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Effects of land use types on the depth distribution of selected soil properties in two contrasting agro-climatic zones

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ABSTRACT

The depth distribution of soil properties are governed by several interacting factors including land use types (LUT) and agro-climate (AgC) factors. Yet, there is little information on the effects of LUT, AgC and their combination on soil properties along depth, which this study aimed to investigate. We collected a total of 36 composite soil samples using the manual percussion of a steel core tube layer by layer vertically up to 30 cm in sites representing both highland and lowlands, and analyzed for selected soil properties. A significant main effects of LUT on the depth distribution of bulk density (BD), Ca, Na, K and Cu, and AgC on soil texture, pH, EC, Ca, Na, K, P, Mn, Fe and Cu were noted. The two-way ANOVA analysis also revealed the significant effects of both LUT and AgC on the depth distribution of BD, Na, K, Cu and EC, reflecting their influences on the paths associated to bio-geo-recycling processes. Compared to crop and forestlands, the average SOC and Fe were lower while EC, CEC, Ca, Na, K, P, Mn and Zn were higher in homegarden located in highland than lowland, possibly the acid nature of the highland soil may make the extractable cations available. SOC was not significantly influenced by AgC, LUT and their interaction effect. Based on the Elemental Enrichment Ratio (EER), the SOC was concentrated in the upper surface soil in forest and cropland located both in highland (1.79, 1.33) and lowland (1.80, 1.57), respectively. The reverse propagation pattern SOC depth distribution in soils under homegarden with EER of 0.7 (highland) ad 0.8 (lowland) showed that implementing such system can accelerate carbon sinking and safely store it in subsoil. Also, diversified species composition associated with respective root architectures in the homegarden system, make it an efficient soil nutrient management, which should be widely promoted.

1. Introduction

Ethiopia is characterized with changing topographical features within short distance interval. This leads the country possesses places of different ecological settings with their own unique physiographic characteristics [1]. Hence, the land use system in the given spots of the country is the resultant effects of agro-climatic, physio-topographic, socio-cultural and economical factors. Forest land,

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cropland and the mixture of the two, commonly called agroforestry land use systems, are the most common practices globally [2] as well as in Ethiopia for various reasons including food, fuel and construction woods, local medicine, generate income, reduce soil erosion, ritual reason are few to mention. In Ethiopia specially in southern part including Sidama region, agroforestry land use systems are the most common and widely practiced system dominated by the indigenous homegarden agroforestry type. In this context, homegardens are usually diverse in plants and their spatial arrangements, which often imitate the natural forest in terms of structure and composition, make the system unique land use type [3,4].

Under any land use types, soil, which usually considered to have physical, chemical and biological properties, is an essential natural resources and important assessment indicator of land quality status [5]. Examining the soil vertical profile provides information related to the distribution of different soil properties including nutrient inputs, outputs and their recycling process, which in turn help to retrieve information related to climate, topographic and vegetation types. Changes associated to land uses generally contributed approximately 20% of greenhouse gases emission [6], where soil organic carbon (SOC) is the most susceptible portion due to its vicinity to the surface. Hence, land use types (forest, crop, agroforestry, etc) coupled with agro-climate regimes (semi-arid, warm tropics, temperate, cool sub-humid, moist-cold, etc) can dictate the dynamics of the input and outputs of carbon and other chemical elements in the soil of a particular site. However, the effects of such factors on the depth distribution of soil properties, which is an important biogeochemical segment of the farming management system, is yet scarce.

In fact, researchers have attempted to study the depth distribution of different soil properties under different land use types [1–15]. For example, Mengistu et al. [16] have reported that as the depth increases the overall mean of pH, organic carbon (OC) %, organic matter (OM) % and available P decreases in soils under *Eucalyptus* and crop land uses. However, their results are crude and failed to clearly show the soil properties spectrum along the depth. Also studies attempted to assess the carbon stock in agroforestry systems in the tropics including southern part of Ethiopia like Gedo Zone [17,18], scientific data related to the vertical distribution of soil properties under specific agro-climate and land use types is still lacking. Besides, land use types including agroforestry systems are site-specific, and additional investigation under different settings is essential before recommendations went out for wider policy applications. Therefore, this study hypothesized that the vertical distribution of selected soil physicochemical properties among homegarden, crop and forest LUTs located in two contrasting AgC locations in Sidama region, southern Ethiopia are similar.

