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Soil-Landscape Characterization and Mapping to Advance the State of Spatial Soil Information on Ethiopian Highlands: Implications for Site-Specific Soil Management

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Abstract: Soil characterization and classification are becoming the primary source of information for precision agriculture, land use planning, and management. Thus, this study was focused on perusing the landscape-scale spatial variation of soils in data-scarce areas using toposequence-based ground sampling to characterize and classify the soils. Six typical pedons representing major landforms were opened and studied for their morphological characteristics and physical and chemical properties. Results indicated that the soils were shallow to very deep in depth, moderately acidic to moderately alkaline in soil reaction, non-saline, and clay to sandy loam in texture. The soils were found to be very low to low in organic carbon, very low to medium in total nitrogen , low to medium in available P, very low in available S, very low to low in available B, high to very high in CEC and very low to very high in base saturation. The soils were found to be deficient in Zn but sufficient in Fe, Cu, and Mn. Following the field survey and soil analytical results, five main reference soil groups, mollic Leptosols (Eutric), Prothovertio Luvisols (Clayic, Aric, Escalic), Skeletic Fluvisols (Arenic, Densic), Haplic Leptosols (Skeletic), Haplic Vertisols (Endocalcaric, Ochric), and Haplic Cambisols (Arenic, Aric) were identified in the different parts of the topographic positions. Pedon 2, 3, 5, and 6 were classified in I to IV land capability class (LCC) and grouped as arable land with some limitations. They were in suitable to a marginally suitable range. The severe constraints to crop cultivation in the area were low fertility, erosion hazard, and climate for all soil units. Therefore, application of manure and compost alongwith chemical fertilizer, reducing complete crop residue removal, and soil and water conservation measures are essential to overcome these common and other limitations.

Keywords: *Catena, classification, landscape position, soil horizon, toposequence*

Introduction

Soils are a non-renewable source and comprise a vital component of the world's stock of natural capital with a prolonged forming process. Soil takes 100s to 1000s years to form a 1 cm of soil and erode in a relatively short time due to improper use or poor management with little opportunity for regeneration (Jonsson and Da viosdottir 2016; Kavitha and Sujatha 2015; Santos-

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Frances *et al.* 2022). Hence, soil scientists strongly recommend understanding the soil beneath our feet, managing it properly, and avoiding destroying the essential building block of our environment and food security. The soil is perhaps the most difficult, underrated, and little understood matrix (Balestrini *et al*. 2015; Saljnikov *et al.* 2022). There is a saying by the legendary Italian artist Leonardo Da Vinci to explain our nuanced understanding of soil resources, i.e., *"we know more about the movement of celestial bodies than about the soil underfoot"* (Colby and David 2019).

The main ecological functions of soils have been grouped into three major categories: (i) regulatory and support functions, (ii) provision functions, and (iii) information, culture, leisure, and religion functions (Devi 2021; FAO and ITPS 2015; Nunes *et al.* 2020). Soil is essential for supporting food production (producing about 95% of humanity's food supply) and providing ecosystem services. However, like other habitats and ecosystems, the soil is under increasing pressure due to anthropocentric activities (Jónsson and Davíðsdóttir 2016) to the extent that a new geologic epoch, the Anthropocene, has been proposed (Will *et al.* 2007). Thus, the soil capital is threatened in Ethiopia and elsewhere due to rapid population growth, higher food demand, land use competition, massive vegetation clearing, desertification, overuse, and mismanagement (Bai *et al.* 2013; Elias 2016; IPBES 2018; Koch *et al.* 2013). These caused it to exceed its capacity to perform, as manifested by land degradation (Chen *et al.* 2022; Saljnikov *et al.* 2022). About 30 % of the world's soils are currently degraded (Zurich Megazine 2021). All of the world's topsoil could become unproductive within 60 years if current loss rates continue (Maximillian *et al.* 2019).

Therefore, understanding the soil types of a given area is a vital pre-requisite to designing optimum management strategies (Sebnie *et al.* 2021). Thus, identifying the spatial distribution of soils and their characteristics is critical because it can enhance natural resources management, predict soil properties in non-sampled locations, and improve sampling designs in agro-ecological and environmental studies. Moreover, given the vital role that soil plays within ecosystems and human life, it is essential to assess soil health, especially on field crop farms that dominate agricultural landscapes like Ethiopia.Therefore, to establish the level baseline of micronutrients, soil analysis is recommended to determine the level of available nutrients (Doula and Sarris 2016). Balancing ecosystem services with agricultural production is essential to meet the needs of a growing global population while minimizing the environmental impacts of agriculture (Udawatta *et al.* 2017). So, analysis and interpretation of spatial variability of soils is a keystone in the site-specific farming system (Iqbal *et al.* 2005) since agricultural soils are in peril (Gebremedhin *et al.* 2022). Various studies on soil properties also confirmed that topographic position largely governs the change in types, characteristics, and distribution of soils (Debele *et al.* 2018; Dessalegn *et al.* 2014; Mulugeta 2004).

Above all, information about the distribution of a country's natural resources is vital for many purposes, including local and regional planning, economic forecasting, food security, and environmental protection. Studies also confirmed that the classification of fields into management zones is based on the variability of soil fertility limitations in precision agriculture (Iticha and Takele 2019). Over the last few decades, the need for landscape monitoring and assessment of changes in spatial patterns has grown as knowledge of the types and properties of soils is critical for decision-making regarding crop production and other land-use types (Leenaars *et al.* 2020). Accordingly, soil characterization, classification, and mapping are among the most important stages and building blocks in natural resources assessment tools for understanding the soil-landscape, classifying it, and getting the best understanding of the environment (Ahmed *et al.* 2013; Esu *et al.* 2008). Apart from information about soil forming factors at the site, soil characterization is done through the description of colour, texture, structure, consistence, voids, cutans, roots, cementations, nodules/concretions, rock fragments/stones, faunal activity, and horizon boundary of each generic soil horizons (FAO 2006a; Saether and De Caritat 1996). The coupling of soil characterization, classification, and mapping provides a powerful resource for humankind's benefit, especially in food security and environmental sustainability (Ahmed *et al.* 2013).

However, Ethiopia lags more in defining its spatial soil sources in detail and fine-scale, yet only 1712 soil profiles are detected according to the World Soil Information Service (WoSIS) (Batjes *et al.* 2020). More profile numbers will be studied than the WoSIS reported; however, only a part from there is readily reachable in a consistent format for the use of the international community. Another lag is that no Ethiopian soil classification system was identified, established, and documented with vernacular languages. This, in turn, creates many problems in the soil use system. In much of the country, lack of or fragmented geospatially explicit information on soil-landscape resources is common (Leenaars *et al.* 2020). Thus, providing up-to-date and site-specific soil information to the beneficiaries based on a detailed soil study at the local or watershed level is indispensable for sustainable soil use. Moreover, the United Nations pledged to achieve sustainable development goals (SDGs) by 2030, and regional land use analyses are essential to achieving these goals. Research findings also highlighted that soil resource information is vital for sound soil use planning and sustainable fertility management (Dinssa and Elias 2021; Elias 2016; Fekadu *et al.* 2018; Gebreselassie *et al.* 2014).

Previous studies have reported that 19 out of the 28 Major Soil Groups of the FAO-UNSECO Soil Map of the World are found in Ethiopia. Because of this, Ethiopia is called "Soil Museum" of the world. However, our knowledge of Ethiopia's soil resources is limited. The soil resources were mapped at 1:2,000,000, which were too coarse and topographically not detailed enough to provide practical information for soil fertility decisions at lower spatial scales (Elias 2016). Past soil survey activities were inadequate in providing basic soil data that can help to manage soils according to the local variability (i.e., watershed or farm scale).Thus, the present study was initiated to characterize and classify the soils of Ayiba catena following the FAO-WRB legends (FAO 2006a; IUSS Working Group WRB 2015). This study was, therefore, set out expressly to (i) provide detailed morphological, physical, and chemical properties of the soils in the Ayiba mountainous landscape and (ii) classify the soils according to the FAO-WRB soil classification system and develop a soil map of the watershed to enable soil-specific farm-scale management interventions.

Materials and Methods

Site description: location, climate, soil, land use, and husbandry

The research was carried out in the Ayiba watershed (4099.14 ha) of the Emba-Alaje district, southern Tigray, northern Ethiopia. Ayiba watershed is part of the Denakil river basin located between 12°51'18"-12°54'36"N and 39°29'24"-39°35'24"E (Fig. 1). Elevation ranges from 2722 to 3944 above Mean Sea Level (MSL) with mountainous landscape and steep terrain at upper and middle slopes. The landform of the study area is dominated by high mountainous relief hills and starkly dissected plateaus with steep slopes (>30% slope gradient) complemented by valley bottoms (Amanuel *et al.* 2015; Elias 2016). Regarding the geomorphological setting, an important artifact in the watershed is different landslides positioned within the toposequence, which occurred due to basaltic parent material deposition down the slope, making them very important for soil distribution (Amanuel *et al.* 2015; Gebresamuel *et al.* 2022). Regarding soil development, Van de Wauw *et al.* (2008) described two essential types of mass movements in similar geomorphological settings: (a) large-scale landslides which move basaltic parent material downslope; and (b) flows of vertic clays deposited at the foot of the sandstone cliff, or similar secondary flows at the foot of large-scale landslides.

The watershed is generally characterized as tepid to cool semi-arid climatic condition with extended 9-10 months of dry periods and 50-60 days of the rainy season and highland agro-ecological zone with a rainfall bi-modally distributed (Amanuel *et al.* 2015; Elias 2016; Negash and Israel 2017). The main rainy season, 'Keremti' (summer: June to September), is preceded by a short rainy season, 'Belgi' (spring: February to May), (Table 1), predominantly derived from the Indian Ocean (Elias 2016; Embaye 2009; Yemane *et al.* 2020). Spatial distribution of the (a) topsoil sampling points and (b) profile sites in the Ayiba watershed in the semi-arid region of Tigray highland, northern Ethiopia is shown in figure 1. According to the 20 years of weather data obtained from four nearby weather stations (Bora, Maychew, Wedisemero, and Korem), the mean monthly rainfall is 72.88 mm, with total annual precipitation of 853 mm. August is the peak period for main rain season and April is the peak for the slight rain season. The area's mean minimum and maximum monthly temperatures are 7.1 and 25.6°C, respectively, with a mean temperature of 16.8°C (Fig. 2). The dotted area on the left and right sides designates the dry season. The area's annual potential evapotranspiration (PET) is about 1411 mm (Elias 2016).

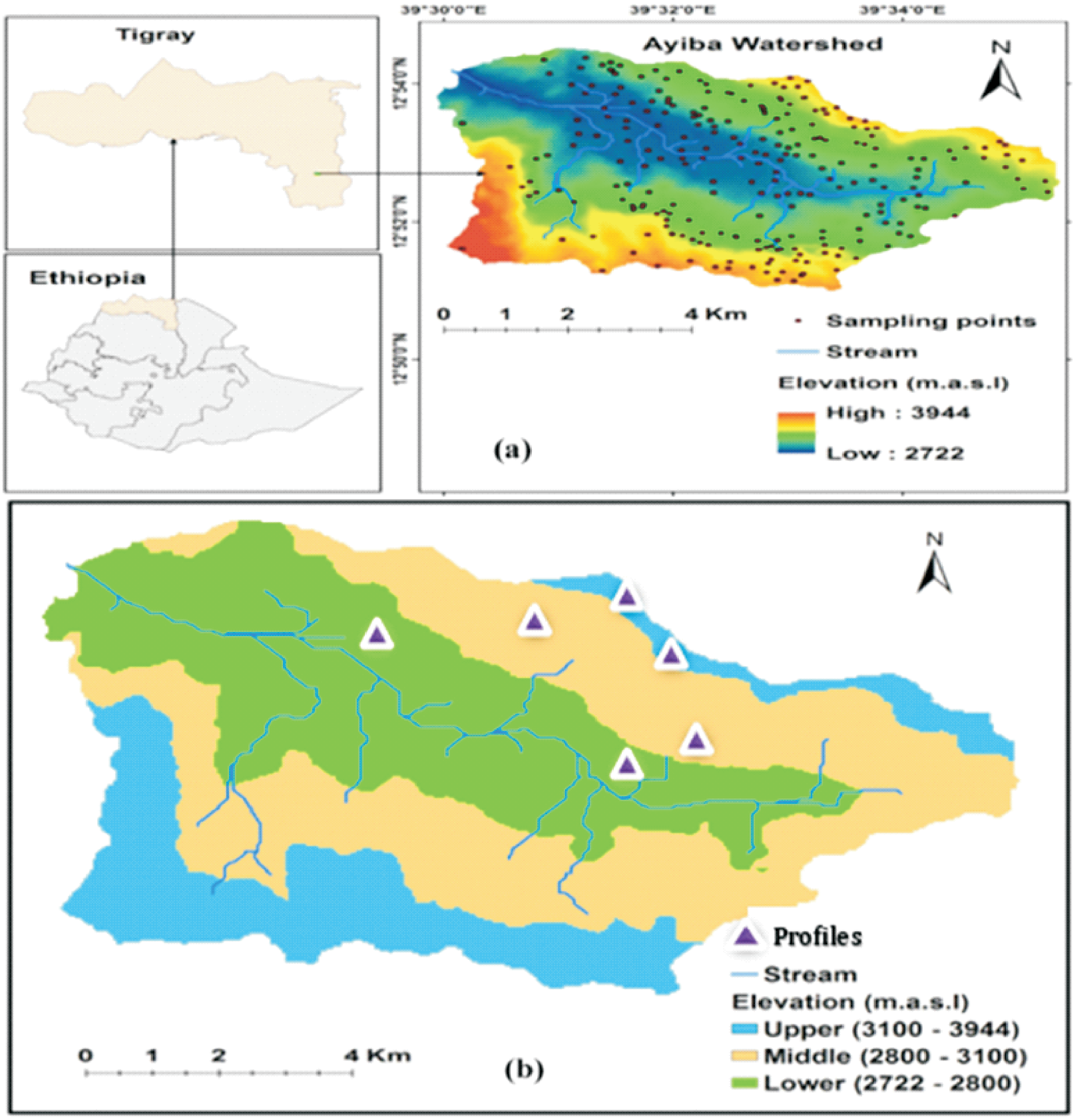

Fig. 1. Spatial distribution of the (a) topsoil sampling points and (b) profile sites in Ayiba watershed located in the semi-arid region of Tigray, northern Ethiopia

