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Characterizing soils and the enduring nature of land uses around the Lake Chamo Basin in South-West Ethiopia

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Abstract

Background: Characterizing and describing soils and land use and make a suggestion for sustainable utilization of land resources in the Ethiopian Rift valley flat plain areas of Lake Chamo Sub-Basin (CSB) are essential.

Objectives: To (1) characterize soils of experimental area according to World Reference Base Legend and assess the nature and extent of salinity problems; (2) characterize land use systems and their role in soil properties; and (3) identify best land use practices used for both environmental management and improve agricultural productivity.

Methods: Twelve randomly collected soil samples were prepared from the above land uses into 120 composites and analyzed.

Results: Organic carbon (OC) and total nitrogen (TN) were varied along different land uses and depleted from the surface soils. The soil units include Chernozems (41.67%), Kastanozems (25%), Solonchaks (16.67%), and Cambisols (16.67%). The identified land uses are annual crops (AA), perennial crops (PA), and natural forest (NF). Generally, organic carbon, total nitrogen, percentage base saturation (PBS), exchangeable (potassium, calcium, and magnesium), available phosphorus (P_2O_5), manganese, copper, and iron contents were decreased in cultivated soils. Soil salinity problem was observed in annuals. Annuals have less nutrient content compared to perennials in irrigated agriculture while it is greater in annuals under rainfed. Clay, total nitrogen, available phosphorus, and available potassium (K_2O) contents were correlated positively and highly significantly with organic carbon and electrical conductivity.

Conclusion: Management practices that improve soil quality should be integrated with leguminous crops when the land is used for annual crops production.

Keywords: Rainfed and irrigated agriculture, Different land uses, Soil physicochemical properties

Background

Agriculture remains a soil-based industry; major increases in productivity are unlikely to be attained without ensuring an adequate and balanced supply of nutrients (IFPRI 2000). Understanding soil properties and their distribution over an area has proved useful for sustainable development and efficient utilization of limited land resources (Buol et al. 2003). Particularly, soil is an important non-renewable land resource determining the agricultural potential of a given area. The soil resource of the Ethiopia was studied at a scale of 1:2,000,000 (Wijntje-Bruggeman 1984). Ethiopia has diverse soil resources largely because of diverse topography, climatic conditions, and geology (Abayneh 2001). In addition, the soil resource assessment under the River Basins Project alone has covered more than 40% of the country at 1:250,000 scale (Abayneh 2001). These studies are of small scale and not comprehensive enough to draw sustainable development planning at basin level. Consequently, sustainable soil management practices that are based on the understanding of soil system are not available for most part of the country (Fikre 2003). Hence, land use and type of vegetation must be taken into account when relating soil nutrients with

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environmental conditions (Ramesh et al. 2007) and in characterizing soil nutrients/soil nutrient stocks.

Study area is located in the Ethiopian Rift Valley within the lakes sub-region in the western and southern side of Lake Chamo particularly from south end of Lake Abaya to northwest of Arba Minch Town along the Arba Minch-Konso all-weather gravel road and surrounded by the Gamo-Konso massifs. The agro-ecological zonation can be defined as a spatial classification of the landscape into area units with similar agricultural and ecological characteristics (Hurni 1999; Tuma 2007). Attributes of such units determine similarities, such as (a) comparable agro-climatic conditions for annual cropping, perennial cropping, or agroforestry; (b) comparable land resource conditions such as soil, water, or vegetation parameters; and (c) similar land management conditions such as ruggedness of agricultural land or general topographic variations. Such attributes determining similarities of units can further be distinguished through on the spot verification of actual conditions and anticipated potentials. Despite the great economic importance of traditional fruit-based land use systems in the area, limited studies have been carried out.

According to the Minister of Agriculture (MoA) (1995), the major indicators for soil characterization and evaluation of potential fertility of soils are (a) effective soil depth, (b) soil organic matter (SOM), (c) cation exchange capacity (CEC), (d) soil pH, (e) soil texture, and (f) available phosphorus (P_2O_5). In addition, standard soil fertility attributes such as soil pH, organic carbon (OC), N, P, and K are important parameters in terms of plant growth, crop production, and microbial diversity and function (Doran and Parkin 1994). A proper understanding of the soil properties, both physical and chemical, is necessary to optimize management processes (Tuma 2007).

SOC and SOM stock per unit area are also important for identification of soil fertility levels in the field (Ramesh et al. 2007). Depending upon the parent material and extent of weathering, the total nitrogen (TN) (%) content of soil all over the world ranges from 0.015 to 0.137 (Ramesh et al. 2007). SOM is a very important fraction of the soil because of its high CEC and retaining nutrients against leaching losses. TN measures the amount of nitrogen bound to soil mineral particles and SOM. However, the soil fertility interventions are constrained by lack of up-to-date data; these interventions depend on major national soil surveys dating to the 1980s (FAO) and macronutrient studies from the 1950s–1960s and inhibit adoption of these practices by smallholder farmers. Also, fertilizer application per hectare of land is not uniform, soil fertility status is not identified, and productivity is lower because of fertilizer use and other related factors that are not determined in accordance with soil types in the Chamo Sub-Basin (CSB) areas.

All soils contain some water-soluble salts, but when these salts occur in amounts that are harmful for germination of seeds and plant growth, they are called saline (Denise 2003). The soluble salts that occur in soils consist mostly of various proportions of the cations calcium (Ca^{2+}), magnesium (Mg^{2+}), and sodium (Na^{+}) and the anions chloride (Cl^{-}) and sulfate (SO_4^{2-}). Constituents that ordinarily occur only in minor amounts are the cation potassium (K^{+}) and the anions bicarbonate (HCO_3^{-}), nitrate (NO_3^{-}), and carbonates (CO_3^{2-}), but soluble carbonates are almost invariably absent. The salt types found in saline soils are mostly sulfates and/or chlorides of Ca and Mg (Appleton et al. 2009). Saline soils are often recognized by the presence of white crusts of salts on the soil surface called “white alkali” (soluble salts) and irregular plant growth. EC of saline soils when a solution extracted from saturated soil is ≥ 4.0 mmhos/cm at 25 °C. Generally, pH is < 8.5, Na makes up < 15% of the exchangeable cations, and the sodium adsorption ratio (SAR) is < 13.

SOC is essential to maintain a good physical condition and to absorb, retain, and supply water and nutrients to crops. Since all the SOC is derived from CO_2 (Ramesh et al. 2007) in the atmosphere, any land use and management that increases SOC will remove CO_2 from the atmosphere, thereby making the soil act as a sink for CO_2. This process of removing CO_2 from the atmosphere and storing it in the soil is termed as carbon sequestration. Every tone of C in soil is equivalent to 3.67 tons of CO_2 removed from the atmosphere (i.e., CO_2e) (http://www.dpi.nsw.gov.au/agriculture) (Ramesh et al. 2007). It has been estimated that 24.5 Mt CO_2e (> 20%) targeted emission reduction could be met by agricultural carbon sequestration particularly introduction of yield-intensifying techniques.

The previous study of soils in the area by Murphy (Senior et al. 1998) was on the soil fertility status and other data on some surface soils. The author indicated that the virgin soils of west to north end of Lake Chamo were neutral in reaction, contain 2% OM, 0.11% TN, and were high in P_2O_5, K_2O, Ca, and Mg. The soils were high in Ca and well supplied with Mg and texture of silty clay and dark brown in color (Senior et al. 1998). According to Tuma (2007), the soils of Abaya-Chamo Basin (ACB) in large scale are Eutric Cambisols and Eutric Fluvisols as per FAO/UNESCO soil map of the world or Inceptisols and Entisols as per USDA/Soil Taxonomy. The author also indicated that the soil physical properties such as structure, bulk density, and total porosity showed notable variations due to differences in land use systems. The soil chemical properties such as OC, TN, CEC, and available micronutrients especially Fe and Cu were influenced due to differences in land use systems. However, the morphological, physical, and chemical characteristic potentials of soils of CSB in relation to soil fertility, salinity, and management alternatives were not well characterized and documented elsewhere. Since proper understanding of the nature and properties of the soils of the country and their management according to their potentials and constraints is imperative for maximization of crop production to the potential limits (Esayas and Debele 2006), consequently, this study was aimed to characterize and describe soils and land uses across landscape position under changing climate and make suggestion for sustainable utilization of land use resources and to generate baseline information, which were important for formulating the management alternatives for different soil types.

Materials and method

Descriptions of the study area

The study was carried out in the Ethiopian Rift Valley system within the lakes sub-region in the northern, western, and southern side of Lake Chamo along the Gamo-Konso massifs. It is located at about 520–560 km south of Addis Ababa, Ethiopia. The Lake Chamo basin comprises a total area of 1943 km^2, and the surface area of the lake itself is 329 km^2. The study focused on the river catchments of the Kulfo river, the Sile-Elgo, and the Waseca rivers of Lake Chamo basins (CSB). They were selected based on their contribution water drained into the Lake Chamo sub-basin and for their known high influence of agricultural activities. Kulfo basin (6° 7′ N, 37° 29′ E), Sile-Elgo basin (5° 57′ N, 37° 19′ E), and Waseca basin (5° 45′ N, 37° 26′ E) with an altitude ranging from 1100 to 1280 masl are located in Southern Nations, Nationalities, and People's Regional state.

The geology and geomorphology of the Rift Valley occurred from Miocene to Pleistocene deposits (King and Birchall 1975). The basin being part of the rift valley was formed by volcanic activities in the Rift Valley during the period of Pliocene and Holocene. Accordingly, it is believed that ancient basement rocks lie under the whole Rift Valley. The parent materials of catchment are alluvium along river and lacustrine along lake which are derived from the rocks (King and Birchall 1975; GME 1975). The pattern of topography of the catchment is composed of flat plain in the west around Lake Chamo and the Rift Valley escarpment hills in the west and north.

According to the records from 1992 to 2012 taken from the nearby meteorological stations (at Arba Minch and Gedole), the mean annual rainfall in the study area is 930 mm. The rainfall season is from May to October, and it has two peaks (May and August) without having a distinct dry season between the peaks. The mean annual temperature is 19.9 °C, and monthly values range between 17.7 °C in July and 22.1 °C in February and March (Fig. 1). In general, the length of growing period (LGP) of Arba Minch area is 61 days (Gonfa 1996); this implies that evapotranspiration is by far greater than rainfall and the need to supplement irrigation water for the growing of different crops. Therefore, Kulfo, Sile-Elgo, and Waseca basins are characterized by hot semi-arid tropical climate with bimodal rainfall pattern.

Selection of sampling site

Transect walk was made in team to CSB areas. The transect lines were laid down using the respective topographical maps of the CSB on different aspect. The team has observed a number of people of different sex and age carrying fuel wood extracted from the forest. This gave the participants an impression on the exploitation of the Arba-Minch forest area. After having the preliminary site visit, soil characteristics were recorded. The survey technique was a free survey which follows random sampling technique.

Land use units and primary data collection

The following are the basis of the three major land/soil characteristics: river drainage and watercourse within watershed, slope, soil depth, and surface soil texture. Slope percentage in the farm ranges from 0 to 2%, and land facets were grouped according to their general slope classes at the first level of generalization. Following, soil depth, as it varies significantly within the farm, was considered to further group land units of the farm. Land with uniform slope and soil depth was further subdivided on the basis of surface texture. Thus, the mapping unit of the farm indicates areas that are uniform in watercourse within watershed, slope, soil depth, and surface texture (Table 1). The land uses were identified on the basis of topographic features and land/soil characteristics using field observations and topographic maps. The land use types (LUTs) were arranged in three replication as AA6-CeMa, AP2-FrBa, PN2-FsAc, AA6-FiCo, PN1-FxTa, AP1-MfMo, AA4-CeSo, and PN1-FsSe.

A landscape was selected along northwest facing landscape to western encompassing landform components into the Chamo Lake, upper landscape (shoulder) to toe landscape of the basin. The landscape was divided into four landscape categories: upper (UCB), middle (MCB), lower (LCB), and toe (TCB). A total of 12 Pedons were excavated on the landscape, three land use units, and three Pedons on each landscape category (Table 1). The location of each pedon was selected on a site which was representative to each land use type.

Soil description and sampling

A 2 m × 2 m × 2 m soil profile pit was excavated on each of the land use types. Soil samples were collected from every identified horizon. The representative soil profiles of all pedons were described in situ following the

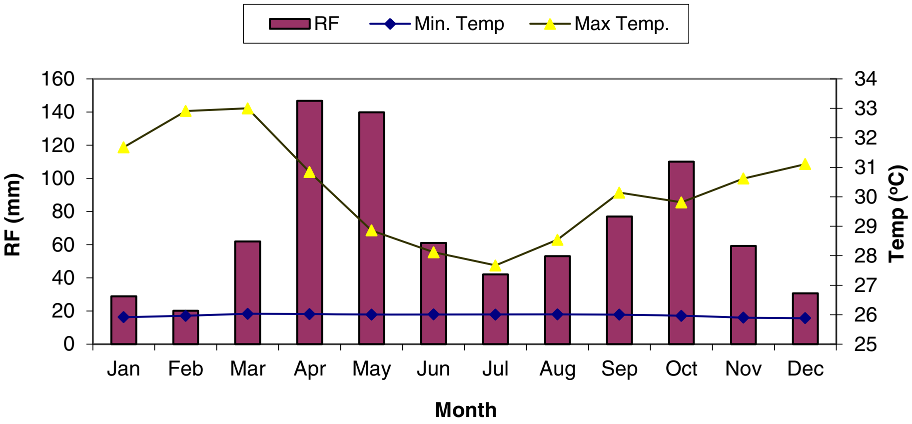

Fig. 1 Rainfall and Temperatures of CSB (1992-2012)

Guidelines for Field Soil Descriptions (FAO 2006) and using the Munsell Chart to identify soil colors. For each slope, categories were described and the horizons were designated in situ according to the guidelines of FAO (2006). Soil color notation was described according to Munsell Color Chart (HKIC 2000). The morphological, physical, and chemical properties of the soils were studied through field observation and laboratory analyses. The soils classification is based on WRB (Gonfa 1996; HKIC 2000) soil map of the world for potential utilization of soil and land.

Laboratory analysis

Soil samples were air dried and passed through 2-mm sieve, processed, and analyzed for determination of physical and chemical characteristics in *Ethiopia Water Works Design and Supervision Enterprise laboratory, 2012.* Particle size analysis was carried out by the modified sedimentation hydrometer procedure (Bouyoucos 1951). Bulk density was determined by using core-sampling method (BSI, 1975). The pH of the soils was determined in H_2O (pH-H_2O) and 1 M KCl (pH-KCl) using 1:2.5 soil to solution ratio using pH meter as outlined by Van Reeuwijk (Van Reeuwijk 1993).

OC content of the soil was determined using the wet combustion method of Walkley and Black as outlined by van Ranst et al. (1999). Soil TN was analyzed by wet oxidation procedure of the Kjeldahal method (Bremner and Mulvaney 1982). The P_2O_5 contents of the soils were analyzed using the Olsen sodium bicarbonate extraction solution (pH 8.5) method as outlined by Van Reeuwijk (1993), and the amount of P_2O_5 was determined by

Table 1 Physiographic characteristics of the pedons studied in CSB

Pedon	Altitude (masl.)	Physiography	Parent material	Slope (%)	Drainage class	Erosion
P1	1221	Alluvial mid plain	Colluvium	1–2	Well drained	None
P2	1234	Alluvial mid plain	Colluvium	1–2	Poor	None
P3	1220	Alluvial plain	Alluvium	2–5	Well drained	None
P4	1100	Alluvial mid plain	Colluvium	1–2	Poor	None
P5	1113	Alluvial mid plain	Colluvium	1–2	Poor	None
P6	1280	Alluvial mid plain	Colluvium	1–2	Well drained	None
P7	1147	Alluvial plain	Alluvium	2–5	Well drained	None
P8	1185	Alluvial mid plain	Colluvium	1–2	Well drained	None
P9	1185	Alluvial mid plain	Colluvium	1–2	Well drained	None
P10	1204	Alluvial mid plain	Lacustrine	1–2	Well drained	None
P11	1120	Alluvial plain	Alluvium	1–2	Well drained	None
P12	1137	Alluvial plain	Alluvium	2–5	Well drained	gully

Generally, the soils in CSB are made of alluvial and colluvial materials from the surrounding western escarpments spectrophotometer at 882 nm and available potassium. The available N was estimated from organic carbon content of the soils. Exchangeable basic cations and the CEC of the soils were determined by using the 1 M ammonium acetate (pH 7) method according to the percolation tube procedure (Van Reeuwijk 1993). The exchangeable cations (Ca and Mg) in the leachate were determined by atomic absorption spectrophotometer (AAS), whereas K and Na were measured by flame photometer. $CaCO_3$ was determined by acid neutralization method using HCl. EC was measured from a soil saturation extract by conductivity meter. Soluble cations and anions were determined by the procedure set in Handbook No. 60 (Senior et al. 1998).