2. Materials and methods

2.1. Description of the study area

The study was conducted in two different districts representing contrasting AgC zones in Sidama region, Ethiopia (Fig. 1). Bilate Zuria (BZ) district is located geographically at 6° 53′N and 38° 15′ E with altitude of 1710 m above sea level, which represents the lowland warm semi-arid agro-climatic zone (locally called Kola). The second study area was Hula district, which is situated at 6° 27′N and 38° 34′ E with altitude of 2745 m above sea level and 366 km away to the south of Addis Ababa, and representing highland of cool

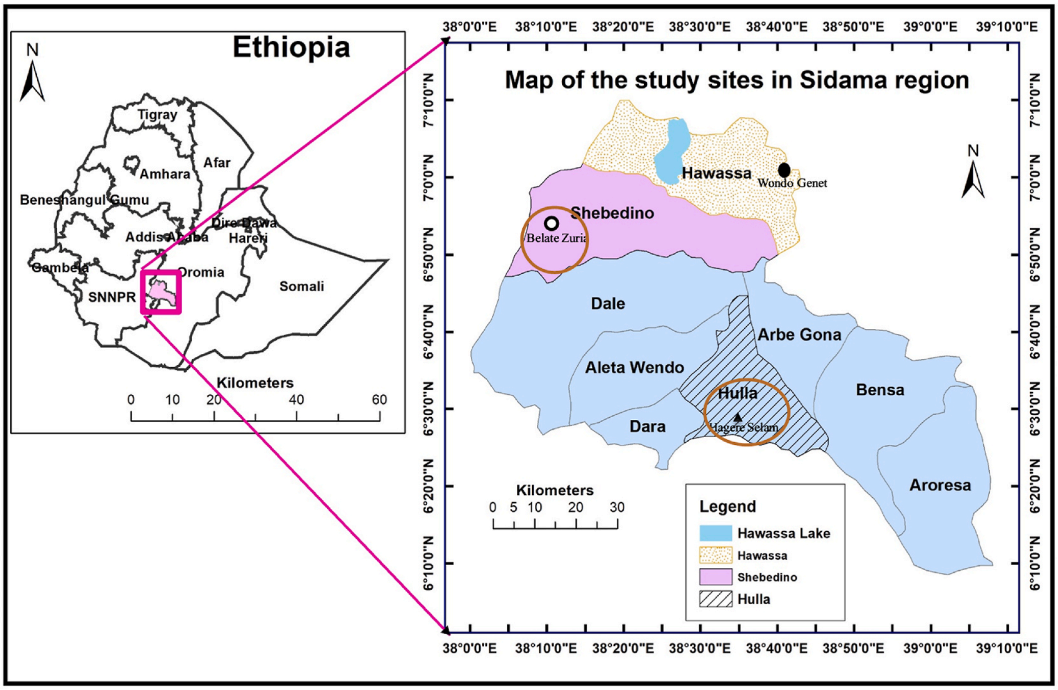

Fig. 1. Map of the sampling sites (indicated in orange circle) located in the Sidama region in Southern part of Ethiopia.

and humid AgC zone (locally called as Dega). Based on the soil map obtained from Sidama Zone Planning and Economic Development Department (SZPEDD), and World Reference Base for Soil Resources (WRB), the soil type in both sites are dominated by Nitosol derived from the Magdala parent material group.

Given the skyrocketing laboratory costs, a well-representative of crop land, forest land and indigenous homegarden were carefully identified and selected in each district for soil sampling. The biophysical characteristics of each selected land use type are detailed in Table 1. Briefly, in BZ district, the arable land was mostly covered with mono-crops including maize, haricot bean, potato and sweat potato while in Hula district beans, peas, barley and wheat are commonly grown depending on market and household consumption demands. The forestlands are composed of purposely retained or planted species including *Croton macrostachyus* and *Dodonaea viscosa* in BZ and highland bamboo, *Eucalyptus globules, Hegenia* spp. and *Erythrina* spp. in Hula district (Table 1). The selected indigenous homegarden at both sites are composed of diverse species of plants with different temporal and spatial arrangements. The upper story of the homegarden consists tree species; the middle layer dominates by fruit trees and other cash crops while the understory consists of herbaceous crops of different species per the district agro-climatic nature (see the detail in Table 1).