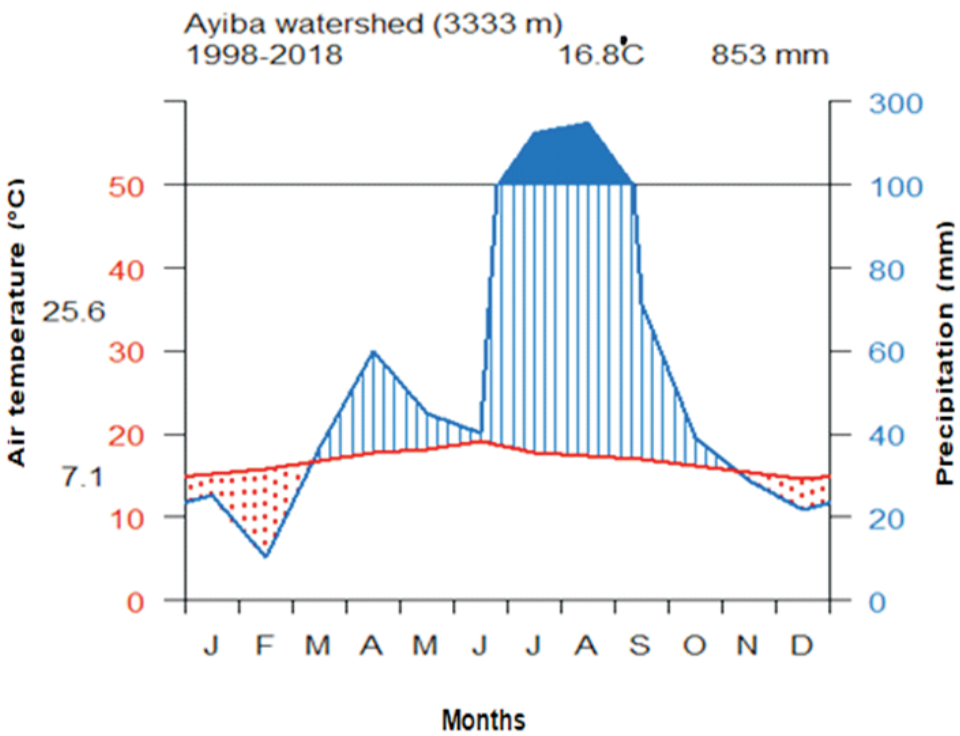

Fig. 2. Climatic diagram of Ayiba watershed from 1998- 2018 (NMSA 2018)

Like as noted in previous studies of northern highland Ethiopia (Delelegn *et al.* 2017; Gelaw *et al.* 2015; Tekle and Hedlund 2000; Zeleke and Hurni 2001), the natural woodland and vegetation of the study watershed had been abandoned in the last more than half century. Only tiny patches of remnant natural forests around churches are presently kept by psychic divining power. There has been religious thinking since antique that "any disturbance to the nature and spirit around the holly church (*e.g.*, cutting a tree, leaving animal for grazing or browsing, *etc.*) will bring a catastrophic consequence" (personal communication with local elders and priests, 2018). The high rate of deforestation and forest degradation is driven by demand for wood products (for energy and construction purposes) and by pressure from other land uses, agriculture, and cattle ranching to support the alarmingly increasing population growth. Therefore, reducing deforestation and increasing reforestation are expected to make good economic sense in their own right and also support agriculture and rural livelihood.

Mixed crop-livestock agricultural systems are the primary means of livelihood in the farming system (Elias 2016). Cereal and legume crops and some vegetable and fruit crops are grown in the study area (Elias 2016; Girmay *et al.* 2014). Wheat (*Triticum aestivum* L.), barley (*Hordeum* spp.), and Teff (*Eragrostistef* (Zucc.) Trotter) are among the significant cereal crops that supply the bulk of the staples for the population in the area (Table 1). Legume crops such as fava bean (*Vicia fava* L.), field pea (*Pisum sativum* L.), Ethiopian pea (Dekeko in Tigrigna) (*Pisum sativum* var. basidium), lentils (*Lens culinaris* or *Lens esculenta*) are also cultivated for dual purpose, *i.e.*, yield and rotation. Tef-wheat-legumes are the standard crop rotation practice in the area. Besides, some other vegetables and fruits like an onion (*Allium cepa* L.), pepper (*Piper nigrum* L.), cabbage (*Brassica oleracea* L.), and apple (*Malus Domestica* L.) are grown by farmers in the watershed (Gebresamuel *et al.* 2022; Girmay *et al.* 2014). Chickpea (*Cicer arietinum* L.) is sown after harvesting using residual moisture (Table 1). Natural pasture is the primary source of animal feed in areas where farmers practice intensive pasture land grazing with a higher stocking rate, resulting in poor natural pastureland management (Atsbha *et al.* 2020).

Table 1. Main crops cultivated and their cropping calendar under main rain, short rain, and irrigation scheme in Ayiba area, northern Ethiopia

Main rain Crops	**basic agronomic activities**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
Barely	Sowing												
	Fertilizer application												
	Harvesting												
Wheat	Sowing												
	Fertilizer application												
	Harvesting												
Teff	Sowing												
	Fertilizer application												
	Harvesting												
Short rain crops													
Barely wheat and	Sowing												
pea	Fertilizer application												
	Harvesting												
Chickpea	Sowing												
	Fertilizer application												
	Harvesting												
Irrigation													
Maize	Sowing												
	Fertilizer application												
	Harvesting												
Onion, tomato &	Sowing												
pepper	Fertilizer application												
	Harvesting												

February to May: Spring (*Belgi*) season (Short rainy season), June to September: Summer (*Keremti*) season (Main rainy season)

Profile site selection and field description

The free-soil survey (traverse survey) method was employed as a survey method along the landscape to detect the variability of soils in the watershed. A transect walk was made to cover the soils at varying physiographic positions and elevations with a team of experts to the Ayiba watershed. Field exploration was conducted to identify the significant soil units and localize profile sampling sites before the actual field survey. In addition, before soil sample collection was done, some basic information about the existing land was gathered from local farmers, elders, and extension experts. A provisional map (1:50,000) was prepared with pre-defined sampling points distributed throughout the watershed using ArcGIS 10.5 software. Extensive auguring was done to identify mapping units and sites for opening profile pits. The necessary soil survey facilities and formats such as the FAO guidelinesfor soil profile description (FAO 2006a), WRB soil classification manual (IUSS Working Group WRB 2015), Munsell colour chart, GPS, soil profile, and auger description sheets were collected and prepared before field work. Slope maps were extracted from a digital elevation model (DEM). The watershed was generally found within a slope range between nearly flat to slopping (1-8%) at the foot slope to steep sloping (>60%) at the upper slopes (Fig. 3).

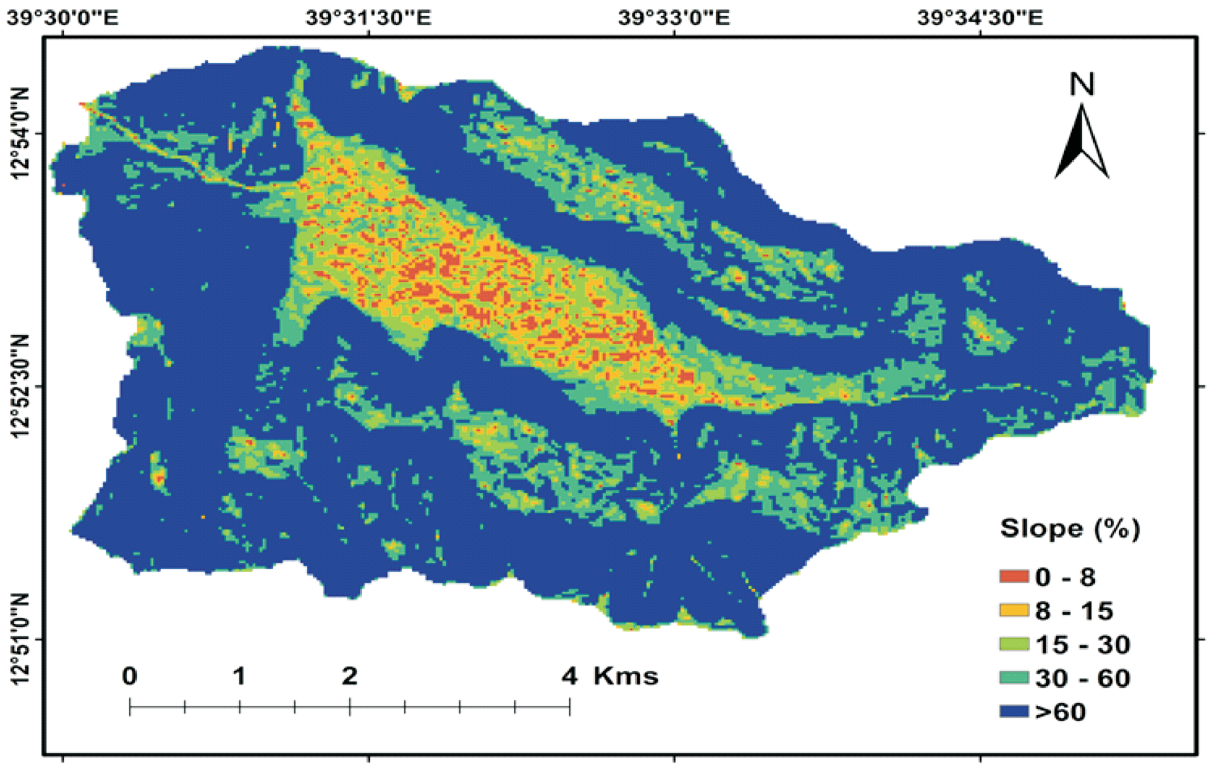

Fig. 3. Spatial slope map of Ayiba watershed, Northern Ethiopia

A catena was selected from the sloping land escarpment at the north to the valley floor at the south encompassing landform components spinning from crest/summit to foot slope/toe slope (Fig. 4a). Accordingly, the selected toposequence was stratified into three landscape positions: upper (Crest + Shoulder slope), middle (Back slope), and foot (toe slope + depressions) slope positions and two profiles were opened at each place (Fig. 4b). From an extensive series of observations along the toposequence, profiles were opened to a depth of 2+ m (unless soil depth is limited or is impracticable due to stoniness) with dimensions of 2 m x1.5 m on a site that was representative of each landscape position. All profiles were geo-referenced, and general site information and soil description were recorded (Table 2). Land use-wise, profiles 1 and 3 were excavated on grassland, while profiles 2, 4, 5, and 6 were excavated on cropland (Table S3). Profiles were described and sampled following the standard procedures to investigate soil morphological, physical, and chemical properties (FAO 2006a; IUSS Working Group WRB 2015). Soil morphological descriptions were completed in-situ according to FAO guidelines (FAO 2006a), and soil colour notation was described using Munsell Colour Company (2009)

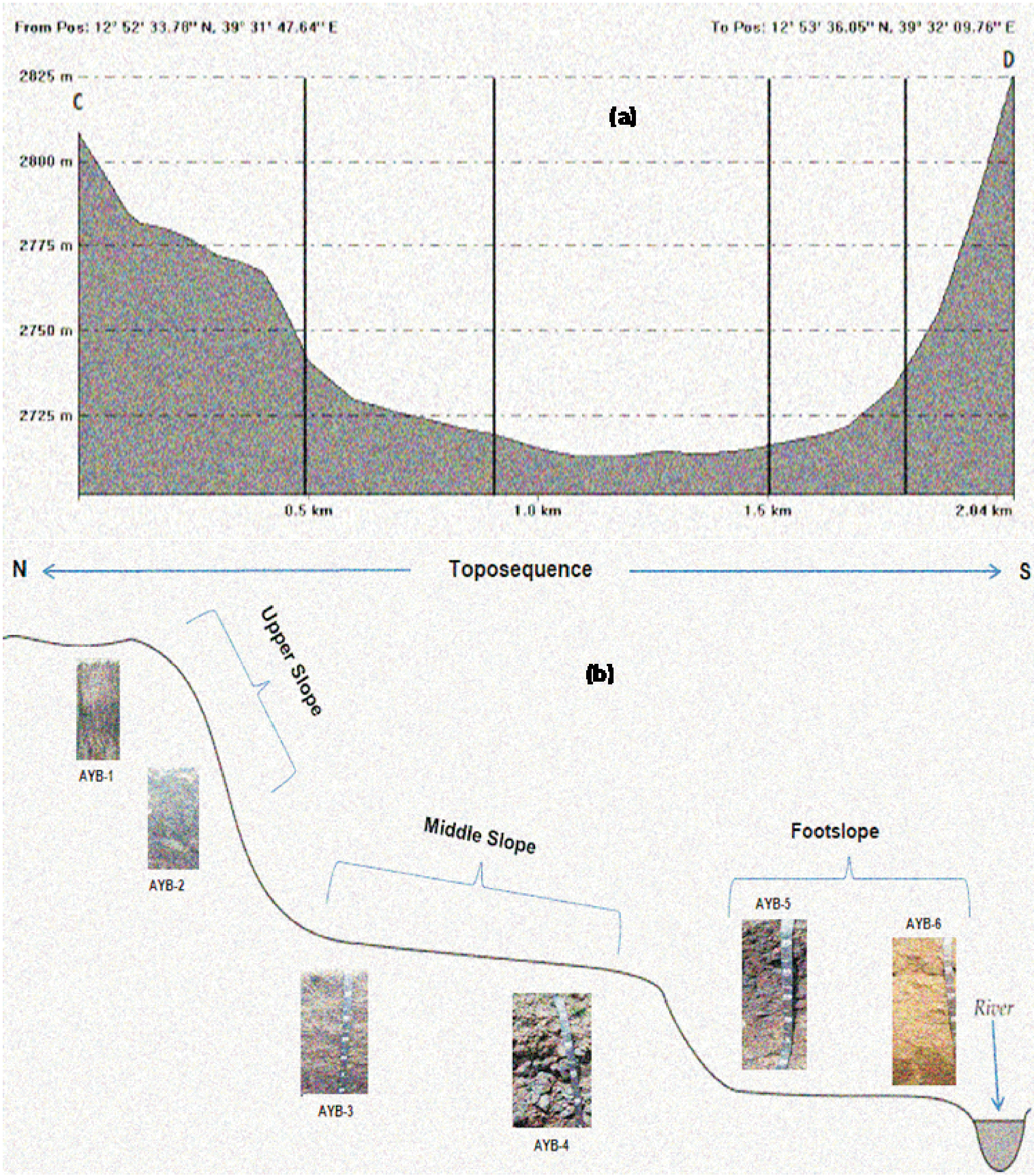

Fig. 4. (a) Cross profile CD dissected plateau of Ayiba watershed, and (b) conceptual toposequence model showing landscape position and profiles opened at the upper slope, middle slope, and foot slope, respectively.

Table 2. Some site characteristics of the studied profiles along the toposequence of Ayiba watershed, Northern Ethiopia

Profile	Geographical location		Altitude (MSL, m)	Landscape position	Landform	Parent material	Land use
	Latitude (N)	Longitude (E)					
AYB-1	12º90'21.8"	39º55'15.1"	3304	Upper Slope	Sloping land	Eluvial basalt deposit	Grassland*
AYB-2	12º89'89.8"	39º33'11.4"	3030	Upper Slope	Sloping land	Recent alluvium	Crop land
AYB-3	12º89'43.6"	39º54'52.6"	2989	Middle Slope	Level plateau	Colluvium of basalt	Grassland†
AYB-4	12º53'04.3"	39º33'00.4"	2905	Middle Slope	Sloping land	Colluvium of basalt	Cropland
AYB-5	12º52'35.5"	39º32'31.9"	2744	Foot Slope	Valley floor	Alluvial basalt deposit	Cropland
AYB-6	12º53'64.3"	39º31'10.4"	2752	Foot Slope	Valley floor	Alluvial basalt deposit	Cropland

AYB: Ayiba, the study area, M.a.s.l = meters above sea level, *exclosure grassland used for cut-and-carry system, †free grazing land.

