; and have a hyperthemic or isomesic or warmer iso soil temperature regime.

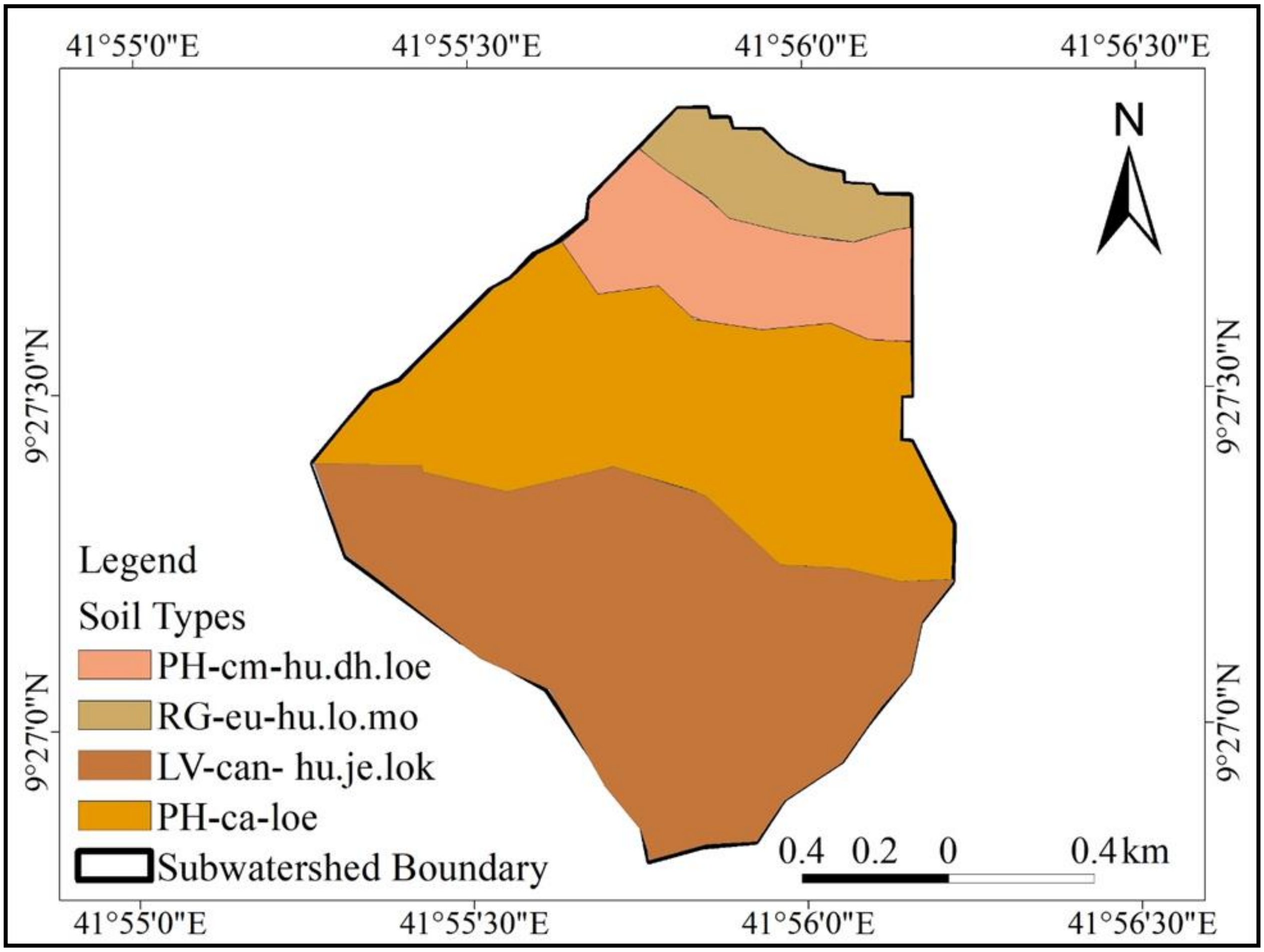

Figure 4. Soil map of Dhengego subwatrshad, Eastrn Ethiopia.

Table 8. Diagnostic characterstics soil classification, and creating map legends.