Available micronutrient (Fe, Mn, Zn, and Cu) contents of the soils were extracted by diethylene-triamine-pentaacetic acid (DTPA) method (Tan 1996), and the contents of available micronutrients in the extract were determined by AAS. Surface soil samples (0–20 cm depth) were randomly collected from 120 soil samples from 12 sites (=12 composites) following the standard procedures of composite soil sample collection. The location of soil sampling sites was marked on the base map on 1:50,000 scale. The soil samples were processed and analyzed for all aforementioned parameters.

Results and discussion

Results

Land use characterization across CSB

For ease of presentation, landscape position, drainage, erosion, type of vegetation, permanent field cropping, traditional agroforestry, indigenous soil, and water management in rainfed and irrigated conditions are treated as land use characterization units in this text. Field observation and selection of representative sampling sites were carried out in relation to farming systems of different land use systems. Private farms like Amibara (former Arba Minch state farm) and Lucy (former Eligo and Sille state farms), Ethiopia, are examples of intensive and irrigated farming systems in the landscapes of the CSB. Generally, cotton, maize, and currently banana are dominantly planted in the CSB landscapes. The data obtained from the study area have shown that there is medium-scale irrigated agriculture in the study area by private farms like Amibara and Lucie, but small patches of lands under small-scale irrigation are in nearby areas. There was a breakthrough in production and transforming the livelihoods of the inhabitants from survival level to elevated way of life by recently introduced banana-based farming practices in the irrigated neighborhood; fast changes are taking place now in farming systems, individual crops, peoples' lifestyles, and breaking of traditional systems. For example, improved farming methods such as mulching, intercropping, and shifting cultivation were also well practiced. The studied land use systems were generally found within slope range between nearly flat (1–2%) and gently sloping (2–5%) (Table 1).

Farms that were located at the verge of the watercourse or on the main flood plains of river systems were used for production of profitable cash crops, such as monoculture banana, mango, or maize, whereas majority of those located distant from the watercourse were predominantly used for agroforestry components. Based on the information obtained from the farm owners (farmers), the yield status of banana was also higher near the watercourse areas (300 quintals/ha) as compared to that of the distant areas (170 quintals/ha) mainly due banana is a water-loving fruit crop (Table 2).

Annual field cropping system (AA) Based on the information obtained from the owners of the land, Kebeles and Woredas, the subsistence farming fields were continuously cultivated for about four decades. Currently, the fields are used for medium maturing maize grown by smallholder farmers under low input. In this system, rotation between maize and/or sorghum and cottons is a common practice. The major cereal crops in the CSB are sorghum and maize. They are the major food crops for humans' diet and also provide feed for animals. Land use units (P1, P5, and P8)—AA6-CeMa, and (P11)—AA4-CeSo represent annual field cropping systems.

Perennial field cropping system (AP) Banana and mango were identified as the dominant fruit crops under traditional production systems in the CSB. The fields of banana and mango were further intercropped with short-season crops such as maize, pepper, and tomato in the spaces between the two main crops for the first 3–5 years of establishment. Then after, the dominant crop will be mango, which will develop to pure stand in 12–15 years. The system represents smallholders' farm field under banana cultivation owed by market-oriented farmers. The fields were used for cultivation of banana crops for more than 10 years. Generally, this type of banana farming system in the area is managed with low inputs and practiced by preparing low mound or ridge for planting and maintaining the soil fertility, ratoon development, and to avoid weeds and pests from the banana plantation. Fruit trees of mango and banana were mixed with other crops, *agroforestry*, in the irrigated agriculture; in water logged and saline conditions somehow, *banana* crop is adversely affected.

Farmers planted *Moringa stenotepala* (*Shifara* or *Halako*), which is an evident drought-tolerant, multipurpose tree cropped with major food crops as an agroforestry practice, particularly in toe landscape position. Leaves of moringa are staple and delicious food used as a substitute for cabbages and also used as a source of cash

Table 2 Agricultural production of common crops in CSB

S/No	Major crops growing in Arba Minch Zuria and Dherashe Woredas	Cultivated land in hectare/2012	Annual production in quintals/2012	Ave. productivity/hectare/quintals
1	Banana	3550	976,250	275
2	Mango	226	62,376	276
3	Lemmon	5	450	90
4	Moringa leaf (as a cabbage)	1500	240,000	160
5	Tomatoes	110	11,000	100
6	Onion	166	19,200	115
7	Sweet potatoes	2050	328,000	160
8	Cassava	165	26,400	160
9	Taro	130	20,800	160
10	Cotton	2500	40,000	16
11	Maize	10,360	455,840	44
12	Sorghum	1550	34,100	22
13	Teff	2305	27,660	12
14	Haricot bean	275	3575	13

Source: Arba Minch Zuria and Derashe Woredas' Agriculture Development Offices

income and locally managed in stressed conditions, and they are related to knowledge of land use, SWC, cultivation, and farming systems. *Moringa stenotepala* tree is adversely affected by water logged and saline conditions.

Grain legumes are another important food and feed crops exhibiting good drought tolerance, which makes them potentially very valuable for crop diversifications in water-scarce conditions. This special attribute makes them important for increasing crop production on sustainable basis. Pigeon pea (*Cajanus cajan*) is a high-value multi-purpose legume crop, with similar uses to chickpea and other legumes. It is a drought-tolerant crop which improves soil fertility by fixing nitrogen, conserves soils, and produces highly valuable grain for export and local consumption. Pigeon pea produce wood for energy supply and above all produces biomass for animal feed; thus, it is a multipurpose crop which integrates crop and livestock production. Selection of crop species and varieties for drought, heat tolerance, early maturing species, and varieties of several legume crops has been adapted in the area including common bean (*Phaseolus vulgaris L.*), cow peas (*Vigna unguiculata*), and pigeon pea (*Cajanus cajan*). Land use units (P2, P4 and P9)—AP2-FrBa, and (P10)—AP1-MfMo represent perennial field cropping systems.

Natural forest and woodland system (NF) The field identified as representative forest land in each landscape has no record of cropping history. The CSB comprises woodland, bushland, grassland, freshwater habitats, and riverine forest. Remnants of forests in some patches and pockets, which were estimated to cover about 8.5%, are found in the catchment along the lakeshore. The shoreline in the western and southern part of the lake under the escarpment is covered by grasses, sedges, and scattered trees. In the CSB, the intermediate zone between the humid highlands and semi-arid low lands are covered by bushland and scrublands. This type of vegetation covered the southern and northern part of the Lake Chamo. Very dense groundwater forest of its kind covered the shoreline in the northern part of the Chamo Lake. It was a source of wood for Arba Minch town. Recently, however, this forest is strictly controlled by the park administration (Nech sar National park). Land Use Units (P3 and P7)—PN2-FsAc, **(**P6**)**—PN1-FxTa, and (P11)—PN1-FsSc represent NF and woodland system.

\NF coverage in the CSB area has been decreasing through time due to rapid population growth, high demand for farmland, and growing demand of land for house construction, private investments, and agriculture caused of deforestation in the area. Currently, shrub, bush, and forest land cover only few percent of the total land area.

Soil and water management practices (*Targa*) It was observed that specialized indigenous soil and water conservation (SWC) practices are used by Dherashe indigenous farmers to adapt moisture stress. This practice is called *Targa* and which could be considered as a "complete conservation tillage" that 35–40% of the soil surface is covered by crop residues (i.e., > 30%); legumes are integrated and no-tillage is practiced (Fig. 2). The *Targa* is divided into smaller compartments called "Pohtayt" which hold water and soil in which the soil is left undisturbed from harvest to planting; the *Targa*

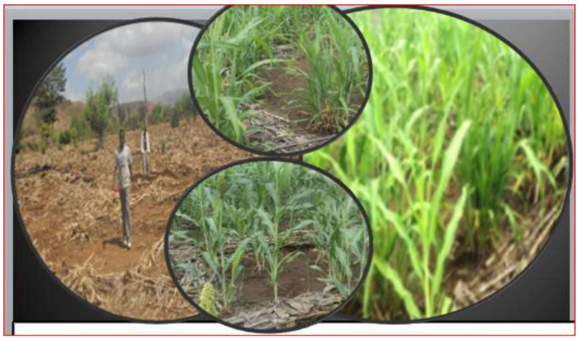

Fig. 2 Tradional Dherashe community soil andwater concentration

structures prevent massive flow of runoff and thus reduce the risk of erosion. Permanent return of residuals in *Targa* systems of AA of rainfed soils (P11) also had the potential to sequester carbon compared to AP-Moringa system of rainfed soils (P10). The *Targa* is a physical SWC method like terracing, whereby stalk of sorghum, maize, and other similar crops are piled in rows and placed at intervals of 2 to 3 m and utilized as an organic fertilizer (humus). Carbon sequestration rates are affected by the amount of plant residues (OM) introduced into the soil and the quality of the plant material (C to N ratio, lignin content, and phenolic compound content). *Targa* is a physical SWC practice like terracing in Konso area, whereby stalk of sorghum, maize, and other similar crops are piled in rows placed at intervals of 2–3 m and utilized as an organic fertilizer (humus). Legume inter-cropping with sorghum and maize is also another method used in the area to reduce SOM depletion.

Physicochemical characteristics of soils across CSB

For ease of presentation, soil depth, horizon, color, structure, and consistency are treated as soil physiographic characteristics and morphological properties in this text. The physico-chemical characteristics of all the studied soils of different land use systems relatively have (> 150 cm) a very deep profile (Table 3).

Physical properties of soils Textural classes of soils determined by feel method in the field were found to be similar in most cases, with the determinations carried out in the laboratory (Tables 3 and 4). Particle size distribution of the studied soils varied along the landscape positions. Soils situated at the LCB position had relatively higher clay content (19.44–49.97%) throughout the soil solum, followed by soils located at TCB (16.21–43.43%), middle (16.39–31.38%), and UCB (6.46–33.43%) positions (Table 3). The textural classes of the surface layers ranged from silt loam, silt clay, and clay in all pedons (Table 4).

Bulk density of the soils was in the range of 1.09 g cm^{-3} in the A horizon of the toe pedon to 1.65 g cm^{-3} in the B horizon of the middle pedon (Table 4).

Chemical properties of soils The pH-H_2O values of soils varied from 5.88 to 8.48 (Table 4). The lowest value (5.88) was observed in the A horizon (0–17 cm) of TCB position (P12), whereas the highest (8.48) was found in Bw horizon (P2) found at the ULS position.

The exchange complex of the soils is dominated by Ca followed by Mg, K, and Na (Table 5). Exchangeable bases for K was rated as low to high for Pedons ranging 0.11 (P1) to 1.37 meq/100g soil (P11). Ca content of Pedons were high and very high in all soil samples, ranging from 17.71 (P12) to 37.58meq/100g soil (P7). The same applies for Mg ranging from 4.62 (P8) to 16.42 meq/100 g soil except for B horizon of P8.

The cation exchange capacity (CEC) of the soils ranged from 28.94 to 56.35 cmol(+) kg^{-1} of soil (Table 5), of which generally high to very high CEC values for surface and subsurface horizons indicate good agricultural soil (Table 5). The percentage base saturation (PBS) of the soils in the pedons ranged from 64 (in the surface horizon (P12)) to 99 at surface horizon (P7), which indicates a high fertility of the soil. The organic carbon (OC) and total nitrogen (TN) values in the pedons varied from 0.18–4.05% to 0.02–0.52% in soil solum, respectively (Table 6), and both decreased with depth.

Classification of the soils according to the World Reference Base

The soils were characterized and classified according to the World Reference Base (WRB) (IUSS Working Group WRB 2006; FAO 2006; FAO 2001; Pedosphere.com 2001) on the basis of soil morphological features (that have been observed and described) and chemical and physical properties (after the analytical data had been analyzed).

The surface horizons for most Pedons (except P3, P8, and P9) had Munsell moist color of chroma ≤ 2 darker, value ≤ 2 and ≤ 3 except for (P10), and value ≤ 3 except for (P10) ≤ 6 (dry) thus, these Pedons had very dark brown *mollic* horizons, whereas for Pedons (P3 and P8) had chroma ≤ 3 (moist), value ≤3 and ≤ 4 (moist) and ≤ 4 (dry), thus, Pedons also had dark brown *mollic* horizons. Both horizons possessed 30–90-cm-thick surface horizon (Table 3); having OC, 0.8–2% and PBS (in 1 MNH_4OAc at pH 7) were 90.5–98.2% which were > 50% (Table 6). Low OC content of pedons (P6 and P10) of surface horizons made them *umbric* and *ochric* surface horizons, respectively. On the other hand, the highest OC content of surface

Table 3 Selected soil morphological features under different land use systems in CSB

Depth (cm)	Horizon	Color		Structure	Consistency			Gr. water table
		Moist	Dry		Dry	Moist	Wet	Depth (cm)
Pedon 1 AMU-farm (AA6-CeMa land use unit)								
0–34	Ah	7.5YR 2/2	7.5YR 3/3	WMSB	HA	SFm	SST, SSP	> 200
34–200+	B	7.5YR 3/4	7.5YR 4/4	MCSB	HA	SFm	SST, SSP	
Pedon 2 Amibara (AP2-FrBa land use)								
0–90	Ah	7.5YR 2/2	7.5YR 3/3	WMGR	HA	Fr	NS, NP	50–100 (P2-G1)
90–97	*UU5*	–	–	–	–	–	–	
97–200+	Bw	7.5YR 3/3	7.5YR 5/4	WMSB	HA	Fr	NS, NP	
Pedon 3 Arba Minch Natural Forest (PN2- FsAc land use unit)								
0–80	Ah	10YR 3/3	10YR 3/4	WMSB	HA	Fm	ST, PL	> 200
80–85	*UU5*	–	–	–	–	–	–	
85–200+	Bk	10YR 3/2	10YR 5/4	MA	HA	Fr	SST, SP	
Pedon 4 Sille (AP2-FrBa land use unit)								
0–35	Ah	7.5YR 2/2	7.5YR 3/3	WFSB	HA	SFm	MS, PL	80–150 (P4-G2)
35–200+	Bk	7.5YR 3/4	10YR 5/4	MMSB	HA	Fr	ST, PL	
Pedon 5 Mage (AA6- FiCo land use unit)								
0–40	A	7.5YR 3/2	7.5YR 3/4	WMSB	HA	SFm	SST, SSP	50–100 (P5-G3)
40–200+	B	7.5YR 3/2	7.5YR 3/3	WCAB	HA	Fr	SST, SSP	
Pedon 6 Eligo Bush Land (FN1- FxTa Land Use)								
0–50	Ah	10YR 3/2	10YR 3/4	WMGR	HA	Fr	NS, NP	> 200
50–58	*UU5*	–	–	–	–	–	–	
58–200+	B	10YR 3/3	10YR 5/4	WMSB	HA	Fr	NS, NP	
Pedon 7 Waseca Natural Forest (FN2- FsAc Land Use Unit)								
0–46	Ah	10YR 2/2	10YR 3/3	WMSB	HA	Fm	ST, PL	> 200
46–200+	BT	10YR 3/2	10YR 3/4	GR	HA	Fr	SST, SSP	
Pedon 8 Waseca Shechara (AA6-CeMa Based Land Use Unit)								
0–30	Ah	10YR 3/3	10YR 3/4	WFSB	HA	SFm	MS, PL	> 200
30–120	Bk	10YR 3/4	10YR 5/4	MMSB	HA	Fr	ST, PL	
120–200^{+}	C	10YR 3/3	10YR 5/3	MA	HA	Fr	SST, SSP	
Pedon 9 Waseca C (AP2-FrBa Land Use Unit)								
0–50	Ah1	7.5YR 3/3	7.5YR 3/4	WMSB	HA	SFm	SST, SSP	> 200
50–54	*UU5*	–	–	–	–	–	–	
54–200+	A2	7.5YR 3/4	7.5YR 3/4	WCAB	HA	Fr	SST, SSP	
Pedon 10 Walessa-Chara (AP1-MfMo Based Land Use Unit)								
0–30	Ah	10YR 5/2	10YR 6/2	WMGR	HA	Fr	NS, NP	> 200
30–80	Bk1	10YR 5/3	10YR 5/4	WMSB	HA	Fr	NS, NP	
80–200^{+}	B2	10YR 5/3	10YR 5/4	WMSB	HA	Fr	NS, NP	
Pedon 11 Walessa-Fora (AA4-CeSo Based Land Use Unit)								
0–46	Ah	10YR 2/2	10YR 3/3	WMSB	HA	Fm	ST, PL	> 200
46–115	B	10YR 3/3	10YR 3/3	MA	HA	Fr	SST, PL	
115–200+	C	10YR 5/3	10YR 5/4	MA	HA	Fr	SST, PL	
Pedon 12 Holite Plantation Forest (PN1- FsSe Land Use Unit)								
0–17	Ah	10YR 2/2	10YR 3/3	WFSB	HA	Fm	MS, PL	> 200
17–70	Bk	10YR 3/3	10YR 3/4	MMSB	HA	Fr	ST, PL	

Table 3 Selected soil morphological features under different land use systems in CSB *(Continued)*

Depth (cm)	Horizon	Color		Structure	Consistency			Gr. water table
		Moist	Dry		Dry	Moist	Wet	Depth (cm)
70–200+	C	10YR 5/3	10YR 5/3	MA	HA	Fr	SST, SSP	

These descriptions were made following the Guidelines for Field Soil Description of WRB (IUSS Working Group WRB 2006; FAO 2006). A soil horizon is a layer (which is different in depths), approximately parallel to the surface of the soil that is distinguishable from adjacent layers by a distinctive set of properties produced by the soil-forming processes (i.e., pedogenesis)

Notes: *L* loam, *C* clay, *CL* lay loam, *WE* weak, *MO* moderate, *ST* strong, *ME* medium, *FM* fine and medium, *CO* coarse, *SB* sub-angular blocky, *SB GR* sub-angular blocky parting to granular structure, *MA* massive, *FR* friable, *FM* frim, *FRF* friable to firm, *ST* sticky, *SST* slightly sticky, *Pl* plastic, *SPL* slightly plastic, *C* clear, *G* gradual, *D* diffuse, *S* smooth. Transportic qualifiers are mainly sandy sand ...UU3, UU5 = Gravels and course sandy material and T for termite channels. *AA4* rainfed arable cultivation, *AA6* irrigated arable cultivation, *AP* non-irrigated perennial cultivation, *AP2* irrigated perennial cultivation, *FN1* woodland/bushland (selective felling), *FN2* natural forest (clear felling), *PN1* plantation forestry (reserves), *PN2* natural forest (parks), *FS* semi-deciduous forest, *FX* xeromorphic forest, *P2-G1, P4-G2 and P5-G3*, ground water tables in P2, P4 and P5 Pedons

horizon (4%) of (P12) which was ≥1.5%; fine to medium sub-angular blocky structure and PBS (in 1 MNH_4OAc at pH 7) was 64% which was > 50%, making this horizon *voronic* horizon (Table 6).