Soil sampling and analysis

A systematic stratified sampling procedure was used to distribute sampling throughout the watershed under careful consideration of topography and spatial pattern of land use. A global positioning system (GPS) was used to identify the sites' longitude, latitude, and elevation. In all soil sampling procedures at each sampling spot, surface litter was scraped, and vegetation cover is removed before collecting samples. Samples pot excluding was also performed if a considerable difference was noted to minimize soil variability among sub-samples for composite preparation to minimize outlying results. Soil morphology was described in the field to interpret their characteristics, and disturbed and undisturbed soil samples were collected from each genetic horizon (starting with the lowest horizon and working to the uppermost to avoid contamination) and from each land use type across the topography for laboratory analysis. Soil sampling locations were selected to best represent by considering variation in terrain attributes and drainage facilities. Soil samples were collected using a soil auger. Accordingly, 20 disturbed and undisturbed samples were collected from each generic horizon for soil characterization and classification analysis.

The collected soil samples were spread for air-drying (to reduce oxidation of soil carbon), crushed and grounded by pestle and mortar, and sieved with a 2 mm sieve mesh for physical and chemical analysis. Rock fragments and gravels (>mm), visible roots, organic residues, and macro-fauna were removed manually at sampling time before pooling. Finally, the soil samples were taken to the laboratory for analysis. Analysis was done at Tigray soil laboratory center, Mekelle (Ethiopia), and plant nutrition laboratory, College of Environmental Science Resources, Zhejiang University, Hangzhou (China). All the soil samples were analyzed following the standard analytical procedures (Table 3). The interpretation of the measured soil properties was made using table S1.

Table 3. Soil parameters and methods usedSoil classification and mapping of Ayiba watershed

Soil parameters	Extraction Method	References
Particle-size distribution†	Modified Hydrometer method	Beretta *et al*. (2014)
Clay Contrast Index (CCI)	$CCI = \frac{\text{Clay in the upper orizon}}{\text{maximum clay in profile}}$	Khomo (2008) and Young (1976)
Soil bulk density (*ρ*d)	Core method	Blake and Hartge (1986)
Soil total porosity	$[1-\frac{pd}{ps}]*100$	Danielson and Sutherland (1986)
Water retention capacity (FC, PWP, AWC)	Pressure plate apparatus	Schoonover and Crim (2015)
Soil pH (H $_2$O and 1M KCl) and EC at 25 °C	Potentiometric method	Mclean (1983) and Rhoades (1996)
Soil organic carbon (SOC)	Dichromate oxidation	George *et al.* (2013)
Total Nitrogen (TN)	Micro-Kjeldahl digestion	Bremner (1996)
Available phosphorus (av. P)	Olsen extraction method	Olsen and Sommers (1982)
Available sulphur (S)	0.5*M* $NaHCO_3$ at pH 8.5	Kilmer and Nearpass (1960)
Available boron (B)	DTPA– hot water extraction	Johnson and Fixen (1990)
Soil micronutrients (Zn, Cu, Mn & Fe)	DTPA-TEA	Lindsay and Martens (1990)
Ex. Bases (Ca^{2+}, Mg^{2+}, Na^{+}& K^{+})	Ammonium acetate (pH-7)	Rhoades (1996)
Soil CEC (cation exchange capacity)	Ammonium acetate (pH-7)	Van Reeuwijk (2006)
Soil $CaCO_3$ (Calcium Carbonate equivalent)	rapid titration method	Van Reeuwijk (2006)

†Soil textural classes were read from the textural triangle (Soil Survey Staff 2014), EC: electric conductivity, ?s= 2.65 g cm-3, %SAS is the percentage of wet stable aggregate (soil aggregate stability), MA+S is the mass of wet stable aggregate plus the mass of sand (g), MS is the mass of sand (g), and MT is the mass of the soil sample (g).

Based on the morphological, physical, and chemical properties, the watershed soils were classified into different units (major soils) following the World Reference Base for soil resources (IUSS Working Group WRB 2015). The presence or absence of specific diagnostic horizons, properties, and materials was used to distinguish soil units and sub-units according to WRB soil classification system. Soils identical in landforms, parent material, relief, topography, and morphology were considered similar and accorded a similar mapping unit. Spatial soil classification was based on the information obtained from field soil profile morphological description and laboratory analysis results following IUSS Working Group WRB (2015) soil classification legend.

Soil capability and suitability assessment

Soil properties and crop yields are strongly interrelated. Agricultural potential is directly related to Land Capability, (I to VIII), as presented in table 4; with Classes I to III classified as prime agricultural land that is well suited for annual cultivated crops, whereas Class IV soils may be cultivated under certain circumstances and specific or intensive management practices, and Land Classes V to VIII are not suitable for cultivation (Schoeman *et al.* 2002). This system give an overview of the agricultural capability and limitations of the soils in question and is helpful for soil capability comparisons. Criticisms of this system, however, include its lack of consideration of the local setting, land use planning, and a lack of financial resources (Nethononda *et al.* 2014). For this reason, the site's soil capability has also been assessed, taking the local setting into account from field checking. After a qualitative assessment, the soil types were grouped into the soil suitability classes (Table 5) and classified as very suitable, moderately suitable, marginally suitable, and not suitable soils for rainfed cultivation of annual crops (FAO 1984; Ritung *et al.* 2007). The suitability of a given piece of land is its natural ability to support specified land use, such as rain-fed agriculture, livestock production, forestry, *etc*.

Statistical data analysis and software used

Soil data obtained from the laboratory work were checked to test the data sets' normality with the Shapiro-Wilk normality test before analysis using R software for Windows. The normality assumption was not violated. Descriptive statistical analyses and variances were then tested following the general linear model (GLM) procedure to obtain the effect of the model: using one-Way ANOA to see the variation among the generic soil horizons. Whenever significant differences among horizon means have been detected, the analysis of variance used Tukey's HSD test at a $p<0.05$ level of probability to differentiate. Data in the present study were presented as mean ± SE. Finally, GIS software (version 10.5) was employed to produce the spatial soil maps of the Ayiba watershed.

Results and Discussion

Profile site and soil morphological characteristics

The site characteristics of the profiles indicated differences in slope, drainage, and extent of water erosion (Table S2). According to FAO (2006a) guideline, the profiles were positioned in a slope gradient range of gently sloping to very steep. The upper and middle landscape comprises most of the sloping to very steep slope gradient classes (Fig. 3). All profiles were well-drained, but AYB-5 was found poorly drained. All Profile sites showed a range of water erosion processes manifested by sheet, rill, and gully formation (Fig. 5). Effects of land use, extensive and intensive farming, and removal of vegetation cover have amplified the erosion process, which was observed at all profiles and their surrounding landscapes. The land use of AYB-1 and 3 are grassland lying on soil developed from basaltic and colluvial parent materials. Whereas that of AYB-2, 4, 5, and 6 represented annual rainfed field cropping with varying land-use histories having soils developed from the outwash of colluvium and alluvium basaltic materials. Rainfed cultivated land, grassland, plantation forest, and barren land were the typical land use type of

Table 4. Land Capability Classes, limitations, and land use (Schoeman *et al.* 2002)

LCC	Increased intensity of use									Limitations	Conservation needs	Use suitability	LCG
I	W	F	LG	MG	IG	LC	MC	IC	VIC	No or few limitations. Very high arable potential, very low erosion hazard	Good agronomic practices	Annual copping	
II	W	F	LG	MG	IG	LC	MC	IC	-	Slight limitations, High arable potential, and low erosion hazard	Adequate runoff control	Annual cropping with special tillage or ley (25%)	Arable land
III	W	F	LG	MG	IG	LC	MC	-	-	Moderate limitations. Some erosion hazard	Certain conservation practices and tillage methods.	Rotation of crops and ley (50%)	
IV	W	F	LG	MG	IG	LC	-	-	-	Severe limitations. Low arable potential. High erosion hazard	Intensive conservation practice.	Long-term leys (75%)	
V	W	-	LG	MG	-	-	-	-	-	Water course and land with wetness limitations	Protection and control of water table	Improved pasture or wildlife	
VI	W	F	LG	MG	-	-	-	-	-	Limitations preclude cultivation. Suitable for perennial vegetation	Protection measures for the establishment, e.g., sod seedling	Veld and/or afforestation	Grazing land
VII	W	F	LG	-	-	-	-	-	-	Very severe limitations. Suitable only for natural vegetation	Adequate management of natural vegetation.	Natural veld grazing and afforestation.	
VIII	W	F	-	-	-	-	-	-	-	Extremely severe limitations. Not suitable for grazing or afforestation	Total protection from agriculture	Wildlife	Wildlife

W: Wildlife, F: Forestry, LG: Light grazing, MG: Moderate grazing, IG: Intensive grazing, LC: Light cultivation, MC: Moderate cultivation, IC: Intensive cultivation, VIC: Very intensive cultivation, LCC/G: Land Capability Classes/Group

Table 5. Definition of the soil suitability classes (FAO 1984; Ritung et al. 2007)

Highly Suitable (S_1)	The land has no significant limitations or only minor limitations to sustain a given land utilization type without a significant reduction in productivity or benefits. It will not require major inputs above the acceptable level, with nil to minor adverse e conomic, environmental, health, and/or social outcomes. These soils are deep enough, have good natural fertility, and can store sufficient water.
Moderately Suitable (S_2)	The land has limitations that, in aggregate, are moderately severe for sustained app lication of the given land utilization type; the limitations will reduce productivity or benefits and increase required inputs to the extent that the overall advantage to be gained from the use, although still attractive, will be appreciable inferior compa red to that expected from S_1 land. Have potential adverse economic, environmental, health, and/or social outcomes if not adequately managed. These can be shallow soils, soils with limited natural fertility, or soils incapable of holding and releasing adequ ate amounts of soil moisture.
Marginally Suitable (S_3)	The land has severe limitations for sustained application of the given land utilization type. It will reduce productivity or benefits or increase required inputs, and any expenditure will only be marginally justified. Have moderate to high risk of adverse economic, environmental, health, and/or social outcomes if not adequately managed. Marginal soils are rocky, sandy, or shallow, with a limited reservoir of nutrients and water available to plants.
Not Suitable (S_N)	The land has limitations that may be insurmountable, and limitations are so severe as to preclude any possibilities of successful sustained use of land in the given manner as the range of inputs required is unjustifiable. If not managed, there is a very high risk of adverse economic, environmental, and/or social outcomes. These are very shallow and stony soils (more on steep slopes) with impeded drainage.

the upper and middle slopes (eroded sites), while cultivated land and grassland land use dominated the foot slope of the watershed (Seifu *et al.* 2020).

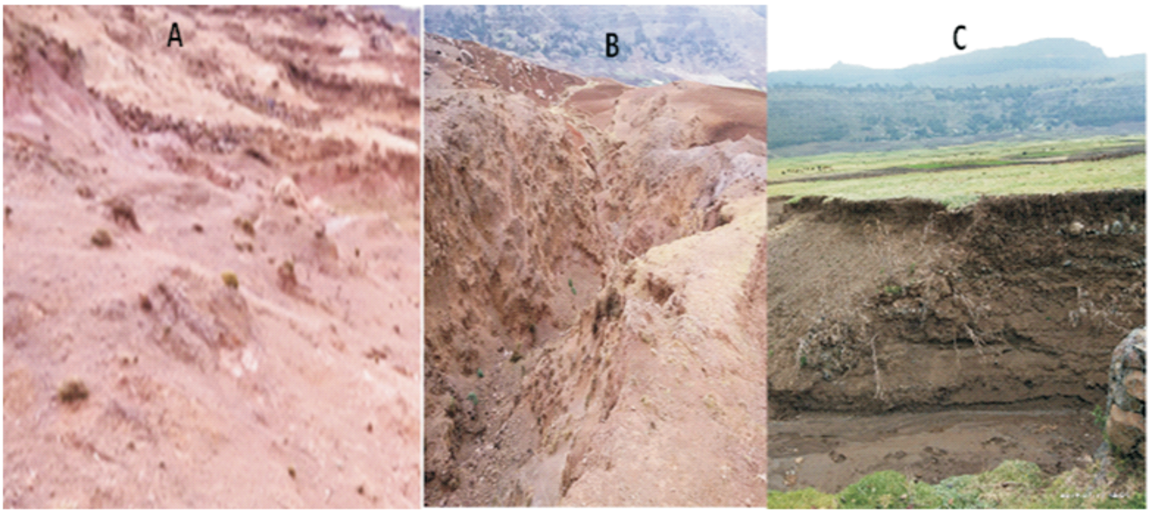

Fig. 5. Field photographs of (a) Sheet erosion (upper slope), (b) rill erosion (middle slope), and (c) active gully erosion (foot slope) around the profiles along the soil catena

Most profiles unveiled an A-B-C master horizon sequence. Morphological characteristics of each horizon's colour, texture, structure differentiation, etc., are presented in table 8. The soil depth varied from 53 cm (shallow) at the upper position to 200+ cm (very deep) at the foot slope position. The thickness of the A-horizon ranged from 0-35 cm along the toposequence. AYB-1 was the shallowest profile indicating little influence of soil-forming processes as rock debris does not accumulate on the spot since they roll down due to gravity. According to IUSS Working Group WRB (2015), the surface horizon of AYB-1 qualifies for mollic epipedons. The diagnostic epipedons of AYB-2 and 3 qualify for argic due to illuvial clay accumulation, high selective clay surface erosion, and the absence of lithic discontinuity. The diagnostic horizons of AYB-4, 5, and 6 were also qualified as paralithic, vertic, and cambic, respectively. Except for AYB-4, which has a weakly developed soil horizon, all the other profiles had well-developed morphological characteristics and deeper rooting depth. AYB-4 is somewhat a strange profile in soil development as it had an A-R-B-R master horizon sequence with a very shallow rooting depth (<35 cm) due to the presence of a lithic contact (R layer) which may probably be developed from the loss process by water erosion. A significant quantity of clay translocation and many distinct clay cutans were observed in the sub-soils of AYB-2 and 3 profiles, indicating that eluviation-illuviation processes are active. At the same time, AYB-1 was developed as a result of melanization. AYB-5 and 6 profiles in the foot slope showed a slight clay increase with soil depth but did not qualify for the argic B horizon. In this study, the soils have a colour hue of 2.5 to 10YR, a value of 2 to 5, and chroma of 1 to 4 in dry and moist conditions. With this range of colour matrix, the soil colour of all the pedons varied from black to greyish brown (dry) and black to yellowish brown (moist). Boundaries between A- horizon and B- horizon were evident due to the darkening effect of organic matter. The field soil texture by feel method varied in all the profiles across toposequence. The surface texture of profiles AYB-1, 2, and 5 were clay dominant, while that of AYB-3, 4, and 6 were sandy loam dominant. The moisture status of surface horizons AYB-1 and 3 were slightly moist. At the same time, AYB-2, 4, 5, and 6 were dry, which might be interconnected to soil organic matter and clay within the horizons. The horizon boundaries, of pedons1 to 6 had clear-smooth, clear-wavy, clear-smooth, clear-smooth, diffuse-smooth, and diffuse-smooth, respectively. Horizon boundary characteristics also showed slight variations among and within profiles along the toposequence (Table 6).