Pedon	Diagnostics				WRB classification	*WRB code	USDA soil taxonomy Subgroup
	Horizons		Properties	Materials			
	Surface	Subsurface					
P1	Mollic	----	-----	MM	Eutric Regosol (Humic, Loamic, Mollic)	RG-eu-hu.lo.mo	Lithic Ustorthents
P2	Mollic	Cambic (Bw)	-----	MM	Cambic Phaeozem (Hypereutric, Profundihumic, Pantoloamic)	PH-cm-hu.dh.loe	Typic hapludolls
P3	Mollic (Ap)	Argic (Bt)	----	Calcaric	Calcaric Phaeozem （Humic, Pantoloamic)	PH-ca-loe	Typic hapludolls
P4	----	Argic (Bt1-Bt3)	-----	Calcaric	Endocalcaric Luvisol (Humic, Katoloamic)	LV-can- hu.je.lok	Udic haplustalfs

*WRB= World Reference Base for Soil Resources, MM= Mineral matrials.

5. SUMMARY AND CONCLUSION

Characterization and classification of soil is the main source of information for precision agriculture, land use planning and management. For an efficient use of the limited land resources, site specific management recommendations based on site specific information are much required. Undulating topography, altitudinal differences and large variations in slope were characteristic features of the present study area (Dhengego subwatershed). A field study was carried out to characterize and classify soils of Dhengego subwatershed at Eastern Ethiopia. The free soil survey (traverse survey) method was employed to identify auger sampling sites. Augers were opened up to 120 cm depth (unless limited by impervious layer) and described in the field to observe the variations in site and soil surface characteristics so as to determine the final pedon opening sites along toposequence within the study area. Four representative pedons, Pedon 1 (Summit), Pedon 2 (Upper slope), Pedon 3 (Middle slope) and Pedon 4 (Lower slope) by the dimension of 150 width x 150 cm length x 2 m deep) were opened along the hill-slope. Selected morphological properties were described in situ in the field as per the FAO guidelines for soil description (FAO, 2006a). The results of the study revealed variations in morphological, physical and chemical properties of the soils across the study area, which indicate their variation in productive potential and management requirements for specific agricultural use. Topography plays a major role and thereby influences the development and characteristics of the soils along the topographic positions.

The soil depth of the pedons was found to be greater than 200 cm for Pedon 3 and 4 but the rest of the pedons were less than 200cm deep, although the identified genetic horizons had variable thickness. The difference in amount and distribution of particle size (sand, silt and clay) content with depth and across the soils was also recorded. Generally, sand size fraction dominated the texture of soils in the study area.

The structure of all pedons in the surface soil layers ranged from moderate fine, weak fine (Pedons 2 and 3) granular, to weak fine subangular blocky structure (Pedon 4). Regarding subsurface layers, soils at the summit and shoulder of the slope position (Pedons 1 and 2, respectively) composed of granular structure throughout the depth. It varied from angular to subangular blocky in subsurface layers of Pedon 3 opened at the back slope, whereas it changed inconsistently from subangular to angular blocky, and agin to subangular blocky in the soil of foot slope (Pedon 4). The friable consistence observed in the surface soils of the pedons could be attributed to the higher organic matter content which may be favorable for the workability of the soils at appropriate moisture content.

Soil pH (water) increased from surface to subsurface of the pedons, which may indicate the presence of vertical movements of exchangeable bases. The pH value was rated neutral to slightly alkaline which was the pH requirement for optimum plant growth. In all the topographic positions the bulk density values of all the soils were found to increase with depth except in Pedon 1 and 2 and pedon 3 and 4 had higher bulk density values. The soil water content retained at field capacity (FC at 33 kPa) ranged from 15.52% to 34% whereas, at permanent wilting point (PWP) at 1500 kPa, it ranged between 6.44% and 19.48% for sandy clay loam and sandy clay textural classes respectively. The Available Water Content (AWC) ranged from 75 mm m^{-1} to 156 mm m^{-1} for the same textural classes and the values were influenced by organic matter and clay contents within the horizons. The electrical conductivity (EC) of the soils showed very low values, indicating that the soils are not saline.