The surface horizons of P7, P8, P9, and P11 had high clay (41–66% throughout 30–50 cm) (Table 3) that was clayey ≥ 35% and was thicker than 25 cm (Pedosphere.com 2001), which was thicker than 30 cm. Increased clay content in Pedon (P7) throughout the profile was due to bioturbation/termite casts that resulted in illuvial accumulation of clay in subsurface horizons. Pedons (P2 and P12) had sandy loam and more "total" clay and as a result had argic horizons (Table 7).

Electrical conductivity and calcium carbonate

The total soluble salt content of these soils, expressed as electrical conductivity saturation (ECe), varied from 0.20 at upper landscape position pedon (P3) to 23.90 dSm^{-1} at the middle landscape position (P5) (Table 6). All Pedons had 2–9% calcium carbonate ($CaCO_3$) equivalent throughout the horizons, which was ≥ 2% $CaCO_3$ equivalent (Table 5) ranged low to moderate and physically visible effervescences of calcaric soil material. Moreover, subsurface horizons for Pedons (P1, P2, P3, P4, P5, P6, P7, P8, P9, P10, P11, and P12) had CaCO3 equivalent ≥ 5% (Table 5).

Mapping categories

The soils of CSB were generally described and classified as Solonchaks, Chernozems, Kastanozems, and Cambisols, according to WRB (2006).

Soil fertility status across CSB

The ultimate objective of the entire study was to focus on the selection of better systems under different land use and management levels from the viewpoint of carbon sequestration and potential soil fertility. The major variable, i.e., the SOC, was related to total N and P which are influenced by the levels of management and land use systems. Keeping the above considerations in view, the SOC stocks were computed in addition to OC (%) for the purpose of identifying the land use systems; CO_2e reduction and nutrient stocks were considered. Moreover, aforementioned soil property (0–20 cm) depth which is influenced mostly by cultivation and management were considered.

Spatial distribution of soil organic matter (SOM) and carbon stock (SOC) contents The SOM and TN values in the Pedons varied from 0.36–8.10% to 0.02–0.52%, respectively (Table 8) in soil solum, and both decreased with depth. Higher TN content in the surface layers as compared to the subsurface layers could be due to SOM content, as there exists strong correlation between TN and OC.

Spatial distribution of primary nutrients (N, P, K) in soils TN content of the soils ranged from 0.06 in the subsurface horizon of the toe Pedon to 0.52% of the upper Pedon (P12). The amount of TN in the surface soils ranged between 0.02% in Pedon (P12) and 0.37% in Pedon (P7). Positive and strong correlation ($r = 0.93^{***}$) was found between OC and TN indicating the strong association of OC and TN in the study area (Table 11).

Available phosphorus (AP) content of the soils ranged from 21.04 mg/kg of soil in the C horizon of the lower Pedon (P8) to 266.62 mg/kg soil in the A horizon of the toe Pedon (P12) (Table 8). Phosphorous is an essential element for plant growth, hence an important soil fertility indicator. The AP content of the surface horizon soils is low for Pedons (P1, P10, and P11), while for other nine Pedons is high to very high (Tables 9, 10, 11).

The available potassium (K_2O) content of the surface horizon soils is relatively medium to high, and it ranged from 110.88 to 471.11 kg ha^{-1} with a mean value of 291.15 kg ha^{-1}. About 52 and 45% of samples tested medium and high in available K, respectively.

Table 4 Soil texture, bulk density, and soil reaction in CSB

Pedon/LUT	Horizon	Depth (cm)	Sand (%)	Silt	clay	Tex. class	BD gm cm^{-3}	pH(H_2O)	pH(KCl)	_pH
Kulfo Watershed = Upper Chamo Basin (UCB) (6° 7′ N, 37° 29′ E)										
P-1	Ah	0–34	67.41	13.04	19.56	SL	1.49	7.54	6.87	0.67
	B	34–200	58.90	32.45	8.65	SL	1.26	7.48	6.56	0.92
P-2	Ah	0–90	10.14	63.56	26.30	SiL	1.52	6.77	6.04	0.73
	UU5	90–97	–	–	–	–	–	–	–	–
	Bw	97–200	10.98	55.64	33.38	SCL	1.34	8.48	7.57	0.91
P-3	Ah	0–80	37.57	55.97	6.46	SiL	1.35	7.10	6.46	0.64
	UU5	80–85	–	–	–	–	–	–	–	–
	B	85–200	33.58	58.92	7.50	SiL	1.42	6.79	6.07	0.72
Sille-Sego Watershed = Middle Chamo Basin (MCB) (5° 57′ N, 37° 19′ E)										
P-4	Ah	0–35	21.63	46.81	31.57	CL	1.32	7.52	6.64	0.88
	B	35–200	27.87	55.74	16.39	SiL	1.44	7.37	6.61	0.76
P-5	Ah	0–40	39.71	43.07	17.23	L	1.55	7.01	6.26	0.75
	B	40–200	18.36	62.89	18.76	SiL	1.65	7.08	6.24	0.84
P-6	Ah	0–50	20.74	59.98	19.28	SiL	1.52	7.70	6.87	0.83
	UU5	50–58	–	–	–	–	–	–	–	–
	B	58–200	8.77	69.50	21.72	SiL	1.59	7.56	6.94	0.62
Waseca-Doyso Watershed = Lower Chamo Basin (LCB) (5° 45′ N, 37° 26′ E)										
P-7	Ah	0–46	30.38	28.28	41.34	C	1.22	8.10	7.14	0.96
	Bw	46–140	28.85	27.36	43.78	C	1.33	8.05	7.14	0.91
P-8	Ah	0–30	10.93	39.10	49.97	C	1.45	7.33	6.45	0.88
	B	30–120	34.13	46.43	19.44	L	1.42	7.66	6.83	0.83
	C	120–200	81.15	14.66	4.19	SL	1.62	7.93	7.05	0.88
P-9	Ah	0–50	2.59	31.71	65.69	C	1.19	7.41	6.45	0.96
	UU5	50–54	–	–	–	–	–	–	–	–
	B	54–200	26.85	46.95	26.20	L	1.24	7.78	7.03	0.75
Arguba-Weseca Watershed = Toe Chamo Basin (TCB) (5° 44′ N, 37° 25′ E)										
P-10	A	0–30	34.08	46.47	19.45	L	1.16	7.90	7.14	0.76
	B	30–80	10.12	67.69	22.19	SiL	1.39	8.35	7.51	0.84
	C	80–200	47.45	45.98	6.57	SL	1.34	7.42	7.48	−0.06
P-11	Ah	0–46	8.80	47.77	43.43	SiC	1.26	6.74	5.91	0.83
	B	46–115	20.04	63.75	16.21	SiL	1.33	7.66	6.97	0.69
	C	115–200	81.15	14.66	4.19	SL	1.42	7.83	7.24	0.59
P-12	Ah	0–17	34.75	45.67	19.57	L	1.09	5.88	5.21	0.67
	B	17–70	24.71	49.11	26.19	L	1.39	7.48	6.64	0.84
	C	70–200	41.18	45.75	13.07	L	1.34	7.66	7.05	0.61

It is difficult to indicate statistical difference as the depth of each profile sampled was different

Notes: *L* loam, *C* clay, *CL* clay loam, *SL* sandy loam, *SiL* silty clay, *BD* bulk density, *PD* particle density, *TP* total porosity

Table 5 Exchangeable cations and cation exchange capacity and base saturation of soils at CSB

Ped on	Depth (cm)	Na	K	Ca	Mg	Sum	CEC	PBS (%)	Exch. bases		
		(cmol(+)/kg)							Ca/Mg	Mg/K	Ca+Mg/K)
Kulfo Watershed = Upper Chamo Basin (UCB)											
P-1	0–34	1.03	0.45	26.78	9.94	38.21	38.97	98.03	2.70	22.09	80.40
	34–200	1.40	0.11	22.90	8.21	32.61	36.63	89.05	2.79	74.64	282.82
P-2	0–90	1.16	0.51	16.57	9.16	27.39	34.12	80.27	1.81	17.96	50.45
	90–97	–	–	–	–	–	–	–	–		
	97–200	1.78	0.41	22.88	13.64	38.71	39.70	97.51	1.68	33.27	89.07
P-3	0–80	0.60	0.55	26.54	8.99	36.68	37.68	97.33	2.95	16.35	64.60
	80–85	–	–	–	–	–	–	–	–		
	85–200	0.71	0.41	22.68	10.27	34.07	38.15	89.31	2.21	25.05	80.37
Sille-Sego Watershed = Middle Chamo Basin (MCB)											
P-4	0–35	0.73	0.64	25.49	9.07	35.93	39.44	91.09	2.81	22.12	84.29
	35–200	1.14	0.31	28.34	6.98	36.77	37.44	98.20	4.06	22.52	113.94
P-5	0–40	1.12	0.49	20.54	9.84	32.00	35.36	90.50	2.09	20.08	61.92
	40–200	1.04	0.46	27.90	6.10	35.51	36.49	97.32	4.57	5.87	32.69
P-6	0–50	0.82	0.28	23.97	8.99	34.05	34.43	98.92	2.67	32.11	117.71
	50–58	–	–	–	–	–	–	–	–		
	58–200	0.85	0.20	25.06	6.91	33.02	35.69	92.52	3.63	8.13	37.61
Waseca-Doyso Watershed = Lower Chamo Basin (LCB)											
P-7	0–46	1.17	0.66	37.58	16.42	55.84	56.35	99.10	2.29	24.88	81.82
	46–140	1.97	1.13	34.44	15.70	53.25	54.03	98.56	2.19	13.89	44.37
P-8	0–30	0.89	1.19	32.83	8.64	43.55	44.61	97.63	3.80	7.26	34.85
	30–120	1.05	0.20	33.38	1.28	35.92	37.68	95.31	3.26	6.40	123.79
	120–200	1.04	0.25	19.32	4.62	25.23	28.30	89.15	4.18	18.48	95.76
P-9	0–50	1.16	0.95	32.26	9.86	44.22	47.23	93.61	3.27	10.38	44.34
	50–54	–	–	–	–	–	–	–	–		
	54–200	1.05	0.20	28.94	8.64	38.84	39.91	97.30	3.35	43.20	187.90
Arguba-Wezeka Watershed = Toe Chamo Basin (TCB)											
P-10	0–30	1.27	0.60	21.83	8.99	32.69	35.36	92.47	2.43	14.98	51.37
	30–80	1.00	0.29	23.76	9.68	34.74	37.30	93.12	2.45	33.38	115.31
	80–200	0.85	0.64	23.54	6.98	32.01	33.65	95.13	3.38	10.91	47.69
P-11	0–46	0.46	0.73	22.03	10.80	34.02	38.03	89.44	1.21	14.79	44.97
	46–115	0.74	0.41	17.98	11.13	30.25	31.63	95.61	2.32	27.12	71.00
	115–200	0.82	0.50	20.80	6.66	28.78	28.94	99.45	2.84	13.32	54.92
P-12	0–17	0.77	0.59	12.53	7.34	21.23	33.34	63.68	2.31	12.44	33.68
	17–70	1.38	1.05	17.71	12.10	32.24	33.34	96.71	4.14	11.52	28.39
	70–200	1.98	0.22	18.58	11.23	32.01	35.22	90.90	5.63	51.05	135.68

Note: It is difficult to indicate statistical difference as the depth of each profile sampled was different

Table 6 OC, TN, EC, exchangeable Na, salt, and $CaCO_3$ of CSB soils

Pedon	Depth (cm)	OC (%)	TN	C/N	EC_e (dS/m)	$EC_{2.5}$	Salt con. (%)	ESP	$CaCO_3$
Kulfo Watershed = Upper Chamo Basin (ULS)									
P-1	0–34	0.91	0.12	7.84	0.35	0.14	0.68	2.65	7.22
	34–200	0.18	0.02	10.60	0.23	0.09	3.32	3.82	7.00
P-2	0–90	1.14	0.12	9.67	0.83	0.33	5.40	2.50	5.56
	90–97	–	–	–	–	–	–	–	–
	97–200	0.41	0.05	8.15	1.70	0.68	12.36	4.48	7.01
P-3	0–80	0.81	0.10	8.22	0.25	0.10	1.60	1.60	2.89
	80–85	–	–	–	–	–	–	–	–
	85–200	0.61	0.07	9.25	0.20	0.08	1.15	1.85	7.15
Sille-Sego Watershed = Middle Chamo Basin (MLS)									
P-4	0–35	2.16	0.20	10.81	0.83	0.33	2.10	1.86	5.01
	35–200	0.36	0.03	10.86	0.38	0.15	4.95	3.04	7.06
P-5	0–40	1.41	0.16	8.58	23.90	9.56	65.20	3.16	3.87
	40–200	0.27	0.03	8.19	13.78	5.51	150.40	2.86	5.06
P-6	0–50	0.57	0.03	17.15	18.05	7.22	61.50	2.38	7.26
	50–58	–	–	–	–	–	–	–	–
	58–200	0.31	0.02	18.46	15.33	6.13	147.68	2.37	6.00
Waseca-Doyso Watershed = Lower Chamo Basin (LLS)									
P-7	0–46	1.24	0.13	9.36	0.55	0.22	1.84	2.08	6.11
	46–140	1.20	0.07	17.93	0.68	0.27	4.7	3.65	7.50
P-8	0–30	1.19	0.15	7.97	0.58	0.23	1.2	2.00	5.01
	30–120	0.28	0.03	8.52	0.35	0.14	1.8	2.79	7.80
	120–200	0.12	0.02	7.13	0.30	0.12	1.6	3.68	7.23
P-9	0–50	1.08	0.12	8.91	0.33	0.13	1.00	2.45	4.40
	50–54	–	–	–	–	–	–	–	–
	54–200	0.27	0.03	8.04	0.38	0.15	4.38	2.64	5.45
Arguba-Wezeka Watershed = Toe Chamo Basin (TLS)									
P-10	0–30	0.42	0.03	12.66	0.40	0.16	0.90	3.61	5.95
	30–80	0.23	0.02	13.61	0.63	0.25	2.00	2.69	7.12
	80–200	0.17	0.02	9.98	0.58	0.23	4.80	2.54	5.06
P-11	0–46	0.94	0.12	8.09	0.25	0.10	0.92	1.21	5.01
	46–115	0.31	0.03	9.36	0.30	0.12	1.38	2.32	5.18
	115–200	0.15	0.02	9.67	0.33	0.13	1.70	2.84	4.30
P-12	0–17	4.05	0.52	7.85	1.30	0.52	1.53	2.31	4.68
	17–70	0.58	0.07	8.69	5.55	2.22	20.14	4.14	8.87
	70–200	0.21	0.02	12.92	4.38	1.75	39	5.63	8.87

Note: It is difficult to indicate statistical difference as the depth of each profile sampled was different

Table 7 Diagnostic horizons and soil unit names of the soils at CSB according to WRB (2006, 2010)

Pedons	Diagnostic horizons of pedons		Soil unit (WRB 2006)	Soil tax (USDA, 1999)	
	Surface	Subsurface		Suborder	Order
P1	Mollic	Calcic + cambic	Calcic Chernozems (CH)	Udolls	Mollisols
P2	Mollic	Calcic + vertic + argic	Luvic Calcic Chernozems (CH)	Udolls	Mollisols
P3	Mollic	Calcic +cambic	Calcic Kastanozems (KS)	Ustolls	Mollisols
P4	Mollic	Cambic	Haplic Chernozems (CH)	Udolls	Mollisols
P5	Mollic + clayey	Salic + cambic	Mollic Solonchaks (SCm)	Salids	Aridisols
P6	Umbric	Salic + cambic	Haplic Solonchaks (SCck)	Salids	Aridisols
P7	Mollic + clayey	Vertic + argic?	Luvic Chernozems (CH)	Udolls	Mollisols
P8	Mollic + clayey	Cambic	Haplic Kastanozems ((KS))	Ustolls	Mollisols
P9	Mollic + clayey	Cambic	Haplic Kastanozems ((KS))	Ustolls	Mollisols
P10	Ochric	Calcic + cambic + argic	Eutric Cambisols (CM)?	Cambides	Aridisols
P11	Mollic + clayey	Cambic	Haplic Chernozems (CH)	Udolls	Mollisols
P12	Voronic	Calcic + cambic + argic	Eutric Cambisols (CM)	Cambides	Aridisols

Nutrient rating and diagnostic methods (correlation, calibration, and interpretation) were presented in Table 9 and linked as the nutrient index levels.