2.2. *Soil sampling and analysis*

At each LUT, a 10 m × 10 m quadrat was deployed at the center of the sampling site to avoid any possible edge effects and a pit was opened at each four corners. Then, soil samples were collected by manually hammering of a steel core tube (with internal diameter of 5 cm and length of 5 cm, 9.83 cm^3) layer by layer vertically up to 30 cm for the six depth intervals (0–5 cm, 5–10 cm, 10–15 cm, 15–20 cm, 20–25 cm and 25–30 cm). The sampling points were purposely selected based on the similarity in land uses and at the flat area of the corners of the quadrat to avoid any slope effect associated morphological differences on the typological soil horizons. Per each sampling site, the soil samples were collected with four replications and then merged together at each respective depth section to well represent the spatial variation [7], which made the final number of thirty six composite soil samples. The maximum depth, 30 cm, was selected as it contains the most biophysical active soil section with slightly additional depth of that of the agriculturally plough layer, and it has been previously used to fully describe the depth distribution of major physicochemical properties of soils at wide-range locations [19–21]. The soil samples were then bagged in polyethene bags, labeled and safely transported to the laboratory for analysis.

In laboratory, unwanted materials like roots, stones, visible plant parts etc. were removed by hand pick from the samples. Then, all the samples were dried to constant weight (at 60–70 °C), gently disaggregated, passed through a 2-mm sieve and then well mixed thoroughly to ensure homogenous sample material for each respective sampling depth and site. Then, different physicochemical properties of the soil at each depth, site and land use types were analyzed based on the respective standard procedures as follow. The physical properties of soil including particle size distribution (texture) with hydrometer method [22] and soil bulk density on dry bases were analyzed. Also, the chemical properties of the soil such as pH $^{(H2O)}$ with pH-meter of glass electrode [23], cation exchanging capacity (CEC) was measured by extraction method using 1 N ammonium acetate (NH_4OAc) as cation exchanger as well as soil nutrients (macro and micro nutrients) were measured Mehlich III extractant and DTPA Sorbital extraction method [24]. The SOC content was determined by wet oxidation method of using the Walkley-Black [25] and applying a correction factor of 1.33 to account for the incomplete oxidation of organic carbon [18].

Enrichment ratio often used in the studies related to the selectiveness of soil erosion processes, and often referred as the ratio of the concentration or amount of the soil constitute in the eroded material to its concentration or amount in the topsoil of the original [26–30]. Depending on the magnitude of the ratio, it can help to infer the direction of the input sources of a specific soil element by redefining to fit to our context. Hence, to clearly visualize the elemental location in our studied soils in the given time-point and space, we adapted and employed the Elemental Enrichment Ratio (EER) of the surface soil (0–15 cm) to that of subsurface soil (15–30 cm) calculated by using quantity sum (mass depth, kg m^{-2}) of the specific element per section as indicated in the following formula:

Table 1
Biophysical characteristics of the study sites.

Characteristics	Bilate Zuria (BZ)	Hula
Altitude (m a.s.l)	1710	2745
Annual rainfall (mm)	800–1000	800–1200
Annual temperature (°C)	25–28	12–22
Major trees/fruit – Homegarden – Forest land	*Albizia* sp., *Cordia africana* Lam., *Croton macrostachyus* Hochst. ex Delile, *Dodonaea viscosa* Jacq., *Ficus* sp., *Persea americana* Mill., *Casimiroa edulis* Llave & Lex Chat (*Catha edulis* (Vahl) Forssk. Ex Endl), *Ricinus* spp. (Castor bean) Coffee (*Coffea arabica* L.),	*Millettia ferruginea* (Hochst.) Bak. Apple (*Malus domestica* Borkh), *Coffea arabica*, *Persea americana*, *Hegenia* spp. , *Erythrina* spp., *Cordia africana,* Bamboo (*Yushania alpina* (K.Schum.) W.C.Lin.)
Major food crops - Homegarden - Crop land	Enset *(Enset ventricosum* (Welw.) Cheesman), Maize, Haricot bean, Potato, Sweat potato (*Ipomoea batatas* (L.) Lam)	Enset *(Enset ventricosum),* Sweet potato, Potato, Tomato, Cabbage (*Brassica oleracea* L), Maize, Haricot bean, Beans, Peas, Barley, Wheat

$$\text{EER} = \frac{\textit{chemical amount in surface soil } (0 - 15\ cm)\ \left(\frac{kg}{m2}\right)}{\textit{chemical amount in subsurface soil } (15 - 30\ cm)\left(\frac{kg}{m2}\right)}$$

where EER: Elemental Enrichment Ratio (unitless), which is sensitive the mass of soil (<2.00 mm particles & elemental concentration). The EER values were evaluated if.