Regarding soil structure, all soils were generally friable on the surface but became firm in the sub-soil. Explicitly, profiles 1 to 4 had weak to moderate grade surface structure and weak to strong grade sub-surface structure in the upper and middle catena. Likewise, in terms of type and size, all profiles were found in massive to crumbly and very fine to medium textured. In AYB-5 the soil structure in the surface horizons is mainly lumpy, mostly created by tillage disturbance, and slightly hard. In the sub-surface horizons, soil morphology changes from subangular blocky forms to weakly developed coarse blocky horizons. In AYB-6, soil structure indicated weak to moderate grade, massive to crumbly type, and fine to medium size. In the foot slope, infiltration is slow, and water may stand on the surface in the rainy season for extended periods. All soils exhibited varied consistency in dry, moist, and wet conditions, mostly following friable on the surface and becoming firm in the sub-soil (Table 6). Except for AYB-5 at its lower layers showed very slightly effervescent (formed few bubbles), in other profiles, the field $CaCO_3$ (using 1*N* HCl solution) was non-effervescent.

Soil physical characteristics of the profiles

Soil particle size distribution and clay contrast index

The particle-size distribution indicated a variation along the toposequence ranging from 18-68%, 14-53%, and 6-68% for sand, silt, and clay parts, respectively. As a result, textural classes of the soils varied from clay to sandy loam texture along with the topography (Table 7). Generally, clay dominated the soil's particle size fraction followed by sand and silt. In almost all profiles, percentage sand and clay parts followed decreasing and increasing trends, respectively, with depth in the geomorphic units, except AYB-3 was inconsistence. On the other hand, higher sand content in the surface layer is associated with the selective removal of clay and silt by erosion, as the degree of sand transportability is lower compared to the finer soil fractions. In this study, we have also observed a seasonal water logging at the foot slope, which may probably cause deterioration of structured B-horizon and dispersion of clay particles down with water table front.

The silt/clay ratio ranged from 0.21 - 4.33 along with the topography, and the ratio ranged from 0.29 – 4.33 in the A-horizons and from 0.21 – 2.94 in the B-horizons and decreased with depth. The highest value of the silt/clay ratio was recorded in the A_h-horizon (4.33) of profile 4, followed by Bw-horizon (2.94) of profile 3, and the lower was recorded at the lower sub-soils of AYB-2 (Table 7). The clay contrast index (CCI) ranged from 0.40-0.95, with the highest at AYB-1 and the lowest at AYB-3. Higher CCI indicated lower textural diffrentiation, while lower CCI indicates higher textural differentiation in the pro?les. Accordingly, the clay enrichment of the profiles was found in the following order: AYB-1 (0.95) < AYB-2 (0.89) < AYB-5 (0.85) < AYB-6 (0.80) < AYB-4 (0.75) < AYB-3 (0.40) (Table 7). AYB-1 to 4 are located on the middle and upper topography, mainly manifested by sloping to a steep slope gradient (Fig. 3), intensively cultivated land with free grazing experiences, which all induced erosion on the site and lower clay content by removing the upper horizon.

Bulk densities, total porosity, and water retention capacity

The surface bulk densities (BD) of the pedons ranged from 1.13 mg m^{-3} in the A horizon of pedon 1 to 1.46 mg m^{-3} in the A horizon of pedon4. In comparison, the sub-soil BD ranged from 1.27 mg m^{-3} in the Bt-horizon of pedon 2 to 2.32 mg m^{-3} in the BC-horizon of pedon 5 and increased with depth (Table 7). Furthermore, the gravimetric water content of the soils at field capacity (33 kPa) ranged from 17.9-44.2%, while the amount at the permanent wilting point (1500kPa) was between 9.1-32.55%, and the volumetric plant available water content (AWC) of the soils varied from 88-127.8 mm m^{-1} across soils of the topography (Fig. 6). The water retention capacity of AYB-3 was higher followed by AYB-1 and 2 compared to the other pedon. This may be attributed to relatively higher organic matter and clay content in these pedons. Surface soils had slightly higher water content at

Table 6. Morphological description of the six profiles studied

Profile	Horizon	Depth (cm)	Munsell soil Colour matrix test				HB [24] Dist/Top	Field Texture [25]	Moisture status [57]
			Colour Code (Dry)	Soil Colour Description	Colour Code (Moist)	Soil Color Description			
AYB-1	A_h	0-27	2.5YR2.5/1	Black	7.5YR2.5/2	Black	C/S	Clay	SM
	B	27-53	10YR3/2	brown	10YR2/1	Black	C/S	Sandy Clay	Dry
	R	53+	-	-	-	-	C/S	-	-
AYB-2	A_p	0-20	2.5YR2.5/1	Black	5YR2.5/1	Black	C/S	Clay	Dry
	Bt	20-80	7.5YR2.5/1	Black	10YR2/1	Black	C/W	Clay	Very dry
	B_C	80-110	7.5YR3/1	Very dark grey	7.5YR3/1	Very dark grey	C/S	Clay	Very dry
	C	110-168+	7.5YR3/4	Dark brown	7.5YR3/4	Dark Brown	C/S	Sandy clay	Very dry
AYB-3	Aa	0-20	5YR3/1	Very dark grey	7.5YR2.5/1	Black	C/S	Sandy Loam	SM
	B	20-45	10YR3/2	Brown	10YR3/1	Very dark grey	C/S	Sandy Loam	Dry
	2B	45-80	5YR4/1	Dark grey	5YR2.5/1	Black	C/S	Sandy Loam	Very dry
	3B	80-128	10YR4/2	Dark greyish brown	10YR2/1	Black	C/S	Loamy Sand	-
	Bw	128-180+	10YR4/1	Dark grey	7.5YR3/1	Very dark grey	C/S	Silt Loam	Very dry
AYB-4	Ap	0-35	10YR5/1	Grey	10YR5/1	Grey	G/S	Sandy Loam	Very dry
	R	35-90	-	-	-	-	G/S	-	-
	BC	90-140	10YR5/2	Greyish brown	10YR5/4	Yellowish brown	G/S	Sandy	Very dry
	Rc	140-200+	-	-	-	-	G/S	-	-
AYB-5	Ap	0-23	5YR2.5/1	Black	5YR2.5/1	Black	D/S	Clay	SM
	Bit	23-80	5YR2.5/1	Black	5YR2.5/1	Black	D/S	Clay	Dry
	Bc	80-110	7.5YR4/1	Dark grey	7.5YR3/1	Very dark grey	D/S	Silt Loam	Very dry
	CR	110-130	-	-	-	-	D/S	-	-
AYB-6	Ap	0-20	10YR5/2	Greyish brown	10YR4/1	Dark grey	D/S	SCl Loam	Dry
	A	20-50	7.5YR4/1	Dark grey	7.5YR3/1	Very dark grey	D/S	Sandy Loam	Very dry
	A2	50-80	10YR4/2	Dark greyish brown	10YR3/1	Very dark greyish	D/S	Sandy Loam	Very dry
	Bw	80-165+	10YR3/2	Brown	10YR3/2	Brown	D/S	Sandy Loam	Very dry

[24, 25, 57] are the tables used for soil description from the guideline and the symbols used (if) are in accordance with it. SM: Slightly Moist, HB Dist/Top: Horizon Boundary by Distinctness/Topography (C/S: clear/smooth, C/W: clear/Wavy, G/S: Gradual/Smooth, D/S: Diffuse/Smooth).

Table 6. Continued …

Profile	Coarse fragments [26,27,29]			Structure [47,49,50]			Consistency [53,54,55,56]			Coatings [64,65,66]			Roots [79,80]	
	Abundance (%)	Size (mm)	Weathering state	Grade	Type	Size	Dry	moist	wet	Abundance (%)	Contrast	nature	Size (mm)	Abundance (%)
	None	FG	F	WE	MA	FI	SO	LO	NS/NP	Common	Distinct	Clay	M	Common
AYB-1	Few	FM	F	ST	SG	ME	SO	LO	NS/NP	Common	Distinct	Clay	VF	V.few
	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Few	FM	F	WE	CR	VF	SO	LO	S/P	Common	Distinct	Clay	Fine	Common
AYB-2	V.few	FG	F	ST	SB	ME	EHA	VFI	VS/VP	Common	Distinct	Clay	Fine	V.few
	V.few	FG	F	ST	SB	ME	HA	FR	SS/SP	Common	Distinct	Clay	-	None
	None	FG	F	ST	SB	ME	EHA	VFI	SS/SP	V.few	Distinct	Clay	-	None
	V.few	FG	F	WE	MA	FI	SO	LO	NS/NP	None	Distinct	Clay	M	Common
AYB-3	V.few	FG	F	WE	GR	VF	SO	LO	NS/NP	None	Distinct	Clay	VF	V.few
	V.few	FG	F	WE	GR	VF	SO	LO	NS/NP	None	Distinct	Clay	VF	Few
	V.few	FG	F	WE	GR	VF	SO	LO	NS/NP	None	Distinct	Clay	VF	V.few
	V.few	FG	F	MO	SB	ME	SHA	VFR	SS/SP	None	Distinct	Clay	-	None
	None	FG	F	WE	MA	VF	LO	LO	NS/NP	None	Distinct	SA	Fine	Common
AYB-4	Abundant	S	F	-	-	-	-	-	-	-	-	-	-	-
	Common	M	F	WE	MA	VF	LO	LO	NS/NP	None	Distinct	SA	-	None
	Stone line	M	F	-	-	-	-	-	-	-	-	-	-	-
	None	FG	F	MO	AB	VF	SO	LO	S/P	N-V	Distinct	Clay	Fine	Common
AYB-5	None	FG	F	MO	SB	ME	SO	LO	VS/VP	None	Distinct	Clay	VF	V.few
	V.few	FG	W	WE	MA	FI	EHA	VFI	SS/SP	None	Distinct	Clay	-	None
	Many	MC	F	-	-	-	-	-	-	None	Distinct	Clay	-	None
	V.few	FG	W	WE	MA	FI	LO	LO	NS/NP	None	Distinct	Clay	Fine	Common
AYB-6	Common	M	F	WE	SG	ME	LO	LO	NS/NP	None	Distinct	Clay	VF	Few
	Common	M	F	WE	SG	ME	LO	LO	NS/NP	None	Distinct	Clay	VF	Few
	Few	M	F	MO	CR	FI	SO	LO	SS/SP	None	Distinct	Clay	VF	V.few

[26, 27, …, 80] are the tables used for soil description from the FAO (2006a) guideline and the symbols used (if) are in accordance with it. The symbols are V.few: very few, FG: fine gravel, FM: fine and medium gravel, S: stones, M: medium gravel, MC: medium and coarse gravel; F: fresh or slightly weathered, W: weathered; WE: Weak; ST: Strong; MO: Moderate; MA: massive, SG: single grain, CR: crumbly, SB; Subangular blocky, AB: angular blocky; FI: fine/thin, ME: medium, VF: very fine/thin; SO; soft, EHA: extremely hard, HA: hard, LO: loose; VFI: very firm, FR: friable, VFR: very friable; NS/NP: non-sticky/non-plastic, S/P: sticky/plastic, SS/SP: slightly sticky/slightly plastic; N-V: none to few, SA: sand coatings; M: medium, VF: very fine.

Table 7. Soil physical properties of pedons along the toposequence

Profile	horizon	Depth (cm)	Particle size distribution (%) Sand	Silt	Clay	Textural class	SCR	CCI	BD (mg m^{-3})	TP (%)
	Ah	0-27	14.3^{b}	32.0^{b}	53.7^{a}	Clay	0.6^{a}	0.95	1.26^{b}	52.5^{a}
AYB-1	B	27-53	32.0^{a}	11.3^{a}	56.7^{a}	Clay	0.2^{b}		1.36^{a}	48.6^{b}
	R	53+	-		-	-	-	-	-	-
	Average	-	23.15	21.65	55.2	Clay	0.4		1.31	50.55
	Ap	0-20	31.3^{a}	15.3^{a}	53.3^{a}	Clay	0.29^{a}	0.89	1.32^{a}	50.2^{a}
	Bt	20-80	29.7^{a}	11.0^{a}	59.3^{a}	Clay	0.19^{a}		1.32^{a}	50.2^{a}
AYB-2	BC	80-110	27.3^{a}	16.7^{a}	56.0^{a}	Clay	0.30^{a}		1.33^{a}	49.2^{a}
	C	110-168+	16.7^{a}	24.3^{a}	59.0^{a}	Clay	0.43^{a}		1.36^{a}	49.8^{a}
	Average	-	26.25	16.83	56.9	Clay	0.30	-	1.33	49.85
	Aa	0-20	60.0^{a}	25.7^{b}	14.3^{a}	Sandy loam	1.80	0.40	1.26^{b}	52.3^{a}
	B	20-45	57.3^{ab}	33.3^{b}	9.3^{a}	Sandy loam	3.58		1.41^{a}	46.9^{b}
AYB-3	2B	45-80	51.3^{ac}	33.3^{b}	15.3^{a}	Sandy loam	2.18		1.42^{a}	46.4^{b}
	3B	80-128	42.7^{bc}	34.4^{b}	23.0^{a}	Loam	1.50		1.43^{a}	46.2^{b}
	Bw	128-180+	34.3^{c}	56.0^{a}	9.70^{a}	Silty loam	5.77		1.47^{a}	44.4^{b}
	Average	-	49.12	36.54	14.32	Sandy loam	2.97		1.40	47.24
	Ap	0-35	54.3^{b}	12.1^{a}	13.7^{a}	Sandy loam	0.88^{a}	0.75	1.26^{b}	52.3^{a}
	R	35-90	-		-	-	-		-	-
AYB-4	BC	90-140	74.3^{a}	15.7^{a}	10.3^{a}	Sandy loam	1.52^{a}		1.5^{a}	43.5^{b}
	RC	140-200+	-		-	-	-		-	-
	Average	-	64.3	13.90	12.00	Sandy	1.20	-	1.38	47.90
	Ap	0-23	32.7^{a}	19.7^{a}	47.7^{a}	Clay	0.44^{a}	0.85	1.64^{a}	38.1^{a}
	Bit	23-80	19.7^{ab}	32^{a}	48.3^{a}	Clay	0.68^{a}		1.6^{a}	39.6^{a}
AYB-5	Bc	80-110	14.7^{b}	29^{a}	56.3^{a}	Clay	0.53^{a}		1.6^{a}	39.6^{a}
	CR	110-130	-	-	-	-	-	-	-	-
	Average	-	22.37	36.9	50.77	Clay	0.55		1.61	39.03
	Ap	0-20	71.3^{a}	13.0^{b}	15.7^{a}	Sandy loam	0.86^{a}	0.80	1.41^{a}	46.7^{a}
	A	20-50	58.7^{b}	26.3^{a}	15.0^{a}	Sandy loam	1.76^{a}		1.39^{a}	47.5^{a}
AYB-6	A2	50-80	57.7^{b}	25.3^{ab}	17.0^{a}	Sandy loam	1.5^{a}		1.41^{a}	46.8^{a}
	Bw	80-165+	57.0^{b}	24.3^{ab}	18.7^{a}	Sandy loam	1.31^{a}		1.43^{a}	46.2^{a}
	Average	-	61.18	22.23	16.6	Sandy loam	1.36		1.41	46.80

SCR: silt to clay ratio, CCI: Clay Contrast Index, BD: bulk density, TP: total porosity. Values are means with pooled SEM, n = 3 per treatment group. Means in a column without a common superscript letter differ ($P<0.05$) as analyzed by one-way ANOVA and the TUKEY test.