Spatial distribution of secondary nutrients (Ca, Mg, S) Generally, Ca/Mg ratios are in between 2.5 and 6 for most Pedons, whereas in low range for two Pedons (P2 and P11), which are favorable ranges of plant growth. Ca +Mg/K ratios are very high for most Pedons, which are between ≥ 40, whereas two Pedons (P9 and P12) are in high ranges; this indicates high Ca, Mg, Ca+Mg, respectively, for plant use (Table 4).

Sulphur in agriculture is now gaining importance because of the recognition of its role in increasing crop production, especially in different cropping systems which are marked by application of no or less sulphur. Soil sulphur exists in organic form, adsorbed, and in soil solution as SO_4^{2-}. Available sulphur or SO_4^{-2} is the primary source of sulphur taken up by most of the crops. Soil solution SO_4^{-2} level determines the amount of S available to plant. The source of the solution SO_4^{-2} is the SOM via the microbial pool or directly from animal residues, atmospheric inputs, or fertilizers. As sulphur is also one of the key components of SOM, understanding its dynamics under varied land use systems helps to understand its relationship with other major soil parameters. This in turn will help identify suitable systems for increased carbon sequestration in semi-arid tropical soils. A major source of solution SO_4^{-2} is desorption of S held on the adsorption complex. If the crop demands for the main nutrients such as N, P, and K are met, then S may become limiting, especially when fertilizers with no S substitute fertilizers contain large amounts of sulphur. Organic S is generally the most abundant form of sulphur in agricultural soils with rapid fluxes between plant available, inorganic, and organic S fractions.

Cationic balance/cation ratios

The cation exchange capacity (CEC) of the soils ranges between 28.94 and 56.35 cmolc kg^{-1} soil, and generally, surface soils have higher CEC values than subsurface soils. Values in excess of 10 cmol (+) kg^{-1} are considered satisfactory for most crops (ISRIC I 2012). The clay content, the clay type, and the OM content all determine the total nutrient storage capacity. Also, the wider CEC range of the soils could be related to a difference in texture and clay mineralogy of the soils.

Cation exchange capacity The CEC status in the soil ranged from 6.5 to 19.2 cmol(+) kg^{-1} (Table 4) and was rated as low to medium (Tables 3 and 4). CEC refers to the exchange phenomenon of positively charged ions at the surface of the negatively charged colloids. The higher the CEC, the more capable the soil can retain mineral elements. Studies have shown that soils with CEC values of between 6 and 12 cmol(+) kg^{-1} are poor in exchangeable bases. Of the surveyed sites, none have CEC values < 12 cmol(+) kg^{-1}. It is generally accepted that SOM is responsible for 25–90% of the total CEC of surface horizons of mineral soils (Oades et al. 1989). The low to medium CEC found in this study could be related to low SOM of these soils (Table 8). The low CEC values in soils have also been implicated with low yield in most agricultural soils. Any intervention such as applying both manure and the required amount of fertilizer with the aim of improving the CEC of the soil is recommended.

Table 8 SOM, available N, P_2O_5, K_2O, and micronutrients content of the CSB soils

Pedon	Depth (cm)	SOM (%)	Av. N (mg/kg)	P_2O_5	K_2O	Cu	Fe	Mn	Zn
P-1	0–34	1.82	1164.24	30.01	166.58	0.45	9.62	1.28	0.91
	34–200	0.36	166.32	27.83	54.66	0.27	8.15	1.46	0.40
P-2	0–90	2.28	1175.02	161.53	228.54	0.81	21.38	2.58	0.61
	90–97	–	–	–	–	–	–	–	–
	97–200	0.82	508.20	160.79	164.36	2.03	25.40	10.77	0.64
P-3	0–80	1.62	988.68	48.29	257.87	0.47	16.95	2.71	0.82
	80–85	–	–	–	–	–	–	–	–
	85–200	1.22	659.12	48.47	183.09	1.03	23.25	2.26	0.78
P-4	0–35	4.32	1995.84	174.59	262.88	2.50	33.08	11.21	0.90
	35–200	0.72	335.72	58.00	154.99	0.43	11.68	0.92	0.44
P-5	0–40	2.82	1647.80	146.31	242.40	0.66	12.43	3.16	0.66
	40–200	0.54	335.72	40.75	194.39	0.86	12.99	2.12	0.58
P-6	0–50	1.14	329.56	153.16	110.88	1.11	11.14	5.33	0.81
	50–58	–	–	–	–	–	–	–	–
	58–200	0.62	166.32	153.13	78.08	0.72	13.04	2.28	1.12
P-7	0–46	2.48	1330.56	148.41	249.87	1.12	10.10	11.57	0.57
	46–140	2.40	671.44	145.74	485.98	0.72	8.72	7.27	0.67
P-8	0–30	2.38	1496.88	139.68	471.11	1.22	11.24	8.75	0.62
	30–120	0.56	329.56	33.51	90.25	0.79	10.49	3.97	0.46
	120–200	0.24	161.70	21.04	106.28	0.54	11.57	1.95	0.25
P-9	0–50	2.16	1207.36	156.35	383.29	1.19	9.97	4.91	0.71
	50–54	–	–	–	–	–	–	–	–
	54–200	0.54	332.64	154.41	88.50	0.58	7.50	2.73	0.40
P-10	0–30	0.84	329.56	52.07	252.71	0.71	12.76	3.88	0.60
	30–80	0.46	169.40	41.12	140.50	0.92	15.27	3.62	0.57
	80–200	0.34	167.86	41.12	288.96	0.46	10.36	1.75	0.51
P-11	0–46	1.88	1164.24	38.74	304.53	0.69	13.85	9.20	0.85
	46–115	0.62	329.56	32.25	195.98	0.21	5.81	1.72	0.53
	115–200	0.30	160.16	23.29	255.65	0.28	10.83	2.11	0.42
P-12	0–17	8.10	5155.92	266.62	242.06	1.94	63.56	19.32	4.10
	17–70	1.16	665.28	105.85	476.31	0.98	10.92	0.91	0.50
	70–200	0.42	166.32	19.82	78.08	0.85	11.24	1.64	0.51

OM% = %TN × 20`; OC = OM × 0.57 and/or %OC ×1.724 = %OM. SOC stock (C (t ha^{-1})) is calculated from SOC concentration (C (%)) by: $C(tha^{-1}) = C(\%) \times \rho \times D$ where D is soil depth (cm) and ρ is soil bulk density (g cm^3); similarly, using these parameters, it was calculated as mentioned (http://www.dpi.nsw.gov.au/agriculture)

Exchangeable bases (K, Mg, Ca) K levels ranged from 0.2 to 7.9 cmol kg^{-1} in the soil (Table 3). It is generally accepted that response to K fertilizers is likely when a soil has an exchangeable K value of < 0.2 cmol(+) kg^{-1} soil and unlikely when it is above 0.4 cmol(+) kg^{-1} soil (Anderson 1973). Ninety-five percent of the surveyed sites were rated as medium or high to very high due to exchangeable K values > 0.4 cmol(+) kg^{-1} soil (Table 3). This result generally suggests that K is not a limiting mineral element to crop productivity except in one site (P10).

The exchangeable Ca^{2+} in the topsoil of these schemes ranged from 0.6 to 3.3 cmol(+) kg^{-1}. All sites were rated as very low to low (Tables 3, 4, and 5). It is generally acknowledged that field conditions that limit Ca^{2+} uptake produce lower crop yields than crops grown with adequate Ca^{2+}. The low to very low levels of Ca^{2+} in all sites indicate higher bondage of Ca^{2+} to P at high soil

Table 9 Limits for soil test values used for rating the soils fertility levels

Soil fertility level	OC (%)	Nitrogen kg/ha	Av. P (P_2O_5)	Av. K (K_2O)	Ca^{2+}	Mg^{2+}	K^+	CEC
					Exchangeable cations (me/100 g soil			
Very high	> 1.00	> 700	> 80.0	> 360	> 20	> 8	> 1.2	> 40
High	0.81–1.00	561–700	64–80	301–360	10–20	3–8	0.6–1.5	25–40
Medium	0.61–0.80	421–560	48–64	241–300	5–10	1.5–3	0.3–0.6	15–25
Low	0.21–0.60	141–420	16–48	121–240	2–5	0.5–1.5	0.12–0.3	5–15
Very Low	< 0.20	< 140	< 16.0	< 120	< 2	< 0.5	< 0.12	< 5

Source: Adapted from Tandon, HLS. Ed (2005); Havlin et al. (1999)

reactions (Table 3). Research efforts should be directed towards packages that can ameliorate this problem. These results also showed that Mg^{2+} content was very high in all soils with values ranging from 4.5 to 23.0 cmol(+) kg^{-1} (Table 3). This was the dominant cation in all sites. The recommended value of Mg^{2+} in most crops is 2 cmol(+) kg^{-1} (MA 1989). The high to very high levels of Mg^{2+} in the soils suggest that these schemes have sufficient Mg^{2+} supplies for crop growth.

Spatial distribution of micronutriments (Fe, Mn, Zn, Cu) in soils across ACB Available micronutrients (Fe, Mn, Zn, and Cu) in all Pedons range between 5.81–63.56 mg/kg for Fe, 0.91–19.32 mg/kg for Mn, 0.40–4.10 mg/kg for Zn, and 0.21–2.50 mg/kg for Cu (Table 8).

The concentration of available micronutrients was found to be Fe > Mn > Zn > Cu in almost all Pedons across the landscape. The available Fe content of the surface horizon soils is high, and it ranged from 6.41 to 40.25 mg/kg with a mean value of 16.30 mg/kg. The available Mn content of the surface horizon soils is high, and it ranged from 0.87 to 13.09 mg/kg with a mean value of 6.08 mg/kg. The available Zn content of the surface horizon soils is relatively marginal to high, and it ranged from 0.65 to 1.27 mg/kg with a mean value of 0.93 mg/kg. The available Cu content of the surface horizon soils is relatively marginal to high, and it ranged from 0.50 to 1.75 mg/kg with a mean value of 0.99 mg/kg.

The available Fe contents of the soils widely varied from 6.41 to 40.25 ppm (Table 8) with a mean value of 16.30 ppm. The available Mn contents of the soils widely varied from 0.87 to 13.09 ppm with a mean value of 6.08 ppm. The available DTPA Zn contents of the soils widely varied from 0.65 to 1. 27 ppm with a mean value of 0. 93 ppm. The available DTPA Cu contents of the soils widely varied from 0.50 to 1.75 ppm with a mean value of 0.99 ppm.

Table 10 Nutrient rating and diagnostic methods

Nutrient index level	Expected relative yield without fertilizer (%)
Very low	< 50
Low	50–80
Optimum	80–100
High	100
Very high	100

Source: FAO, 1980; ISUEP, 1688
ISUEP: Iowa State University Extension Publication PM 1688

The nature and extent of soil degradation across CSB

Soil salinity/soluble salts This study revealed that salinity is gradually building up in soils of CSB because of evaporation of soil moisture from the surface soils and the nature of alluvial plain (Table 1), which implies that the LGP of the area is 61 days and evapotranspiration is greater than rainfall (Tuma 2007; Ethiopian Mapping Agency 1975). The studied soils indicated that, about 83% are non-saline and 17% saline, these were caused by internal soil drainage problem and parent material in CSB.

Anions of soluble salts Pedons (P1, P10, and P11) had Cl^-/SO_4^{--} ratios in between 1 and 5; it is believed that these soils are dominated by chloride ions. Therefore, these soils are characterized as chloride soils, and almost all other Pedons had < 0.05 CO_3^{--}/SO_4^{--} ratios except Pedons (P2 and P10), which are non-SO_4^{-2} soda soils (FAO WRB 2001). Excess Ca is usually associated with excess calcium chloride and sulphate in the soils. Excess Ca was prevalent in saline soils, in which excessive amounts of gypsum ($CaSO_4{\cdot}2H_2O$), calcium chloride ($CaCl_2{\cdot}6H_2O$), or soluble calcium salt have accumulated through capillary rise from the ground water.

Groundwater The measurements of groundwater table of three different Pedons (P2-G1, P4-G2, and P5-G3) showed the maximum water table depth values in all years and months (Table 3).

Land resource degradation Non-vegetated areas/very little vegetation (excluding agricultural fields with no crop cover), dry salt flats, beaches, sandy areas other than beaches, bare exposed rock, strip mines, mixed bare land, and degraded savanna/grass have been

Table 11 The basic cation saturation ratio and their relative proportions of the surface horizons soils (0–20 cm) of the land use units in CSB

Pedon	Land use unit	Ca/CEC		Mg/CEC		K/CEC		Ca/Mg		(Ca+Mg)/K	
		Status		Status		Status		Status		Status	
P1	AA6-CeMa	0.76	Adequate	0.18	Adequate	0.01	Low	4.13	Proportional	114.26	Low K
P2	AP2-FrBa	0.61	Adequate	0.30	Adequate	0.03	Adequate	2.04	Proportional	41.01	Low K
P3	PN2-FsAc	0.64	Adequate	0.20	Adequate	0.02	Adequate	3.23	Proportional	30.53	Favorable
P4	AP2-FrBa	0.71	Adequate	0.21	Adequate	0.02	Adequate	3.42	Proportional	46.53	Low K
P5	AA6-CeMa	0.78	Adequate	0.09	Adequate	0.02	Adequate	8.73	Proportional	53.40	Low K
P6	FN1-FxTa	0.77	Adequate	0.11	Adequate	0.02	Adequate	7.00	Proportional	41.76	Low K
P7	FN2-FsAc	0.75	Adequate	0.20	Adequate	0.01	Low	3.73	Proportional	73.81	Low K
P8	AA6-CeMa	0.76	Adequate	0.16	Adequate	0.01	Low	4.69	Proportional	106.24	Low K
P9	AP2-FrBa	0.67	Adequate	0.25	Adequate	0.01	Low	2.76	Proportional	89.35	Low K
P10	AP1-MfMo	0.74	Adequate	0.18	Adequate	0.01	Low	4.08	Proportional	99.00	Low K
P11	AA4-CeSo	0.52	Adequate	0.25	Adequate	0.04	Adequate	2.05	Proportional	20.18	Med. K
P12	PN1-FsSe	0.61	Adequate	0.18	Adequate	0.02	Adequate	3.50	Proportional	47.85	Low K

Classification according to Abayneh Esayas and Ashenafi Ali (2006) and NSS (1990) guidelines

observed in the CSB as a component of degraded land (Fig. 5). The root causes of these phenomena are lack of integrated participatory wetland management of the area around the lake, population pressure and shortage of farmland in the nearby highlands, absence of other alternative livelihood diversification strategies to rural-urban migrants, and rampant rural poverty and unemployment. Moreover, the policy and institutional gap in the management of common pool resources is a major factor in aggravating the resource depletion and exposing the small-scale communities for food insecurity and unsustainable livelihood.

Discussion

The studied land use systems were generally found within slope range between nearly flat (1–2%) and gently sloping (2–5%) (Table 1). Smooth variations in elevation are suitable for surface irrigation with respect to topography. The slope of the CSB areas is basically within suitable range of slope classification for surface irrigation (< 10%), since slope < 10% is considered to be suitable for surface irrigation with minor adjustment to negotiate the natural slope (Wagesho 2014). The soils of land uses were young and derived from alluvium deposits (Table 1). Mesfin (Mesfin 1998) has also indicated that flooding obstructs the pedogenic material. Generally, low runoff and well permeability of the study area soils (Table 1) might be due to the depth of the soil (Table 3) and slope of the landscape position (Table 1). Based on these criteria, a low land area near the west and east banks of the Main River are under < 10% slope classification characterized by sandy loam to clay loam soil type. In this area, surface irrigation, which can be set with relatively low initial investment and available technology, is of paramount importance. They are having good inherent fertility and high moisture holding capacity. Besides, these areas are with very flat land slope as observed from the DEMs which falls below 10% and are suitable for surface irrigation.

Traditional management of drainage and waterlogging in the CSB is depending on the amount and duration of rainfall, slope, farm size, and the extent of the drainage problem. To cope with this situation, farmers traditionally plant low-yielding crops adapted to the poor internal drainage. However, all these traditional management practices generally result in low yields.