- ➢ EER = 1, the element has nearly a uniform distribution between surface and subsurface soil
- ➢ EER > 1, the element is tended to concentrate on surface soil

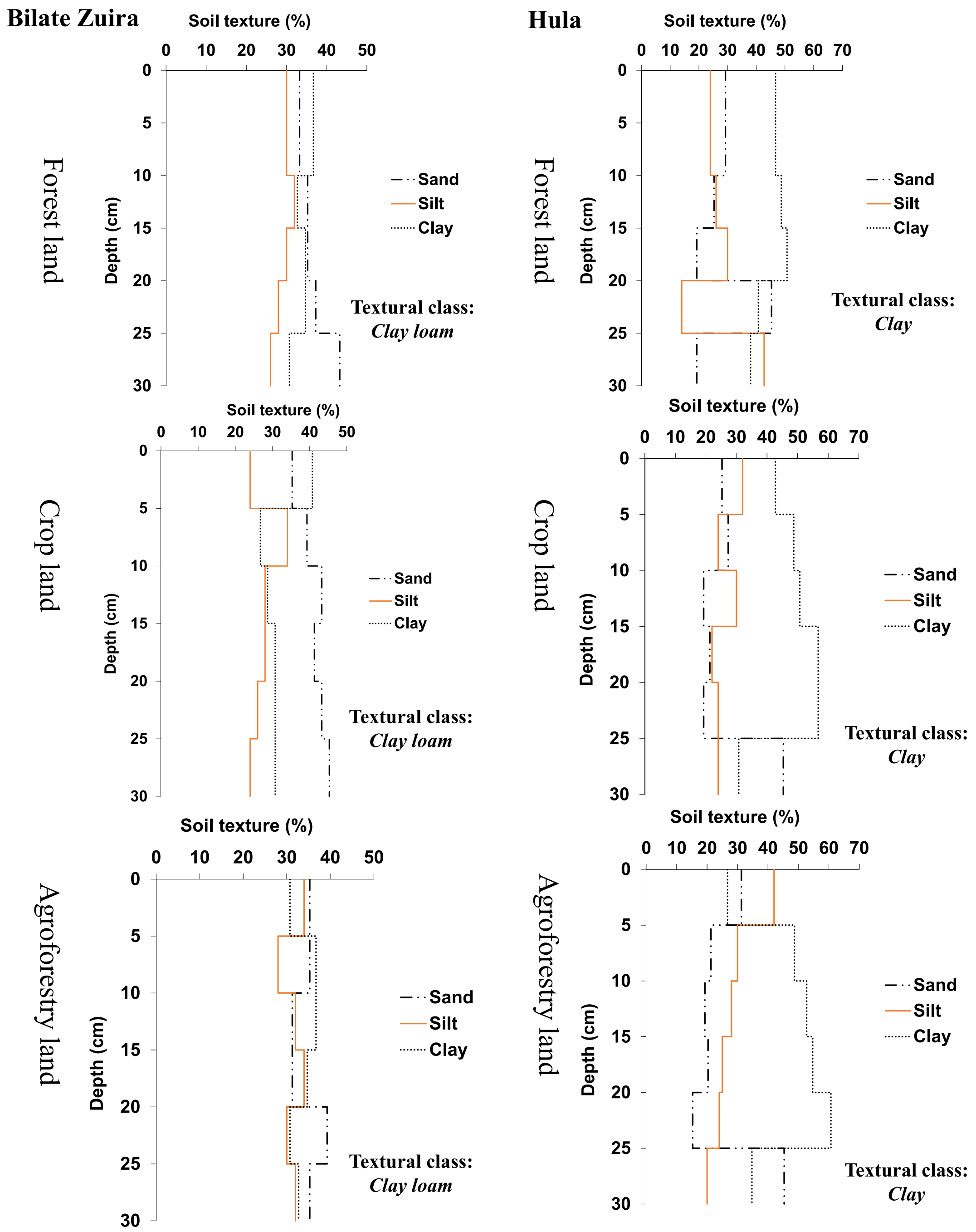

Fig. 2. The depth distribution of the soil texture composition in soils under agroforestry, crop and forest land uses in the study sites. (Left side: for BZ and right side: for Hula study sites).