The total N content of the surface soils ranged from 0.21 to 0.22%, and 0.13 to 0.19% at subsurface, which could be rated as moderate. The OC content ranged from 2.63% to 3.07 % in the surface layers of all pedons and 0.71% to 2.41 % in the subsurface. The C:N ratio of the surface soils across the study area may be considered to be within the optimum range. Available P content of soils in the surface horizon ranged from 11.15 mg kg^{-1} to 25.90 mg kg^{-1}, while in the subsurface horizon it varied from 6.70 mg kg^{-1} to 14.35 mg kg^{-1} with an inconsistent trend in all pedons except in pedon 1; which was generally rated as high. The values of extractable micronutrients were in the order of Fe > Mn > Cu > Zn. The soils of the study area were found to be high to very high in Fe, medium to very high in Mn very low to low in Zn and medium to high in Cu contents.

Recorded values of exchangeable cations increased along the topographic positions, where the maximum value was found at the lower topographic position. Soils were categorized as high to very high with respect to Ca^{2+} and Mg^{2+} contents, low to high for K^{+} and Na^{+}except pedon 1 that had very low to low contents of these cations. The value of cation exchange capacity of soil showed an increasing trend with soil depth, which generally goes with the trend in clay content.

The soils were classified into different Reference Soil Groups following the FAO-WRB of 2015 by detecting diagnosticcharacteristics (horizons, properties and materials). The soil classification revealed that three Reference Soil Groups, namely, Regosols, Phaeozems and Luvisols; the the second level detailed naming of which would be Eutric Epileptic Regosol (Humic, Loamic, Mollic) for pedon 1, Cambic Phaeozem (Hypereutric, Profundihumic, Pantoloamic) for pedon 2, Calcaric Phaeozem （Humic, Pantoloamic) for pedon 3 and Endocalcaric Luvisol (Humic, Katoloamic) for pedon 4. The equivalent names of the USDA-Soil Taxonomy were: Lithic Ustorthents for pedon 1, Typic hapludolls for pedon 2 and 3 and Udic haplustalfs for pedon 4. Since almost all the soils identified were of ample fertility status especially in terms of their base saturation but prone to topographically exacerbated soil degradation, special emphasis should be given to soil OM and integrated soil fertility management coupled with soil and water conservation measures to optimize and sustain crop production in Dhengego subwatershed.

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7. APPENDICES

Appendix Table 1. General site information and profile description of pedon 1.

Profile ID	EH/HW/BG/AD/P1	Land use	Annual and perennial crop
Date	20/12/2021	Human influence	Vegetation strongly disturbed
Surveyor	Mekonnen Keneni	Surface stone cover	Very few
Status	Reference profile description	Erosion category	Water
Location Country	Ethiopia	Erosion area	**0-5%**
Region	East Hararghe	Erosion degree	Slight
Location woreda	Haramaya	Sealing thickness	None
Location kebele	Biftu Geda	Crack width	Fine
Local name	Awudawit	Depth	< 2cm
Longitude	41.93152	Surface salt	None
Latitude	09.46424	Surface drainage	Slow runoff
Elevation	2251 masl	Depth to bedrock	34cm
Topography	0.2-0.5% level	Rootable depth	34cm
Major landform	Plain	Rooted depth	34cm
Position on slope	Summit (Crest)	Depth of observation	34 cm
Slope form	Straight	Local soil name	Biyyee Dima
Slope gradient	2%	FAO-WRB soil group	Eutric Epileptic Regosol (Humic, Loamic, Mollic)
Parent material	Sandstone (residual)		

Pedon	Horizon designation	Depth (cm)	Description
P1	Ap	0-14	Dusky red (2.5YR3/2, moist) and reddish-brown (2.5 YR4/3, dry) colour ; sandy clay loam; moderately fine granular structure; slightly hard when dry, friable to very friable when moist, and slightly sticky and slightly plastic when wet; common, fine roots and many burrows; fine to medium pores; no coatings; few, fine coarse fragments of unknown nature; no mottles; slight reaction with HCl; clear, irregular, smooth boundary.
	ACr	13-34	Dusky red (2.5 YR3/2, moist) and dark reddish brown (2.5YR 3/3, dry) colour; sandy clay loam; weAk fine to the medium granular structure, slightly hard when dry, friable to very friable when moist, and slightly sticky and slightly plastic when wet, many, fine roots and many burrows; fine to medium pores; no coatings; common, fine coarse fragments of unknown nature; no mottles; no reaction with HCl. There was a continuous rock after C (34 cm.