Vegetation distribution across the CSB has been changed greatly over time because of high population pressure and subsequent deforestation. A small part of the border area near Lake Chamo was covered with natural forest, whereas the top of mountains that was previously covered by grass and bushes was deforested. In the escarpment between lowland catchment and highland areas, the scattered trees were also leaving their original place to the new generation of human race because of shortage of farmland in the nearby highlands, absence of other alternative livelihood diversification strategies to rural-urban migrants, and rampant rural poverty and unemployment. Most of the researchers agree that the poor are victims of resource degradation, and the resource depletion and degradation becomes worse when it is an open-access common-pool resource with high demand.

Apart from the deforested hilltops, the study area was remarkably well covered by recently introduced fruit trees. There was a breakthrough in production and transforming the livelihoods of the inhabitants from survival level to elevated way of life at lowlands in the irrigated zone; fast changes are taking place now in landscapes, farming systems, individual crops, peoples' lifestyles, and breaking of traditional systems. For example, improved farming methods such as mulching, intercropping, and shifting cultivation were also well practiced.

According to the information obtained from farmers, high spatial variability in crop growth pattern due to salinity, water sources, and land quality differences existed in the area. The cropping pattern of the area was substantially changed through time; particularly, the fruit crops' production was increased and fruits became the main plants growing in the area. As a result, the smallholders' farming systems in the area are dominantly of banana and mango, mixed farming system or agroforestry, and annual field cropping of maize, sorghum, cotton, and other pulse crops. Moreover, vegetation in the CSB varies according to soil salinity level and soil moisture. Large scales in the fields have high population sizes and show high landrace and genetic diversity.

The rivers draining into Lake Chamo are listed as Kulfo, Sile, Sego, Argoba, and Wezeka. The lands located along the watercourse were used for banana production (P2 at UCB, P4 at MCB, P9 at LCB landscape), whereas lands at mid extreme with water shortage were utilized for maize or cotton production (P1 at UCB, P5 at MCB, P8 at LCB landscape). The soils near the water course were locally termed as *fatty soils* that do not require much water to give adequate yield, since soils on river levees are porous and better drained compared to those of basin areas. During floods, fine sand or silt is deposited on top of the levees, and clay in the basins, whereas gravel and coarse sand are normally found on the channel floor (lag deposits) (FAO WRB 2001). However, soil texture is a relatively permanent feature of the soil that does not change appreciably over a human lifetime.

The soils of the UCB were considered to be of best quality and giving high yields as compared to others (P1 and P2). Similar productive soils were also found in the MCB (P4) and LCB (P8 and P9). The soils of middle landscape were characterized by farmers as "hard" due to its requirement of large quantity of water during irrigation and poor tilth. Increased electrical conductivity in turn resulted in increased osmotic pressure (OP) and decreased water availability and crop yield.

Yields of major crops declined with distance from the watercourse. The farmers distant to water course (in TCB) adopted crop diversification and agroforestry practices to minimize water scarcity constraints and risk of single crop. Crop diversification is a successful approach to achieve water, food and nutrition security, income growth, poverty alleviation, employment generation, thoughtful use of land and water resources, sustainable agricultural development, and environmental improvement (FAO 1995). The cropping pattern of the area was substantially changed through time, particularly with the modern irrigation system intervention and subsequent infrastructure development such as asphalt road facility and land tenuring system during the last 20–25 years, the fruit production was increased, and fruits became the main plants grown in the conventionally cultivated areas. As a result, there was a breakthrough in production and transforming the livelihoods of the inhabitants (> 65%) from survival level to elevated way of life at lowlands in the irrigated zone.

Rainfed agricultural systems at TCB has specialized with indigenous soil and water conservation practices, which called *Targa* by Dherashe community and used for many years by them. *Targa* is a physical soil and water conservation method like terracing, whereby stalk of sorghum, maize, and other similar crops are piled in rows and placed at intervals of 2 to 3 m and utilized as an organic fertilizer (humus). Likewise, people do not allow cutting and destroying some of the trees such as *Dashile* and *Woybeta* since they serve as animal feed/forage and for house construction. If much of this biomass remains in the field, then the soil is likely to have a higher SOM content than other less productive soils, since SOM in the form of humus enhances mineral breakdown and, in turn, nutrient availability. Organo-mineral complexes can also form with ions, particularly metallic ions such as Fe^{2+}, Cu^{2+}, Zn^{2+}, and Mn^{2+}, which will make them more available for plant uptake than the mineral form of these elements.

Selection of crops to be grown along watercourse was dependent upon (a) food habit of the locality, (b) land suitability and adaptability of crops, (c) watercourses, and (d) access to market. Community categorize their farming system based on watercourse soil fertility status, viz. cash crop farming (nearby watercourse), subsistence farming (mid-way watercourse), and mixed farming (at extreme distance to watercourse). Accordingly, the survey result from the Kebele has indicated that maize and banana fields were the dominant land use units in upper (UCB), middle (MCB), and lower (LCB) landscapes, whereas subsistence and mixed/agroforestry farming systems were dominant in toe (TCB) landscape (Additional file 1) as a rainfed agriculture. Reports showed that farmers shape the distribution and degree of diversity for the crops both directly through selection and indirectly through management of biotic and abiotic agroecosystem components. Three dominant land use units were identified and selected from each landscapes, based on the predetermined set of criteria, information obtained through assessment conducted, and field observations made during the survey period from each landscapes. Accordingly, the land use units in the CSB are classified as annual subsistence farming of maize and/or sorghum system (AA); perennial including mixed/agroforestry farming system (AP) and representative natural forest and woodland system (NF) were considered and used as Pedon excavation sites.

The physico-chemical characteristics of all the studied soils of different land use systems relatively have (> 150 cm) a very deep profile (Table 3), although the Pedons (P2, P3, P6, and P9) had stratified sandy layers (UU5). The soils are therefore suitable for cultivation and variety of crops. Negassa and Gebrekidan (2003) indicated that soil depth is one of the important soil quality indicators and determines the responses of soil to intensive land use. Also, low runoff of the study area soils might be due to the depth of the soil.

Pedons (P1, P2, and P3) in the ULS were characterized by Ah-B, Ah-UU5-Bw, and Ah-UU5-Bk; Pedons (P4, P5, and P6) in the MCB were Ah-Bk, A-B, and Ah-UU5-B; Pedons (P7, P8, and P9) in the LCB were Ah-Bk, Ah-Bk-C, and Ah1-UU5-A2; and Pedons (P10, P11, and P12) in the TLS were Ap-Bk1-B2, Ah-B-C, and Ah-Bk-C horizon sequences, respectively. The thickness of A horizon varied along the landscape positions, relatively the shallowest surface horizon (17 cm) in the TLS to the thickest (90 cm) in the ULS positions.

The variation in the thickness of A horizon along the landscape position could be attributed to soil erosion at the UCB position and deposition at the LCB position as suggested by Woods and Schuman (1988) and watercourse. Relatively gentler slope (1–2°) of the land position aids deposition of materials eroded from the upper part of the Rift Valley escarpment. Thickness of B horizons ranged from 50 to 166 cm. Soils situated at the MCB and LCB positions have thick B horizon compared to soils situated at TCB position. In general, unlike the thickness of A horizon, the thickness of the B horizon decreased from the ULS to TCB position. In the UCB and MCB Pedons, distinct horizons and argic B horizon were readily observed which indicates relatively well-developed soils in the landscapes. In these Pedons, considerable increase in the clay content of the Bt horizon (Table 3). Pedons (P2, P3, P6, and P9) had sandy material (UU5) in A and B horizons, which is an indication of fluvial soil material transformation and indicating the weak development of subsurface horizons in these fields.

Moist color of surface horizons varied from very dark brown (7.5YR 2/2) to dark brown (7.5YR 3/2) in Pedons (P1, P2, P4, P5, and P9). Also, the moist color of the surface horizons varied from very dark brown (10YR 2/2) to dark brown (10YR 3/3) in Pedons (P3, P6, P7, P8, P11, and P12), except for (P10) that was brown (10YR 5/2) (Table 3). Surface layers had darker color as compared to subsurface horizons within each Pedon except for (P10) (Table 3), relatively dry horizons. Particularly, dark brown color (7.5YR 3/3) in the Pedons (P2, P4, and P5) was a possibility of water saturation leading to reduction reaction and differences in forms of iron oxide. On the other hand, there were few color variations among the land use units in the B horizons. This is attributed to the effect of relatively higher OM content in the surface horizons compared to the sub-surface. This implies that soil color is highly influenced by SOM in the A horizon, and its continuous transformation processes (Negassa and Gebrekidan 2003; Havlin et al. 1999). Abayneh (Esayas 2005) found that wet soil profiles have darker hues in the B horizons. The dominant soil colors were gray, brown, reddish brown, and yellow (Table 3). Fine mottles of different color combinations were also common at different horizons. However, the soil color tends to be sequential with profile/depth trend. Climate, drainage conditions, and alluvial process were the main agents for soil color development. The dominant soil texture of the investigated area is silty clay loam as compared to other particle sizes. However, the distribution of silt, clay, and sand did not remain constant in all soil matrixes. This was due to the continuous translocation process of silt, clay, and sand. Furthermore, deposits of buried massive clay were frequently found at deep soil layer which was the result of alluvial and erosion processes in the near past. Bulk density of the study area varied from 1.2 to 1. 56 g/cm^3. However, due to soil textural stratification of the profile, it is not uniform with profile/depth trend (Table 4). The relationship between ECe and soil texture showed that as silt content increases, salinity increases with the same proportion.

Distinctness of the boundaries between the A and B horizons, in the three Pedons, was clear with smooth topography, whereas the TCB Pedon had gradual and smooth boundary. Transition within the sub-horizons of B in UCB, MCB, and TCB Pedons (P2, P4, and P5) had clear, diffuse, and gradual smooth boundary, respectively (Table 3). Thicker and distinct horizonation in the UCB positions indicates that under the original intact forest cover, there has been adequate moisture percolation down the profile to foster soil forming process and cause horizon differentiation. In the LCB positions, however, frequent rejuvenation and high moisture regime somehow hindered clay translocation.

All surface horizons of the studied soils had a weak to moderate sub-angular blocky structure and moderate to strong sub-angular blocky structure on the sub surface horizons except two horizons (Table 3). The subsurface horizons had moderate to strong sub-angular blocky structure except two horizons, which had moderate compound sub-angular blocky structure parting to fine granular structure. C horizon in the LCB and TCB landscape position had massive structure. The weak-developed structure of the subsurface soils could be due to the presence of weatherable minerals or relatively higher silt content of the subsurface horizons than that of the surface horizons (Table 3). Good soil structure is critical for maintaining the long-term capacity of agricultural land to produce crops.

Consistencies of most horizons were found to be slightly sticky to non-sticky/non-plastic, which might be due to the large proportion of silt in the soil. Generally, silt dominated the particle-size distribution in almost all Pedons. The non-sticky/non-plastic consistence in the Pedons (P1, P4, and P8) could be also due to the influence of high SOM content. Although consistence is an inherent soil characteristic, the presence of high organic matter could modify it (Negassa and Gebrekidan 2003). The C horizon of the LCB position Pedon had firm moist consistency. The overall friable consistency of the soils particularly in subsurface horizons indicates that the soils are workable at appropriate moisture content. The lack of very sticky and very plastic consistency despite relatively high clay content could be indicative of lack of smectite clays in the soils. The textural classes of the surface layers ranged from silt loam, silt clay, and clay in all Pedons (Table 4). The clay content of Pedons decreased with depth except for Pedons (P2, P7, and P12), while the silt content showed discernable increase throughout the profiles. The accumulation of clay in the subsurface horizon could have been contributed by the in situ synthesis of secondary clays, the weathering of primary minerals in the B horizon, or the residual concentration of clays from the selective dissolution of more soluble minerals of coarser grain size in the B horizon (Buol et al. 2003).

Bulk density of the soils was in the range of 1.09 g cm^{-3} in the A horizon of the toe Pedon to 1.65 g cm^{-3} in the B horizon of the middle Pedon (Table 4). In all Pedons, except P1, P2, and P8, the lowest bulk densities were found at the surface horizons, which have higher OM content. Higher OM content in the A horizon makes soils loose, porous, and well aggregated, thereby reducing bulk density (Hillel 1980). The bulk density values of the surface horizons in Pedons (P3, P4, P7, P9, p10, p11, and p12) were less than the critical values (1 .4g cm^{-3}) for agricultural use (Hillel 1980). This implies no excessive compaction and no restriction to root development (Werner 1997).

Rooting depth is considered an important indicator of soil condition, since changes in this property is likely to affect plant available water capacity, subsoil salinity, SOC content, or other properties to indicate physicochemical constraints in the soil profile. Bulk densities that limit plant growth vary for soils of different textural classes (Doran et al. 1996). General relationship of soil bulk density to root growth based on surface soil textures indicated that Pedons (P3 and P10) silt loams had 1.35 and 1.16 g/cm^3 soil bulk density, that is < 1.40 (ideal value), whereas Pedons (P1 and P2) silty clay loams had 1.49 and 1.52 g/cm^3, respectively, that is < 1.55 g/cm^3 (critical value). Pedons (P5 and P6) clay loams had 1.55 and 1.52 g/cm^3, respectively, which is < 1.60 g/cm^3 (critical value). Pedons (P9 and P11) silty clays had 1.19 and 1.26 g/cm^3, respectively, that is < 1. 49 g/cm^3 (critical value). Pedons (P7 and P8) clays (> 45% clay) had 1.22 and 1.45 g/cm^3, respectively, which is < 1.39 g/cm^3 (critical value). So all surface soils may not affect root growth.

The pH-H_2O values of soils varied from 5.88 to 8.48 (Table 4). The lowest value (5.88) was observed in the A horizon (0–17 cm) of TCB position (P12), whereas the highest (8.48) was found in Bw horizon (P2) found at the ULS position. According to Tan (1996), the pH range of the soils is moderately acidic to moderately alkaline, which is the preferred range for most crops. The pH-H_2O values had shown a general tendency to increase with soil depth in the Pedons found at UCB (P1 and P3), MCB (P4), and LCB (P7) positions compared to the TCB position. As pH increases, $CaCO_3$ increases which was due to the higher solubility of $CaCO_3$ and the greater potential of its hydrolysis. According to FAO/IIASA/ISRIC/ISS-CAS/JRC (ISRIC I 2012), the pH values (pH 7–8.5) are indicative of carbonate-rich soils. Depending on the form and concentration of $CaCO_3$, they may result in well-structured soils which may however have depth limitations when the $CaCO_3$ hardens in an impermeable layer and chemically forms less available carbonates affecting nutrient availability (phosphorus, iron). The pH-H_2O values had shown a general tendency to decrease with soil depth in the Pedons found at UCB (P2), MCB (P5 and P6), LCB (P8 and P9), and TCB (P10, P11, and P12) positions. The pH values for most studied soils were neutral and near neutral indicating that there is no toxicity of aluminum, manganese, and hydrogen, rather do not impair the availability of nutrients such as K, Ca, and Mg especially in alluvial soils (FAO WRB 2001). This is mostly due to the fact that pH changes the form of many of the nutrients and many of the forms are relatively insoluble.

Similarly, the pH-KCl values of the soils ranged from the lowest (5.21) value which was observed in the A horizon (0–17 cm) of TCB position (P12), whereas the highest (7.57) was found in Bw horizon of (P2) at the UCB position. According to Havlin et al. (1999) and Anon (1993), soil pH determination using KCl solution showed the presence of weatherable minerals. In all the soil profiles, _pH (pH-H_2O -pH-KCl) values were positive, ranging from 0.59 to 0.96 (except for C horizon of P10). According to Uehara and Gillman (1981), positive _pH values is an indication of the presence of net negative charges in soils, which increases the ability to hold onto cations at negatively charged sites within the soil. However, the _pH values were < 1, which indicates the absence of potential acidity and weatherable minerals (Buol et al. 2003). However, B horizons of most Pedons had considerable quantities of silt (Table 4), which indicates the presence of weatherable minerals, the absence of clay skins, and insufficient illuviation of clay.

Exchangeable bases for K was rated as low to high for Pedons ranging 0.11 (P1) to 1.37 meq/100 g soil (P11). Ca contents of Pedons were high and very high in all soil samples, ranging from 17.71 (P12) to 37.58 meq/100 g soil (P7). The same applies for Mg ranging from 4.62 (P8) to 16.42meq/100 g soil except for B horizon of P8. The ranges of critical values for optimum crop production for K, Ca, and Mg are from 0.28–0.51, 1.25–2.5, and 0.25–0.5 cmol(+)/kg soil, respectively. The exchange complex of the soils is dominated by Ca followed by Mg, K, and Na (Table 5). This result is in agreement with FAO/IIASA/ISRIC/ISS-CAS/JRC (ISRIC I 2012); tropical confined conditions rich in Ca and Mg in climates with a pronounced dry season encourage the formation of the clay mineral smectite. According to Havlin et al. (1999), the prevalence of Ca followed by Mg, K, and Na in the exchange site of soils is favorable for crop production. The exchangeable cation content of the soils increased with increasing soil depth except K in the MCB, LCB, and TCB Pedons which showed relative decrement. The increment was attributed to the leaching of exchangeable cations. This result is in agreement with the findings of Wakene (2001) on Alfisols around Bako area, Ethiopia. Though different crops have different optimum ranges of nutrient requirements, the response to calcium fertilizer was expected from most crops when the exchangeable calcium is less than 0.2 cmol(+) kg^{-1} of soil, while 0.5 cmol(+) kg^{-1} of soil was the deficiency threshold level in the tropics for Mg (Foth 1990).