➢ EER < 1, the element is tended to concentrate in subsurface soil

Moreover, Two-way ANOVA were performed (α = 0.05) to analyze and compare selected soil properties under different LUTs and AgC zones using IMB SPSS Statistic 26 version. This analysis tool exceptional provides a platform to further run pairwise comparison to identify specially to explain their interaction effect with either Tukey Honestly Significant Difference (HSD) or Least Significant Difference (LSD) as post hoc analysis tools.

3. Results and discussion

3.1. The depth distribution of selected soil physical properties

Soil texture distribution: As it is clearly indicated in Fig. 2, the clay grain fraction (range: 45–48%, Table 2) dominated the depth distribution in Hula study site except on the most upper and lower soil layers in homegarden where silt and sand tended to dominate, respectively. In agreement, according to United States Department of Agriculture (USDA) soil texture triangle presented by Groenendyk et al. [31], the soil textural classification of the study sites in Hula district has been identified as clay while the soil in BZ found to be clay-loam except a slight high sand fraction below 5 cm in soil under crop land use (Fig. 2). As indicated in Table 3, neither the LUTs nor the interaction effect significantly affected the depth distribution of both sand and clay contents but AgC factor ($p < 0.001$), implying the different impacts of weathering processes including bio-cycling processes such as decomposition on the parent materials. Due to its relative high surface area, clay fraction has been reported to possess greater number of CEC sites and associated cations [32]. However, this was not noted in our results especially in Hula where the phenomena is highly expected due to its high clay content (Tables 2 and 3).

***Soil bulk density*:** Bulk density (BD) showed similar distribution pattern except some variation among the land use types in Hula, and relatively high below 25 cm depth in crop land of BZ district. The vertical distribution pattern of the BD along the depth per land use and study site are shown in Fig. 3. The average BD was found to be higher in BZ (1.0 ± 0.2 g cm^{-3}) than Hula site (0.98 ± 0.1 g cm^{-3}) (Table 2). In BZ district, it slightly fluctuated along the depth except the last depth interval (20–30 cm) in soil under cropland which surpassed 1.5 g cm^{-3}, implying relatively compacted soil horizon (Fig. 3). In the case of Hula district, the BD showed a gradual increasing trend from 0.7 to 1.1 ± 0.2 g cm^{-3} along the depth under homegarden system. Whereas, it was stabilized around 1.0 ± 0.1 g cm^{-3} with slight fluctuation in the case of soils under crop and forestland uses in the district (Fig. 3). According to Two-way ANOVA (Table 3), the depth distribution of BD was significantly different by LUTs ($p = 0.03$) and interaction effect ($p = 0.005$). These collectively indicate that the depth distribution of BD could vary depending on the land use but not by agro-climate factor alone.

3.2. The depth distribution of selected chemical properties and elements

3.2.1. pH

The pH of soil in both study sites were found to be below 7 and roughly distributed uniformly along the soil depth in each LUT. The lowest pH was recorded at 20–25 cm depth in forest and cropland uses in BZ and Hula districts, respectively (Fig. 4). In BZ, pH gradually increased and decreased in soils under homegarden located in BZ and Hula districts, respectively. Except at a depth of 20–25 cm, it also gradually increased in soil under forestland at the BZ district (Fig. 4). According to Two-way ANOVA, the depth distribution

Table 2

The average value (± standard deviation) of physicochemical parameters in the studied sites across their respective land use types.