FC and PWP than sub-horizon soils. Sub-horizon had water retention at FC ranged from 24% in pedon 3.0 to 46% in pedon 2, whereas in the sub-surface horizons, it ranged from 12% in pedon 3 to 45% in pedon 2. Available water content (AWC) showed a decreasing pattern but was inconsistent in the lower sub-soil of pedon 3, which may be due to textural change after the 4th layer. In surface and sub-surface soils, AWC ranged from 10 to 12 and 9 to 15 (v %), respectively.

Fig. 6. The studied soil profiles average water retention capacity (FC: Field capacity, PWP: permanent wilting point, AWC: Available water content). Error bars indicate the standard error of the mean

Chemical characteristics of the soils

Soil pH, soil EC, and soil calcium carbonate content

The soils were found in the range of neutral to moderately alkaline for pH-H_2O and moderately acidic to neutral soil reaction for pH-KCl (EthioSIS 2014) in nature, with pH values varying from 7.14 to 8.31 (pH-H_2O) and 6.31 to 7.27 (pH-KCl). The pH variation among each generic horizon differed significantly (Table 8). In all soil horizons, pH (H_2O) was higher than pH (KCl). The delta pH values, the difference between pH (KCl) and pH (H_2O), indicated that the soils have net negative charges and will hold positively charged ions on the colloidal particles of the exchange site. The electric conductivity (EC) of the soils, the average values were found in the range of 0.19 (AYB-4) to 0.35 mS cm^{-1} (AYB-3) with a range between 0.17 to 0.26, 0.15 to 0.32, 0.23 to 0.52, 0.16 to 0.22, 0.09 to 0.38, and 0.22 to 0.49 mS cm^{-1} in AYB-1 to 6, respectively (Table 8). The EC was generally found very low for all horizons. Hence, all soils were found non-saline. The low EC may be due to free drainage conditions, favouring the removal of released bases by percolation and drainage.

Table 8. Soil reaction, electrical conductivity, and $CaCO_3$ of soil profiles

Profile	Horizon	pH (H_2O)	pH (KCl)	-ΔpH	EC (mS cm^{-1})	$CaCO_3$ (%)
AYB-1	Ah	7.72^{a}	6.59^{b}	1.16^{b}	0.17^{b}	0.38^{b}
	Bw	7.84^{a}	7.12^{a}	0.69^{a}	0.26^{a}	0.62^{a}
	R	-	-	-	-	-
	Average	7.78 ± 0.05	6.86 ± 0.03	0.93 ± 0.01	0.22 ± 0.03	0.50 ± 0.04
AYB-2	Ap	7.59^{d}	6.48^{c}	1.10^{b}	0.23^{ab}	0.42^{c}
	Bt	7.82^{c}	6.90^{b}	0.93^{a}	0.15^{b}	0.63^{b}
	Bc	7.98^{b}	7.04^{ab}	0.94^{ab}	0.31^{a}	0.75^{ab}
	C	8.21^{a}	7.14^{a}	1.07^{ab}	0.32^{a}	0.91^{a}
	Average	7.9 ± 0.03	6.89 ± 0.05	1.01 ± 0.01	0.25 ± 0.03	0.68 ± 0.05
AYB- 3	Aa	7.73^{cd}	7.17^{b}	0.56^{a}	0.23^{c}	0.35^{c}
	B	7.69^{d}	6.85^{c}	0.84^{b}	0.27^{c}	0.62^{b}
	2B	7.95^{bc}	6.83^{c}	1.12^{c}	0.31^{bc}	0.73^{b}
	3B	8.14^{ab}	7.15^{b}	0.99^{bc}	0.42^{ab}	0.91^{a}
	Bw	8.31^{a}	7.27^{a}	1.04^{bc}	0.52^{a}	1.02^{a}
	Average	7.96 ± 0.08	7.05 ± 0.02	0.91 ± 0.08	0.35 ± 0.03	0.73 ± 0.05
AYB-4	Ap	7.14^{b}	6.31^{a}	0.83^{a}	0.22^{a}	0.47^{b}
	R	-	-	-	-	-
	Bc	7.77^{a}	6.78^{a}	0.99^{a}	0.16^{a}	0.67^{a}
	RC	-	-	-	-	-
	Average	7.46 ± 0.11	6.55 ± 0.37	0.91 ± 0.26	0.19 ± 0.03	0.57 ± 0.04
AYB-5	Ap	7.26^{b}	6.31^{d}	0.95^{a}	0.09^{c}	0.54^{b}
	Bit	7.69^{a}	6.59^{c}	1.10^{a}	0.13^{bc}	0.74^{b}
	Bc	7.79^{a}	6.86^{b}	0.93^{a}	0.21^{b}	1.43^{a}
	CR	7.97^{a}	6.98^{a}	0.99^{a}	0.38^{a}	1.14^{a}
	Average	7.68 ± 0.11	6.68 ± 0.03	0.99 ± 0.11	0.20 ± 0.03	0.96 ± 0.11
AYB-6	Ap	7.61^{d}	6.65^{d}	0.96^{c}	0.26^{bc}	0.41^{c}
	A	7.85^{c}	6.83^{c}	1.02^{d}	0.22^{c}	0.54^{bc}
	A2	7.95^{b}	7.12^{b}	0.83^{a}	0.37^{ab}	0.63^{b}
	Bw	8.17^{a}	7.27^{a}	0.90^{b}	0.49^{a}	0.85^{a}
	Average	7.90 ± 0.02	6.97 ± 0.03	0.93 ± 0.02	0.34 ± 0.04	0.61 ± 0.06

Values are means (with pooled SEM, n = 3 per treatment group). Means in a column without a common superscript letter differ (P<0.05) as analyzed by one-way ANOVA and the TUKEY test.

Calcium carbonate ($CaCO_3$) content of the surface soils ranged from 0.35 (AYB-3) to 0.63% (AYB-6), whereas in the sub-surface soils, it ranged from 0.62 to 1.14%. Significantly (p<0.001) higher $CaCO_3$ content was recorded in the sub-soil compared with surface soil (Table 8); which might be due to the parent material or due to the semi-arid climate, which is responsible for the pedogenic processes resulting in the depletion of Ca^{2+} ions from the soil solution in the form of calcretes. The $CaCO_3$ content of the soils ranged from 0.38 to 1.14%, showing an increasing trend with soil depth. The variation in $CaCO_3$ content in different generic horizons was significant. The field determination of carbonates with 10 % HCl also confirmed that there was no audible and/or visible effervescence throughout the soil depth except for a few observed at the sub-surface of AYB-5.

The SOC, TN, and C/N ratio analysis

Soil organic carbon (SOC) and total nitrogen (TN) were recorded higher in the surface soils and significantly (Table 9) decreased with soil depth with average values ranging between 0.78 and 2.53% and 0.10 and 0.21%, respectively. The SOC of sub-surface layers ranged from 0.62% on the middle slope of degraded grassland (AYB-3) to 1.87% on the upper slope of the exclosure grassland (AYB-1). The TN content of the surface horizons was higher than the sub-surface horizons, and it followed a similar pattern to that of SOC in all the profiles, implying a strong relation between SOC and TN in the soil system. The amount of SOC and TN were relatively high (3.19 and 0.25%, respectively) at the upper slope position of the surface horizons, which might be attributed to the biomass turnover of the grass.

The C/N ratio of the surface soils along the toposequence in the area ranged from 4.51 to 12.78, while in sub-soil horizons, it ranged from 5.44 to 14.04 with an average range of 6.15 to 12.61 (Table 9). The variability of the C/N ratio was not significant in each pedon, indicating that it was lower than the variability of SOC and total nitrogen contents. It may be suggested that the C/N ratio was more stable than its elements. Besides, the low variation in the C/N ratio across horizons suggested less variability in the degree of humification of organic matter. On the other hand, in the buried horizons of AYB-5 and 6, the C/N ratio was slightly higher than in the rest of the horizons, which might be due to the long-accumulated/sediment undecomposed material rich in carbon in the soil. In almost all pedons, the C/N ration demonstrated a decreasing or increasing variation with depth, suggesting the existence of similar conditions of mineralization in the recognized horizon (Table 9).

Soil available P, S, B, Exchangeable base, CEC, and base saturation analysis

The available phosphorus (av. P) content of the pedonswas high in the surface horizons ofthe pedons, which could be attributed to the relatively higher organic matter contents in the surface layers, application of phosphorus-containing fertilizer on cultivated lands, and presence of free iron oxide and exchangeable Al^{3+} in reduced quantity. Available P content of the soils decreased with depth in all the pedons, but spatially the trend was not consistent. The measured av. P was significantly variable (Table 9) among the different generic horizons except in AYB-4. The highest and lowest av. P was recorded in AYB-5 of Ap and CR horizons. The overall pedon means of av. P content was found in 26.52 to 40.09 mg kg^{-1} soil across the topography (Table 9) and decreased with depth.

Regarding sulphur (S) and boron (B), the result for both followed the trend as of av. P (Table 9). The average available S content in the pedons ranged from 0.67 mg kg^{-1} in pedon 2 to 0.80 mg kg^{-1} in pedon 5 (Table 9). The highest and lowest av. S was recorded in AYB-6 of Ap and Bw horizons, respectively. While, av. B was found in the range of 0.19 mg kg^{-1}soil in the Bw horizon of AYB-1 to 0.77 mg kg^{-1}soil in the Ap horizon of AYB-6, with an average range of 0.24 to 0.77 mg kg^{-1}soil across the landscape.

The result indicated that the exchangeable Ca^{2+} was the dominant exchangeable base followed by Mg^{2+} along the toposequence. Exchangeable cations were

Table 9. The studied soil profiles are SOC, TN, and C/N ratio, available P, S, and B

Profile	Horizon	SOC (%)	TN (%)	C/N ratio	av. P (mg kg^{-1} soil)	av. S (mg kg^{-1})	av. B (mg kg^{-1} soil)
	Ah	3.19^{a}	0.25^{a}	12.78^{a}	43.47^{a}	0.74^{a}	0.29^{a}
AYB-1	Bw	1.87^{b}	0.17^{b}	11.03^{b}	36.71^{b}	0.77^{a}	0.19^{a}
	R	-	-	-	-	-	-
	Average	2.53 ± 0.12	0.21 ± 0.01	11.91 ± 0.6	40.09 ± 1.54	0.76 ± 0.12	0.24 ± 0.04
	Ap	1.53^{a}	0.14^{a}	10.95^{a}	38.38^{a}	0.74^{a}	0.82^{a}
	Bt	1.13^{b}	0.12^{ab}	9.76^{a}	28.93^{b}	0.69^{ab}	0.35^{b}
AYB-2	Bc	0.90^{bc}	0.11^{ab}	8.68^{a}	18.08^{c}	0.62^{bc}	0.31^{b}
	C	0.76^{c}	0.09^{b}	8.46^{a}	20.70^{c}	0.61^{c}	0.21^{b}
	Average	1.08 ± 0.09	0.12 ± 0.01	9.46 ± 0.79	26.52 ± 2.09	0.67 ± 0.02	0.42 ± 0.11
	Aa	2.15^{a}	0.25^{a}	8.72^{a}	47.97^{a}	0.84^{a}	0.98^{a}
	B	1.26^{b}	0.17^{b}	7.37^{ac}	41.15^{b}	0.88^{a}	0.77^{ab}
AYB- 3	2B	0.81^{c}	0.13^{c}	6.43^{bc}	41.07^{b}	0.76^{ab}	0.62^{bc}
	3B	0.71^{c}	0.13^{c}	5.44^{c}	35.39^{c}	0.61^{bc}	0.48^{c}
	Bw	0.62^{c}	0.08^{d}	7.84^{ab}	30.14^{d}	0.49^{c}	0.46^{c}
	Average	1.11 ± 0.08	0.15 ± 0.01	7.16 ± 0.62	39.14 ± 1.38	0.72 ± 0.06	0.66 ± 0.08
	Ap	0.92^{a}	0.21^{a}	4.51^{a}	31.72^{a}	0.73^{a}	0.44^{a}
	R	-	-	-	-	-	-
AYB-4	Bc	0.64^{b}	0.09^{b}	7.78^{a}	27.62^{a}	0.83^{a}	0.38^{a}
	RC	-	-	-	-	-	-
	Average	0.78 ± 0.05	0.15 ± 0.02	6.15 ± 1.51	29.67 ± 4.38	0.78 ± 0.16	0.41 ± 0.08
	Ap	1.62^{a}	0.18^{a}	8.81^{a}	55.80^{a}	0.86^{a}	0.75^{a}
	Bit	1.33^{b}	0.16^{a}	8.33^{a}	31.38^{b}	0.85^{a}	0.65^{a}
AYB-5	Bc	0.99^{c}	0.10^{b}	10.25^{a}	19.81^{c}	0.79^{ab}	0.54^{a}
	CR	0.75^{c}	0.07^{b}	10.84^{a}	13.88^{c}	0.68^{b}	0.44^{a}
	Average	1.17 ± 0.08	0.13 ± 0.01	9.56 ± 1.08	30.22 ± 2.29	0.80 ± 0.03	0.60 ± 0.11
	Ap	1.9^{a}	0.16^{a}	11.64^{a}	47.95^{a}	0.96^{a}	1.14^{a}
	A	1.38^{b}	0.11^{ab}	12.59^{a}	35.56^{b}	0.69^{b}	0.70^{ab}
AYB-6	A2	1.0^{c}	0.08^{b}	12.17^{a}	29.88^{bc}	0.63^{bc}	0.65^{ab}
	Bw	0.83^{c}	0.06^{b}	14.04^{a}	23.14^{c}	0.51^{c}	0.58^{b}
	Average	1.28 ± 0.06	0.10 ± 0.01	12.61 ± 1.19	34.13 ± 2.61	0.70 ± 0.10	0.77 ± 0.11

Values are means (with pooled SEM, n = 3 per treatment group). Means in a column without a common superscript letter differ (P<0.05) as analyzed by one-way ANOVA and the TUKEY test.

found in the range of 0.07 - 0.49, 0.22 - 2.12, 2.46 - 10.20, and 4.46 - 27.10 across the landscape for Na, K, Mg, and Ca, respectively (Table 10). Generally, the abundance of cations occupying the exchange site followed the order of $Ca^{2+} > Mg^{2+} > K^{+} > Na^{+}$ throughout the pedons, which was found in how a productive agricultural soil should contain these basic cations. The percent base saturation (PBS) of the soil of the area varied from 18.7 to 99.4%. Soil horizons in AYB-2 and 6 were recorded high-value PBS compared to others. Regarding Cation Exchange Capacity (CEC), the overall CEC of the soils ranged from 28.7 to 54.52 cmol $_{(+)}$ kg^{-1} soil along the toposequence (Table 10). The lowest and highest values were recorded in the top-soil of AYB-2 (cultivated land) and AYB-3 (grassland).

Extractable micronutrients (Fe, Cu, Zn, and Mn)

In the pedons, the mean values of extractable micronutrients (*i.e.*, Fe,Cu, Zn, and Mn) in different soil depths are presented in table 11.