Exchangeable Na content of the soils is low to moderate, and exchangeable sodium percentage (ESP) of the soils was also less than 6% for all Pedons (Table 4). This indicates that there are low sodicity problems in the studied soils. According to Brady and Weil (1999), ESP of 15% is considered as critical for most crops. The ESP distribution of the studied soils varied along the landscape positions. Soils situated at the TLS position had relatively higher ESP content (4.14–5.63 in B and C horizons of P12, respectively), followed by soils located at UCB (3.82–4.48% in B horizons of P2 and P3) positions (Table 5). The soils at all landscape positions had discernable increase in ESP with soil depth except for Pedons (P5 and P6) found at LCB position.

The cation exchange capacity (CEC) of the soils ranged from 28.94 to 56.35cmol(+) kg^{-1} of soil (Table 5). CEC was the highest under banana and the lowest under grasslands. The latter also had the lowest pH. The dominant cation was Ca. The CEC of a soil generally increases with soil pH due to the greater negative charge that develops on SOM and clay minerals due to deprotonation of functional groups as pH increases. According to Foth (1990), CEC values are rated as very low (< 5), low (5–15), medium (15–25), high (25–40), and very high (> 40). Furthermore, Pedons (P2, P3, P5, P9, and P12) had relatively increased CEC values with depth than for Pedons (P1, P4, P6, P7, P8, and P11), which could be due to the strong association between OC and CEC, according to Brady and Weil (1999).

The percent base saturation (PBS) values of almost all Pedons except surface horizon of (P10) > 80% (Table 5) indicate saturated conditions often calcareous, sometimes sodic, or saline (ISRIC I 2012); thus, all Pedons had 2–10% $CaCO_3$ equivalent throughout the horizons which show presence of calcareous soil material. The very high PBS of the Pedons (except in P7) indicates the presence of $CaCO_3$, which would be dissolved during CEC determination using 1 M NH_4AOc ammonium acetate of pH 7, and contributes to the values of exchangeable Ca. Pedons (P4, P5, P6, P7, and P8) had relatively decreasing PBS values with depth than for Pedons (P1, P2, P3, P9, P10, and P12). Soils with high PBS are considered more fertile because many of the “bases” that contribute to it are plant nutrients. PBS is also directly related to soil pH and represents the relative availability of many positively charged nutrients (cations) such as Ca, Mg, and K (Bandel and James 2002). Cation exchange is the major nutrient reservoirs of K^+, Ca^{2+}, and is also important in holding N in the ammonium ($NH4^+$) form.

The OC contents (Table 6) of surface layers (P4 and P12) could be considered as high according to Herrera (2005), who categorized soil OC values greater than 1.74% in high range. According to Landon (1991), however, the OC contents of the surface layers of the Pedons could be rated as very low to medium. Moderate to high amounts of OC are associated with fertile soils with a good structure. Soils that are very poor in OC (< 0.2%) invariably need organic or inorganic fertilizer application to be productive (ISRIC I 2012). Similarly, the TN content of the surface layer (P12) is high according to Havlin et al. (1999), who indicated TN as low (< 0.15), medium (0.15–0.25), and high (> 0.25), whereas all the other Pedons contained medium TN. OC and TN content decreased with depth in all the Pedons.

It was observed that the C to N ratio varied from 7:1 (C horizon of P8) to 18:1 (B horizon of P6) along different land uses and landscape positions. The high content of C to N ratio P6 (moist) was due to the comparatively low nitrogen content in subsurface horizon. Research findings revealed that cultivation of the land results in reduction of OC and TN and increases C to N ratio of soils (Saikh et al. 1998). The wider C to N ratios in the surface soils than the corresponding subsoil suggested that nitrogen was limiting in agricultural productivity. In most soils, the C to N ratio varies according to the climate, elevation, type of vegetation, and microbial activity and decreases with increasing depth. A good C to N ratio will result in the formation of both effective humus and stable humus. However, the C to N ratio decreased with cultivation for a given period of time (Lal 1996). Generally, the SOC and TN associated with the annual crop management appeared to be more sensitive to changes in land use and management compared with that in perennial crop management. In general, the C to N ratio decreased with cultivation for a given period of time (Saikh et al. 1998; Lal 1996).

In all except the two Pedons (P5 and P6), the soil samples fall in the normal ECe range indicating that salinity is not at all a problem in these soils (Table 6). The lower values of ECe in these soils may be attributed to more macropores, as majority of the soil samples in the area are light textured, resulting in free drainage conditions. However, the salinity hazard in flooded soils may be greater than the ECe values of the soil because of the soil reduction and the solvent action of carbon dioxide that releases large amounts of ions into the soil solution, but due to dilution, it may be less than what the ECe values may suggest (FAO 1995).

The subsurface horizons of P5 and P6 had moist colors of these horizons were 10YR with chromas ≤, which were stronger than that of the underlying horizons; salt precipitates on the surface of the Pedons in dry seasons (Fig. 3); ECe of horizons within 100 cm from the soil surface were 15–24 dS/m at 25 °C within 40–50 cm (Table 4), which was > 15 dS/m; had 60.5–67% salt which was ≥ 60% and that was ≥ 15 cm; and had whitish surface crust when dry. Only grown silicornica or halophyte vegetation such as *Tamarix* and only very salt-tolerant crops such as cotton yielded satisfactorily. Therefore, these Pedons had *salic* horizon (highly saline), according to WRB (FAO 2006; FAO WRB 2001; World Reference Base, (WRB) for S resources 1998). This is in agreement with FAO (FAO 2006) that many Calcisols occur together with Solonchaks that are actually salt-affected Calcisols and/or with other soils having secondary accumulation of lime. Also, Calcisols are common in highly calcareous parent materials and widespread in arid and semi-arid environments; natural vegetation is sparse and dominated by xerophytic shrubs and trees and/or ephemeral grasses (FAO 2006).

All Pedons had 2–9% $CaCO_3$ equivalent throughout the horizons, which was ≥ 2% $CaCO_3$ equivalent (Table 5) ranged low to moderate and physically visible effervescences of Calcaric soil material. Moreover, subsurface horizons for Pedons (P1, P2, P3, P4, P5, P6, P7, P8, P9, P10, P11, and P12) had CaCO3 equivalent ≥ 5% (Table 5). Agriculturally, low levels of $CaCO_3$ enhance soil structural development and are generally beneficial for crop production (ISRIC I 2012). Accordingly, it is believed that ancient basement rocks lie under the whole Rift Valley consist of gneisses, which transform into granites and grandiosities. $CaCO_3$ is the main component of shells of marine organisms, snails, and eggshells. The presence of $CaCO_3$ indicates the precipitation of calcium in the form of carbonate and that calcium as $CaCO_3$ is due to high pH of 7.5 or above, resulting in the formation of $CaCO_3$ precipitates (Tayim and Al-Yazouri 2005). $CaCO_3$ concentrations in Pedons (P2, P4, and P5) were

Fig. 3 Flooded Solonchaks. High salt content in the bare spots prevents the growth of even salt-tolerant plants

soft, whereas in all other Pedons had hard concretions which were generally believed to be of hydrogenic nature.

According to Pedosphere.com., (2001), the subsurface horizons for Pedons (P1, P2, P3, P10, and P12) had 5–9% $CaCO_3$ equivalent within 100 cm which were ≥5%, had sandy loamy to loam skeletal particle-size classes, and contained low clay (4–9%) which were < 18%, and physically, all these Pedons had conspicuous accumulation of secondary $CaCO_3$ (whitish spots) within 50 and 100 cm depth that was tested by using 10% HCl acid which were > 5% (Table 6). Therefore, Pedons (P1, P2, P3, P10, and P12) had *calcic* subsurface horizons, according to WRB (FAO 2006; FAO WRB 2001; World Reference Base, (WRB) for S resources 1998). Moreover, these Pedons had CEC (31–56 meq/100 g of soil) and PBS (80–99%) which were > 24–56 meq/100 g of soil and > 50%, respectively. Since the CSB falls into semi-arid moisture regime where evapotranspiration exceeds precipitation, thus, the length of growing period (LGP) is 61 days and rainfall pattern is a bimodal type with a total rainfall of 830–910 mm per annum (Tuma 2007), and with native vegetation of comprised steppe-like in nature and some bunch grass and short shrub and trees (Murphy 1968).

Saline soils (P5 and P6) had thick surface crusts which occur in depressions (Fig. 3) that collect water from surrounding upland during rainy season but dry out in the warm season. Therefore, these soils were classified Solonchaks and referred to as *flooded Solonchaks*. Calcisols in depression areas are frequently associated with Solonchaks at sub-group level which are given in Table 6 (FAO WRB 2001). One reason why Calcisols as a taxonomic unit have good drainage properties is that carbonate-rich soils in wet positions (depressions, seepage areas) quickly develop a Salic horizon in long dry seasons and a key out as Solonchaks (FAO WRB 2001). The salinity hazard in flooded soils may be greater than the ECe values of the soils because of the soil reduction and the solvent action of CO_2 that releases large amounts of ions into the soil solution, but due to dilution, it may be less than what the ECe values may suggest (FAO 1995), and changes for conductivities are highly related in soil solutions with the Ca and Mg bicarbonate concentration in the alkaline soils (FAO 1995). Production of salt stress-tolerant crop plants is essentially required because of the growing threat of global warming on agricultural productivity, in addition to the predicted population explosion in the near future.

Forms of secondary gypsum in soils are diverse and are considered to be informative for diagnostics of soil genesis, but mineralogical analysis of gypsum equivalent was not determined in this study. In addition to physical field observations, laboratory test for presence of SO_4^{-2} had no turbidity which indicated absence of secondary gypsum. Since CSB is a low-lying basin, incoming water from (flash) floods evaporates inside the basin where its dissolved salts such as $CaCO_3$ and $MgCO_3$ precipitate as calcite, aragonite, or dolomite accumulate in the lowest parts, first (FAO WRB 2001); later, after the lake dry, halite (NaCl) and highly soluble salts like gypsum ($CaSO_4.2H_2O$) segregates and the brine becomes further concentrated (FAO WRB 2001), but there is greater incoming floodwater from upland and the hydrological interconnection of Abaya-Chamo Lakes (Ababu 2006), indicating no chance the lake to be dry.

Gypsum accumulation is common in arid and semi-arid regions, mostly at a depth between 150 and 200 cm, or more below the surface; however, during morphological and physical characterization, there was no secondary gypsum accumulation in the soil profiles. Pedons (P1, P3, P4, P5, P7, P8, P9, P10, and P11) had low to very low ions of gypsum (Ca^{2+} and SO_4^{2-}) accumulation as a soluble salt (Tables 7 and 14), which indicates very low accumulation of ions of gypsum in the soil profiles. Also, Pedons (P2 and P10) had little accumulation of Na^+ and SO_4^{2-} ions as a soluble salt in subsurface horizons (Table 7), which also indicate low accumulation of sodium SO_4^{-2} in the soil profiles (Table 7), as a result, relatively very low and young gypsum accumulation in alluvial deposits of CSB. This is because of downward percolation of water from the surface to subsurface and subsoil layers. Research indicates that up to 2% gypsum in the soil favors plant growth, between 2 and 25% has little or no adverse effect if in powdery form, but more than 25% can cause substantial reduction in yields. It is suggested that yield reductions are due in part to imbalanced ion ratios, particularly K to Ca and Mg to Ca (ISRIC I 2012).

The Pedons (P1, P3, P4, P8, P9, P10, and P11) had moderately developed structure in subsurface horizons and the moist colors of these horizons were with chromas ≤ 4 (Table 3), which were stronger than that of the underlying horizons; had considerable quantities of silt indicates the presence of weatherable minerals under the Bw horizons (Table 4); and had no clay skins in subsurface horizons. These soils also had high base saturation (64–98%). These show that the Pedons (P1, P3, P4, P8, P9, P10, and P11) had AhBC profiles with brown Ah-horizons of medium depth over a brown to cinnamon cambic and with lime accumulation.

It is true that most Pedons except (P6, P10, and P12) had mollic surface horizon, had OC 0.8–2%, and had PBS (in 1 MNH_4OAc at pH 7) 90.5–98.2% which was > 50% (Table 7). Pedons (P2, P7, P10, and P12) had an *argic* subsurface horizons with a CEC (by 1 M NH_4OAc at pH 7.0) 33.34–56.35cmol(+) kg^{-1} of soil (Table 7) which is ≥ 24cmol(+) kg^{-1} clay and high base saturation, starting within 100 cm from the soil surface; also, Pedons (P2, P7, P10 and P12) had relatively higher clay illuviation features in the subsurface than the surface horizons as a result of Pedogenesis processes (especially clay migration), and the Pedons are found in flat to gently sloping land (1–2°) in warm regions with distinct dry and wet seasons (bimodal rainy season). These Pedons were denominated by brown in color with clay illuviation features, accumulation of secondary carbonates directly below the surface horizon, and vertic properties within 100 cm. Therefore, according to WRB (2006; FAO WRB 2001; World Reference Base, (WRB) for S resources 1998), Pedons (P1, P2, P4, P7, and P11) were classified as *Chernozems* and Pedons (P3, P8, and P8) were classified as *Kastanozems*. The CSB is found in the semi-arid agro-ecology of the country (semiarid climate) with native vegetation of comprised steppe-like in nature with some bunch grass and short shrub and trees. Chernozems and Kastanozems soils are related to the soils in the *mollisols* order of the USDA Soil Taxonomy that form in semiarid regions under relatively sparse grasses and shrubs. Also, Pedons (P10 and P11) which qualify *cambic* horizon, according to WRB (2006; FAO WRB 2001; World Reference Base, (WRB) for S resources 1998), were classified as *cambisols* at sub-group (Table 6; Fig. 4); USDA Soil Taxonomy "Inceptisols/Tropept."

The mapping categories include more than one soil group dominantly Chernozems and Kastanozems (CH) (Table 6). Chernozems (41.67%) is the most dominant soil in this area; the second is Kastanozems (25%), and then Solonchaks (16.67%) and Cambisols (16.67%) in CSB. However, according to Zewdu et al. (2017), the soils in the shore lines of southern and western part of the Lake Chamo are mainly covered by Fluvisols and developed from river and lacustrine deposits.

Transformation from the Fluvisols to Cambisols and/or Calcisols then to Solonchaks was expected when soil conditions preserve permanent and/or seasonal saturation with water and when soil formation sets in; for example, on flood plain areas, continuous saturation may inhibit horizon formation where material deposition faster than a soil profile can develop (Norman 1995); as a result, cambic or vertic subsurface horizon will quickly form from the stratified layers of the original deposits (WRB 2006; FAO WRB 2001). Also, the intensive human use of natural vegetation for the past four decades has probably resulted in faster depositions and decomposition that may give rapid transformation process and development of cambic subsurface horizons. Most alluvial sediments contain CaCO3, and the exchange complex saturated with bases (WRB 2006; FAO WRB 2001). The reasons for the absence of clear genetic horizons in Pedons could be due to younger age of the deposition and regular addition of alluvial materials from the surrounding upland mountains/escarpment of rift valley. Aridisols and mollisols are well-drained inceptisols of volcarnic origin; they had little horizon differentiation, are generally fertile, have excellent physicochemical properties, and have a high P-sorption capacity; as a result, they are also excellent agriculture as well as forest soils.

Soil organic matter (SOM) content of the soils is low for subsurface horizons and medium to high for surface horizons, which rated as very low (< 1), low (1.0–2.0), medium (2.1–4.2), high (4.3–6.0), and very high (> 6) (ILACO 1981). The distribution pattern of TN with soil depth was similar to that of SOM. The amount of surface SOM in coarse-textured soil Pedons (P1, P3, and P6) was < 1% while in fine-textured soil Pedons (P2, P4, P5, P7, P8, P9, and P12) was > 1%. Also, soils with SOM content of < 0.6% are considered poor in OM content. OC is generally considered to comprise ~ 50% of SOM (Pribyl 2010) while almost 95% of soil total N (STN) is closely associated with SOM (Schulten and Schnitzer 1997). According to the results of fertilizer trials carried out in Ethiopia, the critical SOM values for the common cereals grown are barley and wheat 2.5%, maize 3.0%, and sorghum and teff 2.0%. This indicates that without application of nitrogen-containing fertilizers, no adequate yields would be achieved. Also the low levels of SOM in the soil are partly because of high temperature of the area that increase decomposion. The high

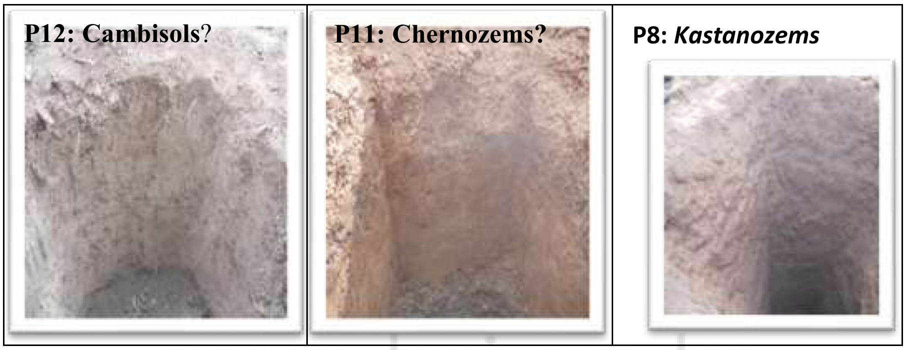

Fig. 4 Chernozems, Kastanozems and Cambisols Pedons

temperature prevailing in the area is responsible for the rapid burning of organic matter, thus resulting in low OC content of the soils. Since SOM content is an indicator of available nitrogen status of soils, thus, the soils of the CSB are also dominantly low to medium category in respect to their available N (Table 8). SOM is a complex mix of chemical compounds that undergo decomposition, mediated by microbes, at different rates depending on the amount of physical and chemical stabilization afforded by the soil mineral matrix and the inherent chemical recalcitrance of the organic material (Krull et al. 2003).