Appendix Table 2. General site information and profile description of pedon 2.

Profile ID	EH/HW/BG/GE/P2	Slope form	Convex
Date	27/12/2021	Slope gradient	15%
Surveyor	Mekonnen Keneni	Parent material	Sandstone (residual)
Status	Reference profile description	Land use	Grazing land
Location country	Ethiopia	Human influence	Terraced (Stone-faced)
Location region	East Hararghe	Surface stone cover	Boulders
Location woreda	Haramaya	Erosion category	Water (Gully, Rill)
Location kebele	Biftu Geda	Erosion area	10-25%
Local name	Genda Erga	Erosion degree	Moderate
Longitude	41.93185	Sealing	None
Latitude	09.46142	Cracking	None
Elevation	2152 masl	Surface salt	None
Topography	10-15%	Surface drainage	Rapid runoff
Major landform	Medium gradient hill	Depth to bedrock	110cm
Position on slope	Shoulder	Rootable depth	110 cm
Slope form	Convex	Local soil name	Biye Cirachawa
Slope gradient	15%	FAO-WRB soil group	Cambic Phaeozem (Hypereutric, Profundihumic, Pantoloamic
Parent material	Sandstone (residual)		

Pedon	Horizon designation	Depth (cm	Description
P2	Ah	0-18	Dark brown (7.5YR3/2, moist) and brown (7.5YR4/3, dry) colour ; sandy clay loam; weak medium granular structure; loose when dry, very friable when moist, and slightly sticky and slightly plastic when wet; common, fine roots and many burrows; medium pores; no coatings; few, fine coarse fragments of quartz and unknown nature; no mottles; no reaction with HCl; clear, smooth boundary.
	Bw	18-43	Dark brown (7.5YR3/3, moist) and brown (7.5YR4/3, dry) colour; sandy clay loam; weak medium granular structure; loose when dry, very friable when moist, and slightly sticky and slightly plastic when wet, few, fine roots and many burrows; medium pores; no coatings; common, fine coarse fragments of quartz and unknown nature; no mottles;no reaction with HCl; clear, smooth boundary.
	C	43-110	Brown (5YR4/4, moist) and strong brown (5YR4/6, dry) colour; sandy clay loam; weak fine granular structure; loose when dry, loose when moist, and non-sticky and non-plastic when wet; very few, fine roots and common burrows; high pores; no coatings; many, fine coarse fragments of quartz and unknown nature; no mottles; no reaction with HCl.

Appendix Table 3. General site information and profile description of pedon 3.

Profile ID	EH/HW/BG/GB/P3	Land use	Rainfed arable cultivation
Date	19/11/2021	Human influence	Vegetation disturbed, terracing
Surveyor	Mekonnen Keneni	Surface stone cover	None
Status	Reference profile description	Erosion category	Water, Rill erosion
Location country	Ethiopia	Erosion area	10-25%
Location region	East Hararghe	Erosion degree	Moderate
Location woreda	Haramaya	Sealing thickness	None
Location kebele	Biftu Geda	Crack width	Medium
Local name	Genda Bukusho	Depth	2-10cm
Longitude	41.93061	Surface salt	None
Latitude	09.45748	Surface drainage	Slow runoff
Elevation	2081masl	Depth to bedrock	Not observable
Topography	5-10 % Slopping	Routable depth	200 cm
Major landform	Medium gradient escarpment	Rooted depth	180 cm
Position on slope	Middle slope	Depth of observation	200 cm
Slope form	Convex	Local soil name	Biyyee Gurracha
Slope gradient	8%	FAO-WRB soil group:	Calcaric Phaeozem (Humic,
Parent material	Sandstone (colluvial)		Pantoloamic)