The contents of available micronutrients varied with soil depth and showed a decreasing trend with increase depth. However, their trend with topographic position was inconsistent. The contents of extractable Fe, Cu, Zn, and Mn in the pedons ranged from 11.42 to 21.10, 1.15 to 3.79, 0.15 to 1.16, and 3.93 to 12.88 mg kg^{-1} soil, respectively. The extractable micronutrients followed the order of Fe > Mn > Cu > Zn in their concentration in all the pedons across the landscape. The result showed that the surface soil layers had higher contents of available micronutrients than the sub-surface soil layers. Mean values of the surface layers' extractable micronutrients were significantly varied compared to the subsurface layers (Table 11). In contrast, the mean difference among pedons along the toposequence was insignificant.

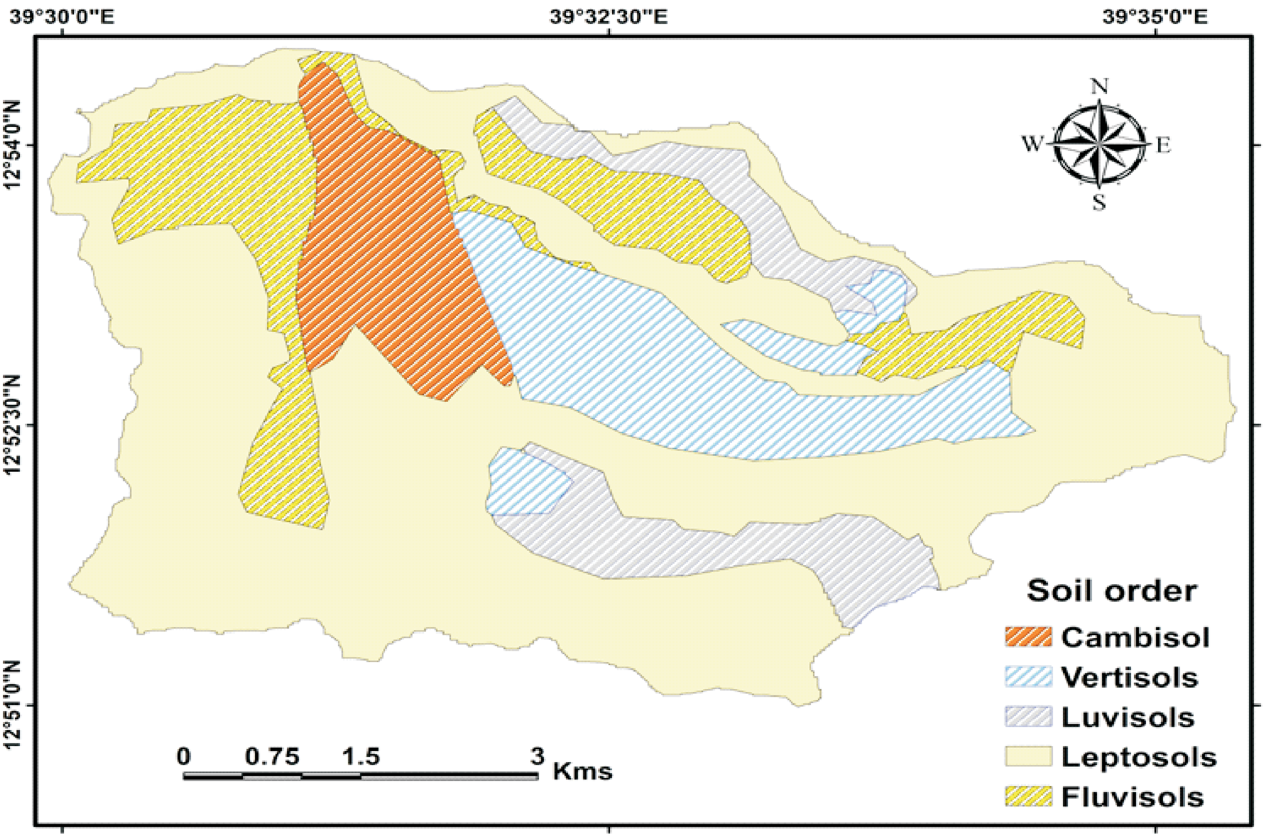

Fig. 7. Spatial soil map of Ayiba watershed according to WRB system

Table 10. Exchangeable base (Na, Mg, K, and Ca) and CEC of the studied soil profiles along the toposequence

Profile	Horizon	Exchangeable bases (cmol $_{(+)}$ kg^{-1})				TEB	CEC	PBS	ESP
		Na	K	Mg	Ca	(cmol $_{(+)}$ kg^{-1})	(Cmol $_{(+)}$ kg^{-1})	(%)	(%)
AYB-1	Ah	0.23^{a}	0.35^{b}	5.18^{b}	17.60^{b}	23.40^{b}	36.80^{b}	63.50^{a}	0.98^{a}
	Bw	0.36^{a}	0.47^{a}	8.44^{a}	22.50^{a}	31.70^{a}	48.20^{a}	66.20^{a}	1.14^{a}
	R	-	-	-	-	-	-		
	Average	[illegible]	0.41 ± 0.03	6.81 ± 0.69	20.05 ± 0.99	27.55 ± 0.96	42.50 ± 3.10	64.85 ± 4.56	1.06 ± 0.31
AYB-2	Ap	0.07^{b}	0.27^{c}	5.62^{b}	17.72^{b}	23.68^{b}	28.70^{c}	82.17^{a}	0.32^{b}
	Bt	0.17^{b}	0.30^{c}	5.67^{b}	24.71^{a}	30.84^{ab}	38.72^{b}	79.70^{a}	0.54^{b}
	Bc	0.30^{a}	1.03^{b}	5.86^{b}	24.81^{a}	32.00^{a}	40.73^{ab}	78.70^{a}	0.95^{a}
	C	0.34^{a}	1.16^{a}	8.87^{a}	28.17^{a}	38.54^{a}	44.40^{a}	99.40^{a}	0.87^{a}
	Average	0.22 ± 0.03	0.69 ± 0.04	6.51 ± 0.86	23.85 ± 2.16	31.27 ± 2.51	38.14 ± 1.63	84.99 ± 6.60	0.67 ± 0.10
AYB-3	Aa	0.12^{a}	0.44^{c}	5.44^{c}	6.23^{b}	12.20^{c}	54.52^{a}	22.50^{d}	0.96^{a}
	B	0.13^{a}	0.98^{b}	6.24^{bc}	7.56^{b}	14.90^{bc}	48.40^{b}	30.70^{cd}	0.90^{a}
	2B	0.13^{a}	1.11^{b}	6.42^{bc}	8.77^{b}	16.40^{bc}	40.96^{c}	40.10^{bc}	0.31^{b}
	3B	0.15^{a}	1.24^{b}	7.69^{ab}	9.85^{b}	18.90^{b}	37.6^{c}	50.30^{b}	0.80^{a}
	Bw	0.17^{a}	2.12^{a}	8.11^{a}	15.30^{a}	25.70^{a}	35.64^{c}	72.10^{a}	0.68^{ab}
	Average	0.14 ± 0.02	1.18 ± 0.14	6.78 ± 0.50	9.54 ± 1.52	17.62 ± 1.50	43.42 ± 1.79	40.14 ± 3.16	0.73 ± 0.13
AYB-4	Ap	0.24^{a}	0.47^{a}	2.46^{a}	5.47^{a}	8.64^{a}	46.20^{a}	18.70^{a}	0.53^{a}
	R	-	-	-	-	-	-	-	-
	Bc	0.16^{a}	0.68^{a}	2.57^{a}	5.57^{a}	8.99^{a}	40.60^{b}	22.10^{a}	0.40^{a}
	RC	-	-	-	-	-	-	-	-
	Average	0.20 ± 0.05	0.58 ± 0.11	2.52 ± 0.23	5.52 ± 0.74	8.82 ± 0.57	43.40 ± 1.90	20.40 ± 1.41	0.47 ± 0.13
AYB-5	Ap	0.07^{c}	0.22^{c}	9.38^{a}	4.46^{b}	14.10^{c}	51.60^{a}	27.40^{c}	0.47^{b}
	Bit	0.11^{bc}	0.32^{bc}	9.69^{a}	9.81^{ab}	19.90^{bc}	50.70^{a}	39.30^{bc}	0.54^{b}
	Bc	0.14^{b}	0.36^{b}	10.20^{a}	14.20^{a}	24.89^{ab}	39.62^{b}	63.30^{ab}	0.59^{b}
	CR	0.49^{a}	0.95^{a}	10.20^{a}	17.90^{a}	29.50^{a}	36.10^{b}	82.00^{a}	1.70^{a}
	Average	0.20 ± 0.04	0.46 ± 0.04	9.87 ± 0.32	11.59 ± 2.74	22.10 ± 2.56	44.51 ± 1.79	53.00 ± 8.35	0.83 ± 0.17
AYB-6	Ap	0.13^{b}	0.22^{c}	3.50^{c}	21.30^{c}	25.20^{c}	44.60^{a}	56.60^{c}	0.52^{a}
	A	0.22^{a}	0.28^{bc}	5.67^{b}	23.78^{bc}	30.00^{b}	41.70^{ab}	71.80^{b}	0.75^{a}
	A2	0.25^{a}	0.49^{ab}	8.16^{a}	25.90^{ab}	34.80^{a}	38.50^{b}	90.40^{a}	0.73^{a}
	Bw	0.29^{a}	0.57^{a}	9.66^{a}	27.10^{a}	37.70^{a}	38.20^{b}	98.60^{a}	0.76^{a}
	Average	0.22 ± 0.02	0.39 ± 0.08	6.75 ± 0.53	24.52 ± 0.91	31.93 ± 1.22	40.75 ± 1.36	79.35 ± 3.13	0.69 ± 0.09

Values are means (with pooled SEM, n = 3 per treatment group). Means in a column without a common superscript letter differ ($P<0.05$) as analyzed by one-way ANOVA and the TUKEY test.

Table 11. Micronutrient availability in the studied soil profiles along the toposequence

Profile	Horizon	Extractable micronutrients (mg kg^{-1} soil)			
		Fe	Cu	Zn	Mn
	Ah	17.78^{a}	3.74^{a}	0.56^{b}	9.78^{b}
AYB -1	Bw	17.21^{a}	3.46^{a}	0.34^{a}	5.49^{a}
	R	-	-	-	-
	Average	17.35 ± 0.78	3.6 ± 0.17	0.45 ± 0.04	7.64 ± 0.22
	Ap	17.2^{a}	3.79^{a}	1.16^{a}	9.50^{a}
AYB - 2	Bt	17.0^{a}	3.03^{a}	0.78^{b}	7.97^{b}
	Bc	13.4^{b}	2.65^{ab}	0.63^{b}	6.35^{c}
	C	13.0^{b}	1.58^{b}	0.17^{c}	4.95^{d}
	Average	15.13 ± 0.83	2.76 ± 0.40	0.69 ± 0.05	7.19 ± 0.31
	Aa	19.64^{a}	3.73^{a}	1.03^{a}	8.77^{a}
AYB - 3	B	17.30^{ab}	2.92^{ab}	0.97^{a}	6.97^{ab}
	2B	14.28^{ab}	2.88^{ab}	0.49^{b}	4.58^{bc}
	3B	12.35^{ab}	2.69^{ab}	0.41^{b}	4.12^{c}
	Bw	11.71^{b}	2.07^{b}	0.33^{b}	3.93^{c}
	Average	15.06 ± 2.34	2.85 ± 0.34	0.65 ± 0.10	5.67 ± 0.81
	Ap	16.47^{a}	3.79^{a}	0.72^{a}	7.85^{a}
	R	-	-	-	-
AYB - 4	Bc	14.51^{a}	2.98^{a}	0.44^{a}	4.38^{a}
	RC	-	-	-	-
	Average	15.49± 2.87	3.39 ± 0.59	0.58 ± 0.30	6.12 ± 1.45
	Ap	19.88^{a}	3.64^{a}	0.39^{a}	12.88^{a}
AYB - 5	Bit	18.48^{ab}	2.48^{ab}	0.24^{b}	9.91^{b}
	Bc	14.83^{ab}	2.41^{ab}	0.16^{b}	8.36^{bc}
	CR	12.58^{b}	2.20^{b}	0.15^{b}	6.88^{c}
	Average	16.44 ± 2.2	2.68 ± 0.43	0.24 ± 0.04	9.51 ± 0.85
	Ap	21.10^{a}	3.35^{a}	0.81^{a}	8.32^{a}
AYB - 6	A	18.20^{ab}	2.95^{ab}	0.50^{b}	6.02^{b}
	A2	16.90^{b}	2.10^{bc}	0.29^{b}	5.67^{b}
	Bw	11.42^{c}	1.15^{c}	0.24^{b}	5.38^{b}
	Average	16.9 ± 1.29	2.39 ± 0.30	0.46 ± 0.09	6.35 ± 0.48

Values are means and pooled SEM, n = 3 per treatment group. Means in a column without a common superscript letter differ (*P*<0.05) as analyzed by one-way ANOVA and the TUKEY test.

Soil classification and mapping

The soil classification system and maps are the final steps of the soil survey, asserting soils by similar characteristics and/or properties and making the knowledge accessible to policy-makers, farmers, and the scientific community (Bockheim *et al.* 2014). Soil maps, which can be effectively produced with statistical models in Digital Soil Mapping (DSM), contain vital information on the spatial distribution of soil properties used in fields such as water and land management and climate studies (van der Westhuizen *et al.* 2022). Currently, Mendes and Demattê (2022) and Hartemink and Bockheim (2013) explained that soil maps at regional and farm levels are essential for the best management of agricultural practices. Therefore, based on the morphological, physical, and chemical properties, the pedonswere classified according to FAO/WRB legend (IUSS Working Group WRB 2015). Accordingly, five soil orders were identified namely Leptosols, Luvisols, Fluvisols, Cambisols, and Vertisols (Table 12, Fig. 7). As reported by Nyssen *et al.* (2019), Leptosols and bare rock were found on the steepest slopes (>40%), which is concurrent with our result.

Potential and limitation of the studied soils for agricultural field crops

The soil units represented by AYB-1 and AYB-4 are not suitable for agricultural use (Table 13) due to stoniness, slope steepness, shallow depth, rock outcrops, and highland position with erosion threats and other soil restraining factors which limit the work ability of the soil. Hence, agricultural production on these soils will cause a decrease in yield and soil loss due to high erosion hazards, and cultural approaches such as soil cultivation, irrigation, and fertilization are not economically feasible. Thus, it is essential to perform conservative and sustainable agricultural practices in these areas like pasture, perennial fruits, and forests. The lower slope area's soil is very suitable for field crop agricultural use with limited fertility, low erosion, and climate. However, the lower slope soils represented by AYB-5 and AYB-6 were very limited in area coverage to accommodate the population size, which is the main reason for expansion to marginal lands.

Besides, during high and prolonged rainfall, the flood flow from all directions is collected to the lower landscape position, damaging farms and grasslands by flood hazards (Seifu *et al.* 2020). In addition, during the high rainfall season, waterlogging is also common in Vertisols soils and the foot slope soils. However, most agricultural production occurs on the middle topography, which is marginal land, and this unsustainable land use contributes to low and declining crop productivity and further land degradation. The substantial area of marginal lands, many of them in steep areas (<30%) with coarse and degraded soils, could adopt sustainable agricultural technologies like integrated organic and inorganic management practices or growing double legumes to improve the long-term sustainability of the system. Not suitable areas must be excluded from land spreading plans due to the high risk of degradation (environmental, economic, and societal).