Generally, land use systems such as forest (NF) and perennial crops (AP) systems had better SOC stock and CO_2e reduction as compared to agricultural system dominated by annual crops (AA) in irrigated soils, whereas in rainfed soils, NF and AA systems had better SOC stock and CO_2e reduction as compared to AP system (Table 7). The SOC stock and CO_2e reduction associated with the AA management appeared to be more sensitive to changes in land use and management compared with that in AP management in irrigated soils. Nutrient concentrations for most of soil properties showed NF > AP > AA systems in irrigated soils, whereas in rainfed soils NF > AA > AP. AP system improves soil productivity provided that nutrients are not removed from the system, because of long fallow period and reestablishment of deep-rooted perennial plants. For example, bananas return substantial quantities of OM (P2, P4, and P9) to the soil and protect soil against erosion as compared to moringa-based agroforestry system (P10) of rainfed soil. Generally, the SOC pool tends to be lower in agricultural soils in comparison to natural ecosystems because of lower inputs of biomass, higher decomposition rates, changes in the soil moisture and temperature regimes, and soil erosion and leaching (Lal 2007). Land use and management have confounding effects on the relationship between climate and SOC. In agricultural soils, the effect of climate is not as significant as it is in soils under natural vegetation, because management may modify the soil's moisture and temperature characteristics.

TN content of the soils ranged from 0.06 in the subsurface horizon of the toe Pedon to 0.52% of the upper Pedon (P12). According to Hurni (1999), the TN content of soils is categorized as < 0.15 as low, 0.15–0.25 as medium, and > 0.25 as high. Accordingly, the TN content of the soils is categorized under the low to medium category. The amount of TN in the surface soils ranged between 0.02% in Pedon (P12) and 0.37% in Pedon (P7). The difference in OC and TN content among the Pedons could be attributed to the effect of variation in land use systems along the landscapes. Intensive and continuous cultivation aggravated OC oxidation, which resulted in reduction of total N as compared to virgin land. The results are in accordance with the findings of Negassa and Gebrekidan (2003) and Tuma (2007) who reported that intensive and continuous cultivation forced oxidation of OC and thus resulted in reduction of TN. Positive and strong correlation ($r = 0.93^{***}$) was found between OC and TN indicating the strong association of OC and TN in the study area (Table 13).

The C to N ratio of surface soils ranged from 7.60 to 15.59 suggesting that the study area has a moderate to good quality SOM (Table 8, (Pribyl 2010)). It is generally accepted that C to N ratios between 8 and 12 (58.33% of the sites) are considered to be the most favorable, implying a relatively fast mineralization of nitrogen from the organic materials. Generally, the observed C to N ratio status in all sites surveyed in this study suggests ideal conditions for plant growth since in such situations mineralization in the soil is greater than immobilization, since there was no higher C to N ratios greater than 23 (Goma 2003).

The AP content of the soils decreased down the profiles. The AP content of the surface soils (0–20 cm) is relatively low to very high, and it ranged from 39.28 to 251.34 mg/kg with a mean value of 101.94 mg/kg (Table 8), which is in a very high range. Higher AP values in surface horizon as compared to subsurface horizons could be attributed to the difference in SOM contents and difference in land use management. In most cases, higher P_2O_5 levels in this study were associated with higher levels of SOM and neutral to mildly alkaline pH. This is associated with the annual crop management appeared to be more sensitive to changes in land use and management compared with that in forest and perennial crop management. The highest AP level in the study area is likely because of flooding in the alluvial plain and the immobile nature of phosphate ions in soils which must have resulted in accumulation of P in soils. In most soils, there is an increase in AP after flooding, due to increased solubility of Ca phosphate in calcareous soils, and greater diffusion (Havlin et al. 1999).

The highest concentration of P_2O_5 was recorded in the forest land, whereas the lowest was found under the annual cropland. The highest concentration of AP under the forest land is attributed to accumulation of SOM due to little soil disturbance as compared to the cultivated lands. The high and positive correlation ($r = 0.91^{**}$) obtained between TN, OC, and P_2O_5 indicates that SOM highly contributes to P_2O_5 of soils. Based on the above results, it is not compulsory to apply P_2O_5-containing fertilizers in all the land use systems studied. The very high and positive correlation ($r = 0.93^{**}$) obtained between OC and AP also indicates SOM highly contributes to AP of soils (Fig. 3). According to Havlin et al. (1999), the available P contents of the soils rated (Olsen P) < 3 mg/kg as very low, 4–7 mg/kg as low, 8–11 mg/kg as medium, and > 12 mg/kg as high, which is high (Table 7) for all Pedons. The high amounts of crop residues often associated with banana farming could also have contributed to the high levels of P. In West Africa, Buerkert et al. (2000) also found an increased P availability due to the use of crop residues.

The K_2O content of soils of upper, middle, lower, and toe landscape Pedons is medium and that of Pedons in lower (P8 and P9) and toe landscapes (P11) is high (Table 9). In the higher content of K_2O in Pedons (P7 and P12) particularly, subsurface horizons is attributed to the prevalence of illite—a K-rich mineral in these soils. Also, the very high CEC values (ranged from 28.94 to 56.35 cmol(+) kg^{-1}) in the surface and subsurface soils generally indicate the presence of illite (micas) clay minerals in the soils. Cultivation has been found to aggravate the situation to the extent that it causes a significant reduction of the exchangeable Ca^{2+} and Mg^{2+} compared to the adjoining uncultivated weathered Indian soils (Saikh et al. 1998). The positive and very high correlation ($r = 0.96^{***}$) obtained between exchangeable K and K2O (Table 13) indicates exchangeable K highly contributes to K2O content of soils. The negative correlation ($r = -0.07$) obtained between clay and K2O indicates that K2O availability is affected by clay contents, the intensity of potassium-rich clay minerals (e.g., illite, micas, and feldspars) decomposition in these soils. The negative and significant correlation ($r = -0.57^{*}$) obtained between exchangeable Ca and K2O (Table 13) indicates that exchangeable Ca has antagonistic effect on K2O availability in the studied soils. Basic elements like K were removed from the soil with intensive harvest of moringa leaves. Clay was negatively ($r = -0.08$) correlated with exchangeable K (Table 13), indicating that the negative association of clay with the exchangeable K^+ in the studied soils.

In general, the K content of a given soil depends on the climatic condition and degree of soil development, the intensity of cultivation, and the parent materials from which the soil is formed and particle size distribution. For instance, soils formed from sedimentary materials are generally low in K content, while soils formed from crystalline rocks contain relatively high K (Buol et al. 2003). Vegetation restoration increases the accumulation of soil K because the nutrient-rich branches and coarse litter fraction are all important nutrient sources. The loss of K from litter was relatively rapid at the initial decomposition stage (Gong et al. 2006).

Accordingly, the exchangeable K, Ca, and Mg contents of the soils are above the critical values, because of low leaching in dry region soils. As a result, it does not prove a balanced proportion of the exchangeable bases. Antagonistic effects are known to exist, for example, between Na and K, between Na and Ca, and between Mg and K (FAO WRB 2001). In higher concentrations, the salts may be directly toxic to plants. Potassium uptake would be reduced as Ca and Mg are increased; conversely, uptake of these two cations would be reduced as the available supply of K is increased (Havlin et al. 1999). In addition, the ratio of exchangeable Ca/Mg should not exceed 10/1–15/1 to prevent Mg deficiency, and also, the recommended K/Mg are < 5/1 for field crops, 3/1 for vegetables and sugar beets, and 2/1 for fruit and greenhouse crops (Havlin et al. 1999). The Ca/Mg ratio of the studied soils was in the range of 2–9 indicating that the response of crops to Mg is not likely. The K/Mg ratio of the studied soils varied from 0.2 to 1.2, and hence, it is within the acceptable range for crop production. Cultivation has been found to aggravate the situation to the extent that it causes a significant reduction of the exchangeable Ca^{2+} and Mg^{2+} compared to uncultivated weathered soils (Saikh et al. 1998).

The base saturation percentage generally increases with soil depth, and the values range between 63.68 and 99.10%. The studied soils are highly base saturated. However (63.68–99.10), this does not prove a balanced proportion of the exchangeable bases. Thus, the basic cation saturation ratio and the relative proportions of the cations in the surface horizons were examined to evaluate the nutrient availability status of the soils (Table 11). The basic cation saturation ratios in the surface horizons and composite soil samples (0–20 cm) indicate that the absolute amount of the exchangeable cations is adequate, as reviewed by Jim (1998). The ratio of Ca to Mg indicates the presence of proportionate amounts of the two cations and implies the absence of disruption in the nutrition of both cations, and it is widely believed that the structure of Ca-dominated soils remains stable even when the salts are flushed out of the soil. However, the ratio of (Ca+Mg) to K indicates that the relative proportion of K to (Ca+Mg) is low and this could likely inhibit Ca and Mg availability. Also, the available potassium (K_2O) content of the surface soils (0–20 cm) is low to very high that it is widely varied along the landscape and land uses from 132.74 to 546.59 mg/kg with a mean value of 269.11mg/kg, which is in a very high range.

The Ca to Mg ratios ranged from 2.05 to 8.73, Mg to K ratio from 1.2–25.5, and K to TEB ratio from 0.01–0.04 (Table 11). According to the established guidelines, the recommended optimum ratio of Mg to K for most crops is 1–4 (NSS 1990). These results indicate that almost all sites have optimal K enrichment sufficient to support plant growth. In relation to Ca to Mg ratio, our data suggests proportional for most crops. The availability of mineral elements for uptake by plants depends not only upon absolute levels but also on relative amounts of individual elements. It has been suggested that the optimal cation ratio for the growth of most crops in the tropical area is assumed to be equal to 12.7:3:1 for Ca:Mg:K, respectively (NSS 1990). Although the general trend for Ca:Mg:K does not indicate a good ratio in relation to the established standards, the individual nutrient ratios are more important, i.e., Ca:Mg; Mg:K and K:TEB. Research has indicated that the Ca to Mg ratio of 3–5 in the topsoil (NSS 1990) is optimal for most crops and the K to TEB ratio of less than 2% is sub-optimal and may limit crop production. Our results have indicated Ca to Mg ratios to be less than the suggested guidelines and plants would probably respond to the addition of Ca which was deficient in most sites (Table 11).

According to critical values of available micronutrients set by Havlin et al. (1999) (Table 12), the amounts of Fe and Mn throughout the soil profile exist as high for crop production as compared to the amounts of Cu and Zn in the surface soils which may not be deficient for crop production. This is in agreement with various works which stated that Cu is most likely marginal, Zn contents are variable, and Fe and Mn contents are usually at an adequate level in Ethiopian soils (Tuma 2007; Esayas 2005; Beyene 1983; Fisseha 1992). The micro-nutrient content of soils is influenced by several factors among which SOM content, soil reaction, and clay content are the major ones (Fisseha 1992).

The available DTPA Cu contents of the soils widely varied from 0.50 to 1.75 ppm with a mean value of 0.99 ppm. According to critical values of available micronutrients (Fe, Mn, Zn, and Cu) set by Havlin et al. (1999), the amounts of Fe, Mn, Zn, and Cu in the surface soils of study area were not deficient for crop production. Mn in very isolated case, for example, in Sesbania-based Natural Forest, was deficient of any other micronutrients (Table 8). Also, these results are in agreement with various works which stated that Zn contents are variable and Fe and Mn contents are usually at an adequate level in Ethiopian soils (Esayas 2005; Beyene 1983; Fisseha 1992). Fe was negatively correlated ($r = -0.35$) with Mn (Table 13) that Fe availability decreased as Mn increases in the soils. Mn was negatively correlated ($r = -0.22$) with Zn that Mn availability decreased as Zn increases in the soils. As described in Table 3, Cu was positively correlated with Fe, Mn, and Zn. Specifically, Fe was positively and very significantly correlated with Zn ($r = 0.75$). Generally, these results indicated that applications of iron and zinc may reduce manganese availability in the soils.

The solubility and availability of micronutrients is largely influenced by clay content, pH, SOM, CEC, phosphorus level in the soil, and tillage practices (Fisseha 1992). Cu in the soil is adsorbed on clays and oxides that complexed with SOM, thus inducing its retention and immediate unavailability for plant. The authors have demonstrated that organic-enriched surface horizons often contain higher concentration of Cu than the lower horizons. Micronutrients become the major limiting factor in soil pH values of pH 7.4–8.4 (http://anlab.umesci.maine.edu).

Climate change, drainage conditions, and alluvial process were the main agents for soil salinity development. Water logging and soil salinity are the two major problems affecting the agricultural productivity and sometimes become too severe to take it out from economic crop production. Most Pedons had $(Ca^{++}+Mg^{++})/(Na^{+}+K^{+})$ ratios in between 1 and 4, and the Ca^{++}/Mg^{++} ratios are ≥ 1 in soil depths (0–200 cm) but varied for Pedons (P2 and P5). It is widely believed that these soils are dominated by Ca and Mg over Na and K and remained stable structure even when the salts are flushed out of the soils, for example in Pedons (P5 and P6). Therefore, these soils are characterized as *calcium-dominated* saline soils (FAO WRB 2001).Variation of these Pedons (P2 and P5) is probably water logging or presence of groundwater table. As reported by Zewdu et al. (2016), in Sego Irrigation Farm in southern Ethiopia, the coverage of moderately and strongly saline areas has increased at an average annual rate of 4.1 and 5.5%, respectively, from 1984 to 2010. The main sources and/or causes of salinity are shallow groundwater tables and natural saline seeps. Poor drainage and lack of appropriate irrigation water management are also known to facilitate secondary salinization (Abebe et al. 2015).

The most satisfactory method for rating the salt content of groundwater involves measuring electrical conductivity (EC) and total dissolved solids (TDS). Hence, the EC of the ground water in these Pedons (P2-G1, P4-G2, and P5-G3) were 675, 4130, and 26400 μS cm^{-1},

Table 12 DTPA-extractable Fe, Zn, Cu, and Mn for deficient, marginal, and sufficient soils

Category	Fe	Zn	Mn	Cu
	mg/kg soil			
Low (deficient)	0–2.5	0–0.5	< 1	0–0.4
Marginal	2.6–4.5	0.6–1	–	0.4–0.6
High (sufficient)	> 4.5	> 1	> 1	> 0.6
Toxic level				

Source: Harrera, (2005); Havlin et al. (1999)

Table 13 Simple correlation surface soil (0–20 cm) between land use and soil properties

	Fe	Mn	Zn	Cu	Ec	Silt	Clay	Na	K	Ca	Mg	CEC	PBS	TN	OC	AP	AK	CaCO3	PH(H2O)	PH(KCl)	Cations	Anions
Fe	1	− 0.35*	0.75***	0.31*	− 0.07	0.2	− 0.35*	− 0.01	0.28*	− 0.35*	0.1	− 0.07	0.47**	0.51**	0.5**	0.72***	0.12	− 0.07	− 0.26*	− 0.33*	− 0.06	− 0.12
Mn		1	− 0.22*	0.49**	0.06	− 0.48**	0.53**	0.03	0.42**	0.27*	0.08	0.42**	0.04	− 0.03	0.03	− 0.48**	0.48**	− 0.13	0.48**	0.47**	0.38*	0.38
Zn			1	0.52**	0.12	0.02	− 0.12	0.29*	0.42**	− 0.28*	0.21	0.05	0.21*	0.68**	0.69**	0.69**	0.25*	− 0.38*	− 0.1	− 0.12	0.06	0.04
Cu				1	0.1	− 0.18	0.28*	− 0.03	0.74***	− 0.42**	0.2	− 0.12	0.42**	0.21*	0.14	0.08	0.66**	− 0.36*	− 0.08	− 0.13	− 0.02	− 0.05
Ec					1	0.08	− 0.14	0.5	0	0.06	0.78	0.38*	0.06	− 0.17	0.08	0.12	0.07	0.04	0.04	− 0.02	0.6**	0.56
Silt						1	− 0.84***	− 0.29*	0.23	− 0.62**	0.14	− 0.74***	0.29*	− 0.48**	0.47**	− 0.12	0.31*	− 0.15	− 0.17	− 0.27*	− 0.5	− 0.54
Clay							1	0.29*	− 0.08	0.37*	0.35	0.55**	0.3	0.37	0.31*	0	0.15	0.07	0.17	0.2	0.19	0.23
Na								1	− 0.29*	0.49**	− 0.1	0.22*	0.65**	0.44**	0.57**	0.23*	0.34*	− 0.15	0.48**	0.41*	0.47**	0.47
K									1	− 0.59**	0.24*	− 0.23*	0.57**	0.08	0.02	− 0.9***	0.96***	− 0.5	− 0.07	− 0.11	− 0.19	− 0.22
Ca										1	0.15	0.78***	0.71***	0.22*	0.34*	− 0.13	0.57**	0.34*	0.54**	0.62**	0.6**	0.64
Mg											1	0.36*	0.19	0.48**	0.22*	− 0.03	0.11	− 0.49**	0.09	0.08	− 0.47**	− 0.42
CEc												1	0.45**	0.56**	0.53**	0	0.31*	0.11	0.4	0.49**	0.4**	0.45
PBs													1	0.13	0.17	− 0.26*	0.54**	− 0.03	0.66**	0.68**	0.16	0.2
TN														1	0.93***	0.61**	0.14	− 0.31*	0.03	0.04	0.25*	0.27
OC															1	0.7***	0.16	− 0.11	0.16	0.18	0.44**	0.44
AP																1	0.21*	0.19	− 0.24*	− 0.25*	0.18	0.15
AK																	1	− 0.4	0.04	0.01	− 0.16	− 0.21
CaCO3																		1	− 0.02	0,04	0.08	0.07
pH(H2O)																			1	0.97***	0.33*	0.32
pH(KCl)																				1	0.36*	0.35
Cations																					1	0.99
Anions																						1