Pedon	Horizon designation	Depth (cm)	Description
P3	Ap	0-23	Dark reddish-brown (5YR 3/2, moist, moist) and dark red brown (5YR3/3, dry) color; sandy clay loam; weak fine granular structure; slightly hard when dry, loose when moist, and slightly sticky and slightly plastic when wet; common, fine roots and many burrows; common pores; no coatings; few, fine coarse fragments of quartz and unknown nature; no mottles; Visible effervescence HCL; clear, smooth boundary.
	A1	23-60	Dark reddish-brown (5YR2.5/2, moist) and very dark grey (5YR3/1, dry) color; sandy clay loam; moderate medium angular blocky structure; hard when dry, friable when moist, and slightly sticky and slightly plastic when wet, few, fine roots and many burrows; common pores; no coatings; common, fine, coarse fragments of quartz and unknown nature; no mottles; Visible effervescence; clear, wavy boundary.
	AB	60-90	Dark reddish-brown (5YR3/2, moist) and dark reddish brown (5YR3/3, dry) color; sandy clay loam; strong coarse sub-angular blocky structure; very hard when dry, friable when moist, and slightly sticky and slightly plastic when wet; few, fine roots and few burrows; few pores; no coatings; many, fine coarse fragments of quartz and unknown nature; no mottles; no reaction with HCl; gradual, wavy boundary.
	B1	90-130	Dark reddish grey (5YR4/2, moist), and brown (5YR4/4, dry) color; sandy clay loam; moderate coarse sub-angular blocky; hard when dry, friable when moist, sticky and plastic when wet; fine roots and few burrows; very few pores; no coatings; many, fine coarse fragments of quartz and unknown nature; no mottles; fine graver fragments very few no reaction with HCl; , gradual, wavy boundary.
	Bt	130-200+	Very dark grey (5YR3/1, moist) and black (5YR2.5/1, dry) color; sandy clay; moderate fine sub-angular blocky; hard when dry, friable when moist, very sticky and plastic when wet; very few, fine roots and very few burrows; very few pores; no coatings; many, fine coarse fragments of quartz and unknown nature; no mottles; fine graver fragments; no reaction with HCl.

Appendix Table 4. General site information and profile description of pedon 4.

Profile ID	EH/HW/BG/GH/P4	Land use	Annual and perennial crop
Date	17/12/2021	Huma influence	Vegetation strongly disturbed
Surveyor	Mekonnen Keneni	Surface stone cover	None
Status	Reference profile description	Erosion category	Water, sheet erosion
Location country	Ethiopia	Erosion area	0-5%
Location region	East Hararghe	Erosion degree	Slight
Location	Haramaya *Woreda*	Sealing thickness	None
Location kebele	Biftu Geda	Crack width	Wide (2-5cm)
Local name	Ganda Hassan	Depth	(10-20cm)
Longitude	41.93139	Surface salt	None
Latitude	09.45375	Surface drainage	Moderate
Elevation	2037 masl	Depth bedrock	Not bserved
Topography	Gently undulating (1-5%)	Rootable depth	200+ cm
Major landform	Plain	Rooted depth	175cm
Position on slope	Lower slope	Depth of observation	200+ cm
Slope form	Straight with concave	Local soil name	Biyyee Gurracha
Slope gradient	Gently sloping (3 %)	FAO-WRB soil group	Endocalcaric Luvisols (Humic, Katoloamic)
Parent material	Colluvial		