In contrast, an improvement or remediation plan should be developed and implemented. The soil units in the lower landscape and at a nearly gentle slope of the middle terrain have well-drained, deep soil and are less stony than others. However, erosion, climate, and soil fertility are still significant problems in all topographic positions for agricultural production (Table 13).

Profile site and soil morphological characteristics

The slope, parent materials, and land use types are the major contributing factors to the differences in site characteristics. Effects of land use, extensive and intensive farming, and removal of vegetation cover have amplified the erosion process, which was observed at all the pedons and their surrounding landscapes. Debie *et al.* (2019) also confirmed that accelerated soil erosion by water is a critical problem in Ethiopia's soil landscape. For instance, Ibrahim *et al.* (2020) reported upper topography was well-drained while the middle and valley bottom was poorly drained, and soils in the lower topographic locations were saturated with moisture for longer period than upper slope soils. Likewise, earlier research findings also highlighted that erosion intensity

Table 12. Classification of soils studied at Ayiba watershed according to the FAO-WRB Soil Classification System.

Profiles	Diagnostic horizon	Diagnostic material	WRB[1] Soil unit
AYB-1	Mollic	Mineral	Mollic Leptosols (Eutric)
AYB-2	Argic	Mineral	Prothovertio Luvisols (Clayic, Aric, Escalic)
AYB-3	Argic	Fluvic	SkeleticFluvisols (Arenic, Denis)
AYB-4	paralithic	-	Haplic Leptosols (Skeletic)
AYB-5	Vertic	Mineral	Haplic Vertisols (Endocalcaric, Ochric)
AYB-6	Cambic	Mineral	Haplic Cambisol (Arenic, Aric)

1World Reference Base (IUSS Working Group WRB, 2015)

Table 13. Suitability classification of the different soil units for agricultural field crops

Soil units	LCC/G	Suitability for field crops	Limitations*
AYB - 5 & 6	I & II/ arable land	highly suitable (S_1)	f, le, c
AYB - 3	III/ arable land	Moderately suitable (S_2)	f, se, c
AYB - 2	IV/ arable land	Marginally suitable (S_3)	f, he, c, s
AYB -4	V to VII/ grazing land	Not suitable (N)	f, ma, he, c, s
AYB - 1	VIII/ wildlife	Not suitable (N)	f, ma, he, c, s

LCC/G: Land Capability Class/Group, f - fertility, ma - moisture availability, c – climate, e - erosion hazard (le-low erosion, se- some erosion), t – topography (altitude/elevation), s – stoniness, * - waterlogging problem in Vertisols might depend on slope class, topographic position, and land use. Deressa *et al.* (2018); Schaetzl (2013) reported that slope controls the movement of matter and energy downslope. It was minimal on summit position and an erosional, transportational, and depositional effect on shoulder, middle, and foot slope positions.

Soil colour may vary with depth in the pedons and from place to place ona landscape (Phogat *et al.* 2015). Soil colour is also used to determine soil classification and its physical, chemical, and biological properties (Baek *et al.* 2022). The variation in soil colour matrix noticed within and amongst the pedons might be attributed to the soil's difference in mineralogy and chemical composition, organic matter and clay contents, and drainage condition, which may affect the redoximorphic responses in the soils. Moreover, the yellow and brown color is typically related to the extent of oxidation, hydration, and diffusion of Iron oxides in the soils and mostly due to the presence of goethite and magnetite, respectively (Phogat *et al.* 2015). For instance, the darker color indicates the presence of higher decomposed organic matter (humus). As a result, most surface layers have a darker color than sub-surface horizons. Others reported similar results in Ethiopia and China (Abate *et al.* 2014; Ali *et al.* 2010; Beyene 2017; Dinssa and Elias 2021; Liu *et al.* 2016). The sub-surface horizon (<80 cm) colour of the foot slope was dark grey to brown, suggesting that soils comprised fine-textured colluvial and alluvial materials. In harmony with this work, Tunçay and Dengiz (2020) reported a similar result in Turkey's central Black Sea Region.

Soil structure, which refers to how particles of soil are grouped by physical, chemical, and biological processes, is most usefully described in terms of grade (degree of aggregation), class (average size), and type of aggregates (form). The structure formed in the sub-surface horizons is due to the overlying layers, reduction in organic matter, high clay accumulation, and reduction in plant root abundance, as was also discussed by (Dinssa and Elias 2021). From A horizon down to the bedrock R-horizon the, structure changed from massive to crumbly structure with depth. All the pedons showed weak grade granular type soil structure in the A-horizon due to relatively high organic matter content, and the gravel content was observed to be higher in the parent material layer (Boateng *et al.* 2013; Dinssa and Elias 2021; Yitbarek *et al.* 2016).

The sticky to very sticky/plastic to very plastic consistency in surface and sub-surface horizons indicated low organic matter content and hard to work with these soils. On the other hand, soils with very sticky and very plastic consistency indicated that smectite clays in the soils are high (Ali *et al.* 2010; Kumari and Mohan 2021). Dinssa and Elias (2021) and Ayalew *et al.* (2015b) reported a similar result in the soils of Bako Tibe district and Yigossa watershed, Ethiopia. In northern Ethiopia, Nyssen *et al.* (2019) also analyzed those mass movements in many landscapes that transported materials from their in-situ basaltic upland over the lower-lying sedimentary rocks, raising the chance for clay soil to develop. Available water for plant roots is strongly affected by stoniness (Nyssen *et al.* 2019), and the soil texture becomes fine with an increase in plant root components (Liu *et al.* 2016).

Soil physical characteristics of the pedons

Soil texture is the most stable physical property which influences the other soil properties like soil structure, consistency, soil moisture regime and infiltration rate, run-off rate, erodibility, workability, permeability, root penetrability, and fertility of the soil. The soil texture distribution of the fine earth fraction demonstrated an abrupt textural change between surface and sub-surface horizons, where an increase in clay was accompanied by a decrease in sand-sized particles across the horizon boundary. The general increase in clay content with depth might be attributed to the vertical translocation of clay through the processes of lessivage and illuviation from surface to subsoil. Likewise, others have also reported similar findings in different parts of Ethiopia (Fekadu *et al.* 2018; Kebede *et al.* 2017; Yitbarek *et al.* 2016). According to Hazelton and Murphy (2016) rating the general abundance of the particle distribution was found in low to medium sand, low silt, and very high clay at upper slope profiles; high to very high sand, low to medium silt, and low clay at middle slope profiles; and low to very high sand, low to medium silt, and low to high clay at foot slope basaltic. The variation indicated that topography influenced the pattern of soil particle distribution over the landscape (Esu *et al.* 2008).

The decreasing or increasing pattern in soil fractions with depth indicated the existence of soil water erosion from in-situ formation or accumulation and weathering of primary minerals in B-horizons. For instance, the increase in clay content with depth indicated the clay migration or probably showed the presence of active eluviation-illuviation pedogenic processes. In contrast, the seasonal water erosion effect and redoximorphic features could explain the decrease at the surface horizon. Clay translocation and enrichment ful?lled requirements for the argic sub-surface horizon development (IUSS Working Group WRB 2015; Soil Survey Staff 2014). The variation in soil development may be due to unstable landscape features (rugged and sloppy) where pedogenesis trends are often altered.

The water logging at the foot slope, which may probably cause deterioration of structured B-horizon and dispersion of clay particles down with water table front, was also reported by Choudhury *et al.* (2016). Li and Lindstrom (2001) correspondingly explained that water erosion has the potential to modify the spatial patterns of soil properties on hilly landscapes. Our result is also consistent with the justification of Ellerbrock and Gerke (2013). They revealed that soil particles could be transported along slope gradient during erosion, accumulate in the foot slope position (depressions), and form colluvial soil. Likewise, others also observed a decrease in the fractions in the steeper slope due to the selective removal of fine particles by water erosion (Ezeabasili *et al.* 2014; Seifu *et al.* 2020; Wubie and Assen 2020).

Contrary to our result, Uwitonze *et al.* (2016) reported that particle size distribution did not show a clear trend with depth, and Amanual *et al.* (2015) reported higher clay content on the top and declining with depth. Clay deposition in the sub-surface is episodic, possibly in conjunction with the wet and dry cycle climate experience, regarding the eluviation-illuviation pedogenic processes. According to this idea, fine-grained deposits may be converted into typical loess due to weathering and soil-forming processes.

The silt/clay ratio of the sub-soil waslower than the surface horizons, and the higher percentage in the surface layers reflects the annual alluvial enrichment of the surface through deposition by annual floods. Such a result suggests the presence of weatherable mineral reserves in the soil (Elias 2017). The result is in the similar line with the as that of findings in Nigeria and Ethiopia (Adegbite *et al.* 2019; Mohammed *et al.* 2017; Sharu *et al.* 2013). According to Asamoa (1973) and Egbuchua and Ojobor (2011), the silt/clay ratio below 0.15 indicates that such soils are of old parent material, while those above 0.15 are of young parent materials. All the pedons along the toposequence recorded far above 0.15, confirming that the soils are young with weatherable reserve materials and have not gone through ferralitic pedogenesis, which was in accord with other findings (Achimota 2021; Adegbite *et al.* 2019; Van Ranst and De Coninck 2002).

The variations in degrees of clay enrichment were related to slope positions and land use. The relatively small diferences between the highest and lowest amounts of clay contents in the foot slope position are attributed to active pedoturbation through the shrink-swell phenomenon. While the high clay enrichment ratio in the upper position of AYB-1 is probably due to minimum erosion mainly splash and sheet erosion in which its severity is highly correlated to rainfall intensity and longevity. Crusting is more severe in coarse and medium-textured soils than in fine-textured soils, and soils with an organic matter of less than 1% are more prone to crusting (Phogat *et al.* 2015).

The relatively lower BD values obtained at the surface soil horizons may be attributed to the structural aggregation of the soils due to relatively high organic matter content and congelifraction. This facilitates the development of porous soil structure with low rooting impedance (Brady and Weil 2017; Washburn 1979), which is common in high latitudes and altitudes (Anonymous 2008). Besides, soil compaction resulting from intensive cultivation and overgrazing might have caused higher bulk density in the cultivated, and free grazing land uses compared to others. Soil type may be a possible reason for high bulk density and low porosity. Compaction affects nearly all soil properties and functions, affecting roots' growth, distribution, function, and crop productivity. Correspondingly, others reported an increase in soil strength further down the soil profile (Ali *et al.* 2010; Chaudhari *et al.* 2013; Gao *et al.* 2016).

The ideal BD for plant growth ranges from <1.10 mg m^{-3} for clay to <1.6 mg m^{-3} for sands (Schoonover and Crim 2015). Thus, following the aforementioned critical values for root penetration, some are expected to be limited and affected, while the rest are in a reasonable range. As per the rating system of the effect of BD on soil condition (Hazelton and Murphy 2016), pedons at upper, middle, and foot slope topography are too compact to very compact, very open to satisfactory, and very available to excessively compact, respectively. The bulk densities in the area were moderate in the upper and middle landscape, whereas low to very high in the foot slope landscape. The data indicated that BD is not expected to impede root penetration and water movement restriction in these soils.

Nevertheless, the BD values of the soils are favourable for crop production since the values are within the range that favours the growth of crops in tropical soils. However, pedons 5 (Vertisols) had relatively high BD (>1.6 mg m-3), which might be due to the smectite/montmorillonitic group of clay minerals which show cracks between hard clods when dry and are difficult to till. Such soils need corrective management like manuring, cover crop, and other agronomical recommended field management. Bulk density values exceeding 1.8 mg m-3 indicated the likely presence of duripans or fragipans (Kefas *et al.* 2020). In addition, the total porosity also almost lay within the usual range of 30% to 70% (Hazelton and Murphy 2016). Hence, most soils in the Ayiba watershed have an acceptable range of total porosity values for crop production.

Water content plays a central role in soil physical dynamic processes, and high water retention capacity enables soils to have more water, which acts as a moisture reserve for plants during watershortage periods (de Lima and da Silva 2022). Soil water holding capacity for use by plants is critically important for all farmers.Soil that stores large amounts of water without waterlogging problems can keep plants alive and well for prolonged periods during droughts. Topography influences soil properties through two main "tools": The gravity-driven lateral migration and accumulation of water and spatial differentiation of the temperature regime of slopes (Florinsky 2016). According to Hazelton and Murphy (2016), available soil water holding capacity (% v) for a soil profile is rated as low (<10), medium (10-20), and high (>20). Hence, the AWC at the upper slope was found medium, while low to medium in the mid and foot slopes. Soils that fall below the stated ideal range are probably due to high bulk density caused by intensive cultivation, unrestricted grazing, and low organic matter content due to the complete removal of crop residue.

Chemical characteristics of the studied soils

The lowest pH was found in the upper horizon soils at each site, with higher pH values at depth which might be due to the movement of cations from surface soil to sub-surface soil. Similar results were also reported by Ali *et al.* (2010); Ayalew *et al.* (2015a); Sharu *et al.* (2013); Yitbarek *et al.* (2018), who confirmed that an increment in soil pH down horizon might indicate the presence of vertical movements of exchangeable bases, which is caused by decreased in organic matter content with depth. The pH of soils are favourable for most crops as per the pH scale stated by EthioSIS (2014) and Hazelton and Murphy (2016). The low EC may also be due to free drainage conditions, favoring the removal of released bases by percolation and drainage. The variation in soil pH is probably attributed to the nature of the parent material, leaching of basic cations, and presence of $CaCO_3$ and exchangeable Na as discoursed by Deressa *et al.* (2018); Shalima and Anil Kumar (2010).

The higher concentration of $CaCO_3$ in the subsurface than at the surface horizons might be ascribed to the effect of leaching and parent material which was in accord with the result of others in Ethiopia and else where (Ahmed *et al.* 2018; Debele *et al.* 2018; Ozsoy and Aksoy, 2007; Sebnie *et al.* 2021). Regarding the rating of $CaCO_3$, there is no clear and precise rating for the contents of free carbonates, but values of over 40% can be considered highly calcareous (Avery 1964). In addition, FAO (2006a) also stated that soil horizons having a $CaCO_3$ content of >15% within 100 cm from the soil surface qualifies for a calcic horizon and such high carbonate contents affect both physical and chemical properties of soils. In the present study, the level of $CaCO_3$ is recorded <15%.

The results regarding SOC and TN are similar to that of (Akhtaruzzaman *et al.* 2018; Fekadu *et al.* 2018; Ibrahim *et al.* 2020; Ostrowska and Porebska 2015) who reported SOC and TN had significant variation with depth. The values are under the category of low to very low rate for SOC and medium to very low rate for TN according to the rating of EthioSIS (2014), and this coincides with the amounts usually present in arid climates due to the rapid rate of mineralization. The low SOC and TN in most pedons could be ascribed to the removal of vegetation at the expense of cultivation and complete removal of crop residue mainly for livestock feed, limited use of organic fertilizer sources, unrestricted grazing, and rigorous cultivation, which was similar to the result observed in other studies (Ali *et al.* 2010; Elias 2017; Fekadu *et al.* 2018; Sebnie et al. 2021). As a result, the low SOC and TN content recorded on most soils cannot sustain crop production for a long time. Thus, the organic matter content has to be substantially enhanced through effective crop residue management and organic fertilizers.