*, **, *** significant at 0.05, 0.01, and 0.001 or than probability levels, respectively

respectively (Table 3). All the EC values are rated as moderate to very high salinity hazard. TDS of these Pedons (P2-G1, P4-G2, and P5-G3) were 438, 2684, and 17,160 mg/l (105 °C), respectively, which were higher than WHO maximum allowable concentration < 1000 mg/l (EIA 2000). Only P2, P4, and P5 (Table 3) were critically shallower < 150 cm level (EIA 2000), and this permanent submerged underground water < 2 m was characterized as sub-aquatic qualifier. The results of Pedons, which are located in middle landscapes (P4-G2 and P5-G3), are affected by rising groundwater level more than Pedons in upper landscape (P2-G1) and showing increasing trends of rising groundwater table. The groundwater depth during the rainy and main irrigation season was shallower than the dry months and its salinity was low. This was due to the dilution effect of the irrigation. As a result, waterlogging is a common problem in these areas since 25% of the studied Pedons/land units had shallow water table (50 cm depth). These land units are classified into wet and waterlogged since they are found in the river basins and can be temporarily classified as a marsh area unless properly managed. It was observed that poor irrigation water management and operation coupled with the absence of drainage system in the studied area could be the causes of groundwater rise (waterlogging), salinization, and considerable losses in crop yields which ultimately led to abandonment of substantial irrigable areas.

The development of shallow groundwater table usually was the result of one or more of the following conditions: (1) seepage from floods supply and (2) use of excessive water for irrigation. Plants respond to the TDS in soil water, which in turn depends on the TDS in the groundwater and on irrigation practices. Electrical conductivity and other salinity parameters were highly correlated to saline soils (Tables 7 and 14). Salinization is chemical form degradation often the result of a combination of improper irrigation, higher evapotranspiration, and human-induced changes of hydrological regimes. Due to high osmotic potential of the saline soil solution, salinization reduces the amount of water available to plants (Mitiku et al. 2006). Primary salinization occurs naturally where the soil parent material is rich in soluble salts (P5 and P6) or in the presence of a shallow saline groundwater table (P2-G1, P4-G2 and P5-G3). In arid and semiarid regions, where rainfall is insufficient to leach soluble salts from the soil or where drainage is restricted, soils with high concentrations of salts may be formed. Several geochemical processes can also result in salt-affected soil formation (WRB 2006). Secondary salinization occurs when significant amounts of water are provided by irrigation, with no adequate provision of drainage for the leaching and removal of salts, resulting in the soils becoming salty and unproductive. Salt-affected soils reduce both the ability of crops to take up water and the availability of micronutrients. They also concentrate ions toxic to plants and may degrade the soil structure (WRB 2006). This high salinity problem is also related to uncontrolled irrigation practice and lack of knowledge on crop-water requirements and water management leading to increased saline groundwater level or capillary rise.

Notably, the anions are equally important in affecting the growth potential of the plants if they are in the order of importance $HCO_3^- + CO_3^{2-} > SO_4^{2-} > Cl^-$ (FAO 2001). As is shown in Table 7, though all the anions are not in safe range except Pedon (P12), the anionic composition of the soils of the study areas is in the order of $HCO3^- + CO_3^{2-} > Cl^{--} > SO_4^2$ except for Pedons (P4, P5, P6, and P7), which is in order of $SO_4^{2-} > HCO_3^- + CO_3^{2-} > Cl^-$; this indicates there is a nutritional imbalance in the soils.

The productivity of severely eroded soil was restored in the first year of fertilizer or manure application. The amount and timing of precipitation varied from year to year. Erosion had a greater effect on yields in the drier years. The whitish surface crusts of salt precipitates, also called "white alkali" were also observed on the surfaces of land uses during dry seasons.

The CSB is a lake basin and is a home of large number of human population engaged in various activities, which are directly or indirectly related to the wellbeing of the lake ecosystem in general, and the agriculture in particular on which the livelihood of the community mainly depends. Demographic, economic, and socio-political changes threaten the existence and long-term sustainability of the common pool resource of Lake Chamo. The increase in population, high demand of fish products, lack of livelihood diversification strategies, and high unemployment rate have put serious stress on the common pool agricultural resource of CSB. Lake Chamo has an average surface area of 350km^2; however, due to different reasons, the surface area of Lake Chamo has shown significant decline since 1960s. An empirical study conducted by Ababu (2006) has shown that the surface area of Lake Chamo is about 328.63km^2.

There has been some deforestation caused by the establishment of the scheme due to continuous use of wood for fuel consumption. However, the shift in cropping pattern from cotton to perennial crops like banana in the state farm and surrounding banana cultivation by smallholder farmers makes the area evergreen and significantly reduces soil erosion that may create siltation problems in the nearby Lake Chamo. On the other hand, rainfed agricultural practices as shown in Fig. 5 during rainy seasons can form gullies and environmental degradation comes worse. These deep soils are relatively unlikely to experience flow

Table 14 Soluble salts (cations and anions) of the CSB soils

Pedon	Depth (cm)	Na (Meq/l)	K	Ca	Mg	Sum	CO^{3-}	HCO_3^-	Cl^-	SO_4^{2-}	NO^{3-}	Sum
Kulfo Watershed = Upper Chamo Basin (UCB)												
P-1	0–34	0.57	0.03	0.80	0.20	1.60	Trace	0.44	0.84	0.09	0.12	1.49
	34–200	0.55	0.00	0.60	0.40	1.55	Trace	0.66	0.56	0.30	0.01	1.53
P-2	0–90	0.67	0.14	0.80	0.40	2.00	Trace	0.88	0.84	0.29	0.04	2.05
	90–97	–	–	–	–	–	–	–	–	–	–	–
	97–200	4.57	0.03	0.40	0.80	5.79	0.44	0.66	0.14	4.42	0.11	5.77
P-3	0–80	0.50	0.04	1.20	0.80	2.54	Trace	0.44	1.68	0.17	0.02	2.31
	80–85	–	–	–	–	–	–	–	–	–	–	–
	85–200	0.61	0.02	0.80	0.40	1.83	Trace	0.22	0.14	1.40	0.02	1.78
Sille-Sego Watershed = Middle Chamo Basin (MCB)												
P-4	0–35	0.56	0.32	0.60	0.20	1.67	Trace	0.44	0.14	0.86	0.23	1.67
	35–200	0.90	0.01	1.00	0.40	2.31	Trace	0.22	0.14	1.78	0.02	2.16
P-5	0–40	1.08	2.36	0.80	0.40	4.64	Trace	0.22	0.28	3.79	0.03	4.32
	40–200	0.98	0.99	1.80	0.60	4.37	Trace	0.22	0.28	3.80	0.15	4.44
P-6	0–50	0.96	0.05	2.00	1.60	4.61	Trace	0.44	0.28	3.85	0.10	4.65
	50–58	–	–	–	–	–	–	–	–	–	–	–
	58–200	0.64	0.03	4.20	2.00	6.87	Trace	0.44	0.28	5.79	0.18	6.69
Waseca-Doyso Watershed = Lower Chamo Basin (LCB)												
P-7	0–46	0.48	0.14	1.40	0.60	2.61	Trace	0.66	0.28	1.53	0.09	2.56
	46–140	0.30	0.08	1.00	0.60	1.98	Trace	0.44	0.28	1.25	0.08	2.05
P-8	0–30	0.46	0.15	0.80	0.60	2.01	Trace	1.10	0.56	0.02	0.15	1.84
	30–120	0.53	0.07	1.00	0.20	1.80	Trace	1.10	0.14	0.51	0.03	1.77
	120–200	1.03	0.10	1.20	0.60	2.93	Trace	2.20	0.14	0.41	0.02	2.77
P-9	0–50	0.31	0.07	1.20	0.40	1.98	Trace	1.32	0.14	0.36	0.05	1.87
	50–54	–	–	–	–	–	–	–	–	–	–	–
	54–200	0.40	0.01	0.80	0.60	1.80	Trace	1.10	0.14	0.35	0.05	1.63
Arguba-Wezeka Watershed = Toe Chamo Basin (TCB)												
P-10	0–30	0.91	0.11	1.40	1.20	3.63	Trace	2.20	0.84	0.28	0.10	2.98
	30–80	2.65	0.01	1.20	0.80	4.66	1.76	1.76	1.12	0.25	0.05	3.41
	80–200	2.57	0.04	1.20	1.40	5.20	1.32	2.20	1.68	0.37	0.06	4.93
P-11	0–46	0.49	0.05	0.60	0.40	1.55	Trace	0.88	0.14	0.45	0.07	1.54
	46–115	0.44	0.04	0.80	0.40	1.68	Trace	1.10	0.14	0.44	0.02	1.74
	115–200	0.70	0.07	1.00	0.80	2.57	Trace	1.54	0.42	0.36	0.02	2.34
P-12	0–17	0.74	0.87	1.40	0.40	3.42	Trace	1.10	0.14	0.70	1.23	3.17
	17–70	0.36	1.26	3.20	0.80	5.66	Trace	1.10	0.14	1.65	2.46	5.35
	70–200	1.76	0.06	3.40	0.80	6.02	Trace	1.32	0.28	0.96	3.33	5.88

gradients that will significantly contribute towards gully and tunnel erosion susceptibility. Soil erosion is the detachment and movement of soil particles by the erosive forces of water (Fig. 5).

According to Charman and Murphy (Murphy 1991), the land degradation analysis based on OC% is in the range of low > 3, moderate 1.5–3, and high < 1.5. Therefore, OC% content of surface soils (0–20 cm) was moderate to high that it is widely varied along the landscape and land uses from 0.74 to 2.41% with a mean value of 1.72%, which is in a moderately degraded land range. Biological degradation is related to the depletion of vegetation cover and organic matter content in the soils; this in turn denotes a reduction in beneficial soil

Fig. 5 Typical degraded land (burning and guly erosion) in the CSB

organisms and soil fauna. Biological degradation is the direct result of inappropriate soil management (Fig. 5). Soil organisms and SOM content can influence the physical structure of the soils, especially with regard to transportation within the soils, mixing mineral and organic materials, and changes in soil micropore volume (Doran and Parkin 1994). On-site soil degradation leads to declining soil productivity, which primarily threatens the livelihood of rural land users. Off-site impacts of soil degradation, such as flash floods, sedimentation of water reservoirs, water quality decline, mobile dunes, or dust storms, were affected society as a whole (Fig. 5). Physical degradation basically includes a negative impact on physical soil properties, such as structure, texture, aggregate stability, porosity, permeability (compaction), and crusting. According to Mitiku et al. (2006), in Ethiopia, the main causes for soil degradation are agricultural mismanagement (56%) and deforestation (28%). The most important causes of erosion by water are deforestation (43%), overgrazing (29%), and agricultural mismanagement (28%).

Conclusion

The soils of the study area are developed from similar parent material group namely ignimbrite. Topography had influence on the characteristics of the soils in the studied site. The soils are generally dark reddish brown to very dark brown and very deep (> 150 cm). There is discernable difference in amount and distribution of clay content with depth along the toposequence. The overall friable consistency, low bulk density (1.00–1. 26 g/cm^3), sub-angular to angular blocky structure, and high total porosity (53–61%) indicate that the soils have good physical condition for plant growth. The soils are moderately to slightly acidic with pH values between 5.8 and 6.4. Surface soils in the upper and middle Pedons have lower pH than subsurface soils.

Seemingly, salinity is building up gradually and deposits in the soils with this trend and pace will cause phytotoxicity and eventually will impair plant growth. The principal quality of saline soils injurious to plants is the high osmotic pressure of the soil solution, which reduces the availability of water. Presumably, reclamation of the areas should begin now considering range of options starting from leaching to crop selection. Crop selection can be a good management tool for these soils. Where satisfactory drainage can be economically established, leaching readily removes salt.

However, the toe slope Pedons have uniform pH distribution with depth. In general, OC content, micronutrient cations, and CEC of the soils decreased with soil depth. However, exchangeable cations (except K) in the middle lower and toe slope Pedons increased with increasing soils depth. P2O5 content of the soils ranged from very low to high. Low available P content of the soils could be due to high P retention, whereas high available P content of the soils could be due to application of P-containing fertilizers. Available Fe, Zn, and Mn contents of the soils may not be deficient for crop production. Available Cu content of the soils (except in the upper Pedon) is marginal to deficient. Macromorphological observations have shown that clay translocation and accumulation has taken place in the soils. In the upper and middle Pedons, there was a marked increase in clay content with depth and common to many distinct clay coatings were observed. Hence, in those Pedons, the clay increase requirement of argic horizon was met.

Additional file

Additional file 1: Different LUTs/Sample sites across Landscape Poster in the CSB, 2012. (PDF 119 kb)

Abbreviations

AA: Annual crops; AAS: Atomic absorption spectrophotometer; ACB: Abaya-Chamo Basin; AP: Available phosphorous; C: Carbon; Ca: Calcium; $CaCO_3$: Calcium carbonate; CBS: Chamo Basin; CEC: Cation exchange capacity; Cl^-: Chloride; cmol(+) kg^{-1}: Centimol per kilogram; CO_2: Carbon dioxide; CO_3^{2-}: Carbonates; Cu: Copper; DEM: Digital elevation model; DTPA: Diethylene-triamine-pentaacetic acid; EC: Electric conductivity; ESP: Exchangeable sodium percentage; FAO: Food and Agriculture Organization; Fe: Iron; HCl: Hydrochloric acid; HCO_3^-: Bicarbonate; IIASA: International Institute for Applied Systems Analysis; ISRIC: Soil information service; ISS-CAS: Institute of Soil Science Chinese Academy of Sciences; ISUEP: Iowa State University Extension Publication; IUSS: International Union of Soil Sciences; JRC: Joint Research Centre; K: Potassium; K_2O: Potassium peroxide; LCB: Lower Chamo basin; LGP: Length of growing period; MCB: Middle Chamo basin; Mg: Magnesium; Mn: Manganese; MOA: Ministry of Agriculture; Mt.: Metric ton; N: Nitrogen;

Na: Sodium; NaCl: Sodium chloride; NF: Natural forest; NO_3^-: Nitrate; OC: Organic carbon; OM: Organic matter; OP: Osmotic pressure; P: Phosphorous; P_2O_5: Phosphorus pentaoxide; PA: Perennial crops; PBS: Percent base saturation; PBS: Percentage base saturation; p^H: Power of hydrogen; S: Sulphur; SAR: Sodium adsorption ratio; SO_4^{2-}: Sulfate; SOM: Soil organic matter; SWC: Soil and water conservation; TCB: Toe Chamo basin; TDS: Total dissolved solid; TEB: Total exchangeable base; TN: Total nitrogen; UCB: Upper Chamo basin; UNESCO: United Nations Educational, Scientific and Cultural Organization; USDA: United States Department of Agriculture; WRB: World Reference Book; Zn: Zinc

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Authors' contributions
TA contributed to the design of this study. TA and DA collected the data. TA, DA, and MA assist in analyzing and interpreting the data. TA and DA drafted the manuscript for important intellectual content. All the authors reviewed and revised the draft further and approved the final version for submission. All authors read and approved the final manuscript.

Ethics approval and consent to participate
The study was conducted after getting approval from Arba minch University institutional research Directorate office and peer reviewed in the department. Written permission was obtained from Agricultural office and administrative leaders of respective districts. The verbal (non-written) consent was obtained. To maintain confidentiality, each and every one collected data were coded and locked in a separate paper bag to submit sample to laboratory to analysis. Following data entry into the computer all data were protected by password.

Consent for publication
Not applicable.

Competing interests
The authors declare that they have no competing interests.

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