Pedon	Horizon designation	Depth (cm)	Description
P4	Ap	0-18	Dark gray (5YR4/1, moist) and dark reddish-brown (5YR3/2, dry) color; sandy clay; weak fine subangular structure; soft when dry, friable when moist, and slightly sticky and slightly plastic when wet; many, fine roots and many burrows; common pores; no coatings; few, fine coarse fragments of quartz and unknown nature; no mottles; no reaction with HCl; gradual, wavy boundary.
	Ak	18-50	Black (5YR2.5/1, moist) and dark reddish-gray (5YR4/2, dry) colour; sandy loam; moderate coarse subangular blocky structure; hard when dry, firm when moist, and sticky and plastic when wet, few, fine roots and few burrows; common pores; no coatings; few, fine, coarse fragments of quartz and unknown nature; no mottles; Visible effervescence HCl; gradual, wavy boundary.
	Bt1	50-110	Dark reddish-gray (5YR4/2, moist) and very dark gray (5YR3/1, dry) color sandy clay loam; moderate coarse angular blocky structure; hard when dry, firm when moist, and sticky and plastic when wet; few, fine roots and few burrows;few pores; no coatings; few, fine coarse fragments of quartz and unknown nature; no mottles, no reaction with HCl; clear, smooth boundary.
	Bt2	110-150	Dark reddish-brown (5YR3/4, moist) and dark reddish-brown (5YR3/4, dry) color; sandy clay loam; moderate medium granular; soft when dry, friable when moist, slightly sticky and slightly plastic when wet; fine roots and few burrows; very few pores; no coatings; many, fine coarse fragments of quartz and unknown nature; no mottles; fine graver fragments very few, no reaction with HCl; clear, smooth boundary.
	Bt3	150-200+	Very dark grey (5YR3/1, moist), and dark reddish grey (5YR4/2, dry) color; sandy clay; strong coarse sub-angular blocky; hard when dry, firm when moist, very sticky and plastic when wet; no roots and very few burrows; very few pores; no coatings; many, fine coarse fragments of quartz and unknown nature; no mottles; many graver fragments; no reaction with HCl.

Appendix Tabble 5. Auger point coordinates within the study area.

Pedon	Y_Coordinate	X_Coordinate
P1	9.464102	41.931366
	9.46340	41.932674
	9.463789	41.932312
	9.464281	41.931608
P2	9.451436	41.934107
	9.462554	41.932669
	9.461905	41.935861
	9.462367	41.930301
	9.462387	41.930541
P3	9.458472	41.930279
	9.457914	41.928629
	9.457094	41.929810
	9.457912	41.932966
	9.459436	41.928829
P4	9.452461	41.930810
	9.452797	41.932431
	9.453915	41.933393
	9.454601	41.932262
	9.455421	41.929257
	9.451023	41.934316

Appendix Table 6. Ratings of analytical parameters.

Parametrs	Very low	Low	Medium	High	Very high	Sources
Organic carbon(%)	<5	0.5-1.5	1.5-3	>3	Not given	Tekalign (1991)
Total nitrogen (%)	Not given	<0.01	0.01-0.12	0.12-0.25	>25	Tekalign et al,. (1991)
Available P (mg kg-1)	<5	5-9	10-17	18-25	>25	Cottenie (1980)
CEC (cmol (+) kg-1)	<5	5-15	15-25	25-40	>40	Landon (1991)
Exchangeable Mg (cmol (+) kg-1)	<0.3	0.3-1.0	1.0-3.0	3.0-8.0	>8.0	FAO(2006b)
Exchangeable K (cmol (+) kg-1)	<0.2	0.2-0.3	0.3-0.6	0.6-1.2	>1.2	FAO (2006b)
Exchangeable Na (cmol (+) kg-1)	<0.10	0.1-0.3	0.3-0.7	0.7-2.0	>2.0	FAO (2006b)
Exchangeable Ca (cmol (+) kg-1)	<2	2-5	5-10	10-20	>20	FAO (2006b)
Available Fe (mg kg-1)	0-2	2- 4	4-6	6-10	>10	Lindsay and Norvell (1978)
Available Mn (mg kg-1)	0-0.5	0.5-1.2	1.2-3.5	3.5-6	>6	Lindsay and Norvell (1978)
Available Zn (mg kg-1)	0-0.5	0.6-1.0	1-3	3-6	>6	Lindsay and Norvell (1978)
Available Cu (mg kg-1)	0-0.1	0.1-0.3	0.3-0.8	0.8-3	>3	Lindsay and Norvell (1978)

Appendix Table 7. Mean monthly rainfall, maximum and minimum temperature (1994-2020)

Months	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC
Mean rainfall (mm)	6.23	12.78	46.98	101.1	72.08	47.92	109.49	132.58	101.48	42.62	19.67	8.21
Mean minimum (^{o}C)	9.5	11.2	13.1	14.6	14.9	15.4	14.6	14.3	14.4	12.0	10.4	9.3
Mean maximum (^{o}C)	29.9	32.0	33.0	32.1	31.9	31.5	30.3	28.6	28.9	29.2	28.5	28.4