The lower the C/N ratio, the faster the decomposition of fresh organic matter. Thus, the C/N ratio influences the decomposition of organic matter, either toward the primary mineralization (low C/N), or towards humification (high C/N) (Yerima and Van Ranst 2005). The C/N ratio mainly controls the decomposition rate and is a source of food and energy for plants in the soil. The higher C/N percentage leads to a slow decomposition rate, nutrient immobilization, and wastage of carbon and energy. In contrast, low C/N ratio, but cause shortage of carbon and energy and the C/N ratio varies from 10 for leguminous and young plant materials to about >100 for cereal straws (Thippeshappa and Vadivel 2011). The C/N ratio in plant tissue is variable, depending largely on plant species and age. Still, the end-product of plant tissue decomposition is always humus which has areasonably constant C/N ratio (Yerima and Van Ranst 2005).

The variability of the C/N ratio was not significant in eachpedons , indicating that it was lower than the variability of SOC and TN contents. It may suggest that the C/N ratio is more stable than its elements. Likewise, in agreement with present finding, Kirkby *et al.* (2011) observed insignificant differences between C/N ratios in SOM and the soils. Others (Yitbarek *et al.* 2016) in the Abobo area, western Ethiopia, and Yimer (2017) in the central rift valley area of Ethiopia also reported a similar result. Although the decomposition rate was not measured, a higher C/N ratio signifies moderate stress in the microbial decomposition of organic matter and N-mineralization (Elias 2017).

The soil C/N ratio is often considered a soil nitrogen mineralization capacity sign. A C/N ratio of about 10 suggests a relatively better decomposition rate. It indicates better nitrogen availability to plants, and there will be possibilities to incorporate crop residues into the soil without the adverse effect of nitrogen immobilization. According to Gebreselassie (2002), the optimum range of the C/N ratio is about 10:1 to 12:1, which provides nitrogen over microbial needs. Yerima and Van Ranst (2005) also classified the C/N ratio as low (<10), medium (around 20), and high (>50). Accordingly, the C/N ratio of the surface soils across the topography may be considered below the optimum range in all soils for microbial needs except in AYB-1 and 6. Sakin *et al.* (2010) found the C/N ratio of arable soils much lower than 10, might indicate N input from external sources, mainly from fertilizers and deposits. On the other hand, prolonged intensive farming also led to a continuous increase in soil nitrogen (Deng *et al.* 2014; Yang *et al.* 2021).

The lower P content in the sub-surface horizons could be ascribed to the fixation of P by clay minerals and oxides of iron and aluminum. The overall pedons means, av. P content was found in harmony with the result observed in other studies (Bekele *et al.* 2021; Debele *et al.* 2018; Fekadu *et al.* 2018; Raghuvanshi *et al.* 2020; Sebnie *et al.* 2021). Based on the ratings of EthioSIS (2014), the average av. P content was found in the low to medium category. Phosphorus deficiency in Ethiopian soils is well documented as a result of depletion and slow recycling due to a fixation on the inherent low occurrence (Bekele *et al.* 2021; Elias 2016; Fekadu *et al.* 2018; Mesfin *et al.* 2017). Moreover, the low content of av. P could be attributed to fixation by Ca content as Ca-P (Ca bounded) - the significant inorganic P fraction in alkaline soils (Landon 2014).

The S and B in agriculture are now gaining importance because their role in increasing crop production is recognized. Available S is the primary source of S taken up by most crops. The source is the SOM *via* the microbial pool or directly from animal residues, atmospheric inputs, or fertilizers (Zebire *et al.* 2019). Whereas B, usually present in soil solution as a non-ionized molecule (H3BO3), is an essential trace element desired for the physiological functioning of higher plants. B deficiency is considered a nutritional disorder that adversely affects the metabolism and growth of plants because B is involved in the multi-structural and functional integrity of the entire plant system. The difference between deficiency and toxicity limits is very narrow; hence, B requires judicious fertility management (Das and Purkait 2020; Shireen *et al.* 2018) also emphasized that site-specific and crop-specific nutrient management should be taken care of while dealing with B soils under divergent geographical and climatic zones.

Generally, the av. S and B contents of the pedons decreased with depth and were found in very low and very low to low, respectively (EthioSIS 2014). Similarly, Dinssa and Elias (2021) reported very low to low B distribution in the Bako Tribe of western Ethiopia. The pH is retained as the main factor affecting B adsorption in agricultural soils (Santos *et al.* 2019), as well as soil texture, soil moisture, parent material, clay nature and content, Al and Fe hydroxides, clay minerals, calcium carbonate, and organic matter and interrelationship with other elements affect the B concentration in soil (Ahmad *et al.* 2012; Arora and Chahal 2010). Wójcik (2000) reported high B deficiency on coarse texture soils and recommended the application of calcium nitrate or ammonium nitrate would be appropriate to keep B more available to plants.

Only a small percentage of the available nutrients move freely in the soil solution. Most are loosely bound on mineral and organic surfaces in exchangeable form. This mechanism acts as a store house both for nutrient cations and anions. For instance, clay minerals, especially illitic and montmorillonitic types, have large negatively charged surfaces on which cations like Ca^{2+}, Mg^{2+}, and K^{+} are adsorbed and, therefore, protected against leaching (FAO 2006b) and according to FAO (2006b), a deviation from the order of $Ca^{2+} > Mg^{2+} > K^{+} > Na^{+}$ can create ion-imbalance problems for plants. The prevalence of Ca^{2+} followed by Mg^{2+}, K^{+}, and Na^{+} in the exchange site of soils is favourable for plant production (Tizita 2016). The result might be related to the parent material from which the soils developed and their differential attraction to the soil's exchange complex. The extent of exchangeable base distribution was not consistent along the toposequence. However, soil depth showed an increasing trend for all exchangeable bases. The soils were very low to medium in Na, low to very high in K and Ca, and medium to very high in Mg as per the rating suggested by EthioSIS (2014). Others have also reported similar findings in Ethiopia's agroecological settings (Abate *et al.* 2014; Abu 2021; Ali *et al.* 2010; Bekele *et al.* 2021). The per cent base saturation (PBS) increased with depth possibly due to the leaching of bases from the overlying layers and subsequent accumulation in the sub-surface horizons. The PBS was also recorded very low to very high along the toposequence (EthioSIS, 2014; Hazelton and Murphy, 2016). The high base saturation of the soil was consistent with high contents of exchangeable bases (chiefly Ca^{2+} and Mg^{2+}), as reported Abu (2021); Elias (2017); Fekadu *et al.* (2018); Sekhar *et al.* (2014).

Cation exchange capacity (CEC), the capacity of a soil or any other substance with a negatively charged exchange complex to hold cations in an exchangeable form, mainly depends on the type and proportion of clay minerals and organic matter present in the soil (FAO 2006b). The data of CEC indicated its range high to very high rating (EthioSIS 2014; FAO 2006b; Hazelton and Murphy 2016), which corresponds to clay content, organic carbon content, and type of clay mineral present.

Other studies also showed a direct relationship between organic matter, clay content, and CEC (Fekadu *et al.* 2018; Tizita 2016; Yitbarek *et al.* 2016). The high CEC rrevealed that the soils of the pedons had good nutrient retention and buffering capacity. Many previous studies confirmed that deforestation, intensive cultivation, land-use change, and the nature of the topographic position led to a decline in CEC (Abate and Kibret 2016; Bore and Bedadi 2015; Sanaullah *et al.* 2016; Yitbarek *et al.* 2016).

Micronutrients are essential for good crop performance (Ilori and Shittu 2015). The higher micronutrient distribution at the surface than in sub-surface soils in this study may be attributed to the accumulation of organic matter content on the top-soil or supplementary additions through chemical fertilizers and continuous transport of the micronutrients from root depth (*via* absorption by plants and subsequent litterfall). A decrease in the extractable micronutrient level of the sub-surface horizon also provides evidence that these elements were phytomining and redeposited on the surface with organic matter. The acquisition of biomass in the top layer leads to higher organic matter and increased clay content in the surface soils. Organic matter decreases oxidation and precipitation loss, and the chelating agents present in the organic matter, depending upon their solubility potential, improve micronutrient solubility, thereby increasing their availability. Similar results have been reported by Akhtaruzzaman *et al.* (2018); García-Marco *et al.*(2014); Ivana *et al.* (2015); Jiang *et al.* (2009); Joshi *et al.* (2020); Sarker *et al.* (2020) who reported the highest micronutrient concentrations in topmost of soil, with concentrations decreasing down the pedons as available micronutrients are strongly associated with soil organic matter content in surface soil. Yitbarek *et al.* (2016), reported the influence of texture and organic matter content on extractable micronutrients. Moreover, Sharma *et al.* (2004) also highlighted that extractable micronutrients increased with increased organic carbon content and CEC and decreased with increasing pH, sand, and calcium carbonate content.

Topology, parent materials, irrigation water, land use types, biological cycling, anthropogenic disturbance, leaching, pH, and organic matter contents significantly affected the micronutrient availability to a different extent (Jiang *et al.* 2009; Zhang *et al.* 2012) added Dibabe *et al.* (2007) and Jiang *et al.* (2009) reported that the high levels of micronutrients are consistent with high organic carbon content and low soil pH. Soil organic matter favours a lower redox potential environment and enhances soil health and the accessibility of micronutrient cations in the soil (Dhaliwal *et al.* 2019). A reduction in the availability of micronutrients with increasing pH can be attributed to the conversion of micronutrients to insoluble forms in soil (Fageria and Baligar 1997). With an increase in pH, the primary soluble form of Mn (Mn_{2+}) oxidizes to form higher oxidation states (Mn_{3+}/Mn_{4+}) which are insoluble in soil water and become unavailable to plants. With an increase in pH, higher oxidation states of Cu predominate, which show more retention by soil colloids (OM, clays, *etc.*), thus reducing their availability (Ivana *et al.* 2015; Kumar and Babel 2011).

According to the critical interpretative values for extractable micronutrients set by EthioSIS (2014), the mean values for extractable Fe, Cu, Zn, and Mn in all the pedons were rated as high, medium, low, and high, respectively. Accordingly, none of the soils were deficient in Fe, Cu, and Mn; however, Zn deficiency was observed along the toposequence. High calcium carbonate content (>15%) in neutral to alkaline soils of semi-arid/arid regions, low OM in sandy soils, waterlogging conditions, precipitation or adsorption of zinc with various soil components depending on the soil pH,organic matter, pedogenic oxides, and redoxpotential are reported to be responsible for low Zn availability (Arunachalam *et al.* 2013; Lal *et al.* 2022). Although the significant contribution of chemical fertilizers (*e.g.,* DAP to supply P) was found effective in nutrient supply for intensive cultivation, the increased use of these fertilizers in an imbalanced manner is also responsible for micronutrient deficiency. The Zn deficiency problem is growing daily as Zn plays numerous roles in the biological functions of plants and humans and is considered an essential micronutrient fortheir growth and development (Alloway 2008).

Potential and limitation of the studied soils for agricultural field crops

Soil suitability, the fitness of a given type of soil for a defined use, is a precondition for sustainable land use planning (Doula *et al.* 2017; Jagdish Prasad 2013; Sarkar *et al.* 2014) and is necessary for precision as attributes of land can be suitable for specific crops but unsuitable to others. Unsuitable land use has potential limitations or constraints that can severely impair its function or not meet the requirement for a particular service. Pressures on land resources by conversion from their natural state to human use are pushing the productive capacity of land systems to the limit (FAO 2022; Liu *et al.* 2014). Therefore, the erroneous of selecting the correct land for the cultivation of a particular agricultural product is becoming a long-standing and mainly empirical issue. Although many recommended and provided a framework for optimal agricultural land use, it is suspected that much agricultural land use is still below its optimal capability in different parts of the world.

The land used for agricultural production must be used according to its potential for optimization and sustainability of soil productivity. This becomes vital to Ethiopia when precision farming is gaining wider acceptance. The relevance is particularly more now a days in the developing world where the use to which a land functions very often is not related to its capacity. A significant problem of agricultural development in Ethiopia is poor knowledge and appraisal of land suitability for agricultural production. Hence, in this study, the different soil units were classified according to their capability and suitability for agricultural field crops into very suitable soils, moderately suitable soil, marginally suitable soils, and not suitable soils, according to internationally recognized suitability classes outlined by FAO (1984) and Schoeman *et al.* (2002) which can be adapted and applied at both regional and local scale.

In harmony with this result, Girmay *et al.* (2018) also reported similar problems for Gateno watershed soil suitability analysis. Others also mentioned these problems and signified the importance of soil suitability analysis for particular areas for sustainable land resource use and better production (Alemu *et al.* 2013; Nyssen *et al.* 2019; Yohannes and Soromessa 2018). In addition, Liu *et al.* (2014) noted that landscapes are not managed sustainably when marginal lands are cultivated or more fertile. It can lead to soil erosion and degradation, loss of livelihoods, and a decrease in the overall resilience of the social-ecological system.

Therefore, employing different soil and water conservation measures and adopting integrated soil fertility management coupled with appropriate agronomic practices and appropriate land-use systems according to their fitness is critically important to reduce the continuing soil degradation and to increase production sustainably. In general, the relationships between features of the landscape, soil characteristics, and soil types will help to advance soil-landscape relations and show a less costly way of acquiring soil foundation since the performance of any crop is mainly dependent on soil properties such asdepth, drainage, texture, fertility, *etc.,* as conditioned by climate and topography.

Conclusion

Low soil fertility and poor management practices influence the crop production in the area. Hence, detailed information on soil properties by soil characterization and classification is essential to plan operative land use and soil fertility management. With this in mind, detailed soil information is needed to understand the functional variability across landscapes to improve the management and efficiency of agricultural practices and ultimately improve food security in the Ayiba area. The study involved soil profile description and understanding of soil-landscape relations which indicated that plateau and the steepest slope had shallow soils (Leptosols), mountain foot slopesare associated with barerock, but younger soils occur on the terraced beds (Fluvisols, Luvisols, and Vertisols), and the footslope and valley bottoms had deeper soils occur (Vertisols and Cambisols). Some soil physico-chemical properties showed significant variability within each generic horizon along the toposequence. In addition, moving down the slope, soil depth and profile development improved, but soil drainage conditions deteriorated.

This study indicated that the soils in the area were very low to low in SOC, av. S, and av. B; low to medium in TN and av. P, and high to very high in CEC. Most of the soil attributes were better in the lower topographic positions than those in the upper and middle topographic positions. Therefore, the low fertility status of the soils can be brought to better use for agriculture by improving soil organic matter level through the incorporation of organic fertilizer sources such as farm yard manure and by reducing the complete removal of crop residues. Moreover, some soil-landscapes had a slope position greater than 30% in the area and hence terracing, slope reduction, run-off velocity limitation, and the installation of appropriate drainage should be incorporated into the site management plan to limit soil erosion. These results also suggested that soil management interventions should be based on land use and site-specific information for appropriate resource management, like the application of inorganic fertilizers and rehabilitation of soils over heterogeneous landscapes to improve crop yields in the area. Further lower position and some nearly gentle slope gradients of the middle position have suitable land for agricultural purposes. Still, not all these soils can sustain agriculture in the long term. Yet, the high percentage of unsuitable soils for cultivation found in the middle and upper topography clearly shows that the Ayiba watershed has high production potential if correct land management decisions are made, like pasture, forestry, and perennial crop production. Thus, information on soil and related properties obtained from the soil survey and classification can help better delineate soil and land suitability.

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