Physicochemical parameters	Study sites (agro-climatic zone)					
	Bilte Zuria (BZ)			Hula		
	Cropland	Homegarden	Forestland	Cropland	Homegarden	Forestland
Sand (%)	41.3 ± 3.6	34.6 ± 3.0	36.3 ± 3.7	26.3 ± 9.9	25.4 ± 11.1	27.9 ± 9.6
Silt (%)	27.3 ± 3.7	31.7 ± 2.3	29.3 ± 2.1	26 ± 4.0	28.2 ± 7.6	26.8 ± 9.4
Clay (%)	31.4 ± 4.8	33.7 ± 2.8	34.4 ± 2.3	47.7 ± 9.9	46.4 ± 13.0	45.3 ± 4.9
BD (gcm^{-3})	1.2 ± 0.2	0.94 ± 0.1	0.90 ± 0.1	0.98 ± 0.1	0.93 ± 0.2	1.1 ± 0.1
pH	6.6 ± 0.5	6.4 ± 0.5	6.1 ± 0.7	4.8 ± 0.4	5.4 ± 0.4	4.8 ± 0.3
EC (mS m^{-1})	1.9 ± 0.6	13. ±0.2	1.4 ± 0.3	0.3 ± 0.1	0.7 ± 0.3	0.2 ± 0.1
CEC (cmol kg^{-1})	18.8 ± 3.8	22.1 ± 1.0	20.7 ± 0.8	19.2 ± 2.2	20.0 ± 1.5	18.8 ± 1.6
SOC (%)	2.4 ± 0.9	2.1 ± 0.5	2.0 ± 0.8	2.3 ± 0.5	2.1 ± 0.6	2.2 ± 1.0
Ca (cmol kg^{-1})	35.2 ± 22.4	64.8 ± 9.4	52.1 ± 7.0	7.5 ± 4.8	36.8 ± 16.3	5.1 ± 5.5
Na (cmol kg^{-1})	0.17 ± 0.07	0.09 ± 0.02	0.11 ± 0.01	0.05 ± 0.01	0.07 ± 0.01	0.05 ± 0.01
K (cmol kg^{-1})	5.8 ± 1.4	1.6 ± 0.8	2.4 ± 0.2	0.4 ± 0.1	1.3 ± 0.4	0.3 ± 0.2
P (ppm)	49.4 ± 44.0	14.3 ± 5.4	15.4 ± 14.7	6.6 ± 2.6	7.6 ± 2.7	6.5 ± 4.4
Mn (mg kg^{-1})	19.8 ± 6.3	8.1 ± 7.5	10.2 ± 11.5	42.8 ± 12.1	49.7 ± 5.6	48.7 ± 10.5
Fe (mg kg^{-1})	9.0 ± 3.4	4.7 ± 2.1	8.5 ± 5.4	42.8 ± 14.8	35.1 ± 9.9	40.8 ± 15.2
Cu (mg kg^{-1})	0.12 ± 0.1	0.12 ± 0.09	0.22 ± 0.04	1.48 ± 0.41	2.08 ± 0.59	2.91 ± 0.90
Zn (mg kg^{-1})	3.9 ± 2.0	3.2 ± 1.2	2.7 ± 1.4	2.6 ± 2.3	3.7 ± 2.3	2.4 ± 1.9
* Soil mass depth (kg m^{-2}) (0–30 cm)	348.6	280.7	268.5	292.8	277.8	318.6

BD = Bulk density; * soil mass depth is the total dry soil mass (<2 mm fraction) within depth observation depth per unit area.

Table 3
Results Two-way ANOVA at 0.05 significant level.

Physicochemical parameters	Experimental factors					
	Agro-climate (AgC)		Land use type (LUT)		Interaction effect (IE)	
	F_{cal}	p-value	F_{cal}	p-value	F_{cal}	p-value
Sand	18.21	0.0002[a]	0.73	0.49	0.68	0.51
Silt	1.76	0.195	1.03	0.37	0.11	0.89
Clay	29.25	0.00001[a]	0.014	0.99	0.43	0.66
BD	0.057	0.84	4.09	0.027[a]	6.48	0.0046[a]
pH	73.68	1.4×10^{-9}[a]	2.82	0.076	2.19	0.13
EC	99.21	5.0×10^{-11}[a]	2.76	0.079	4.97	0.014[a]
CEC	3.09	0.089	2.98	0.066	1.6	0.299
SOC	0.008	0.93	0.51	0.603	0.074	0.93
Ca	66.0	4.5×10^{-9}[a]	17.72	8.3×10^{-6}[a]	2.28	0.12
Na	40.07	5.6×10^{-7}[a]	5.49	0.006[a]	9.72	0.0006[a]
K	131.33	1.7×10^{-12}[a]	25.39	3.5×10^{-7}[a]	43.45	1.4×10^{-9}[a]
P	9.2	0.005[a]	3.15	0.06	3.31	0.05
Mn	123.45	3.7×10^{-12}[a]	0.21	0.81	3.47	0.044[a]
Fe	94.65	8.6×10^{-11}[a]	1.21	0.31	0.089	0.914
Cu	159.56	1.5×10^{-13}[a]	7.74	0.002[a]	5.89	0.007[a]
Zn	0.374	0.55	0.91	0.41	0.79	0.46

[a] Significant p - value at $\alpha = 0.05$, F_{cal} = calculated F value.

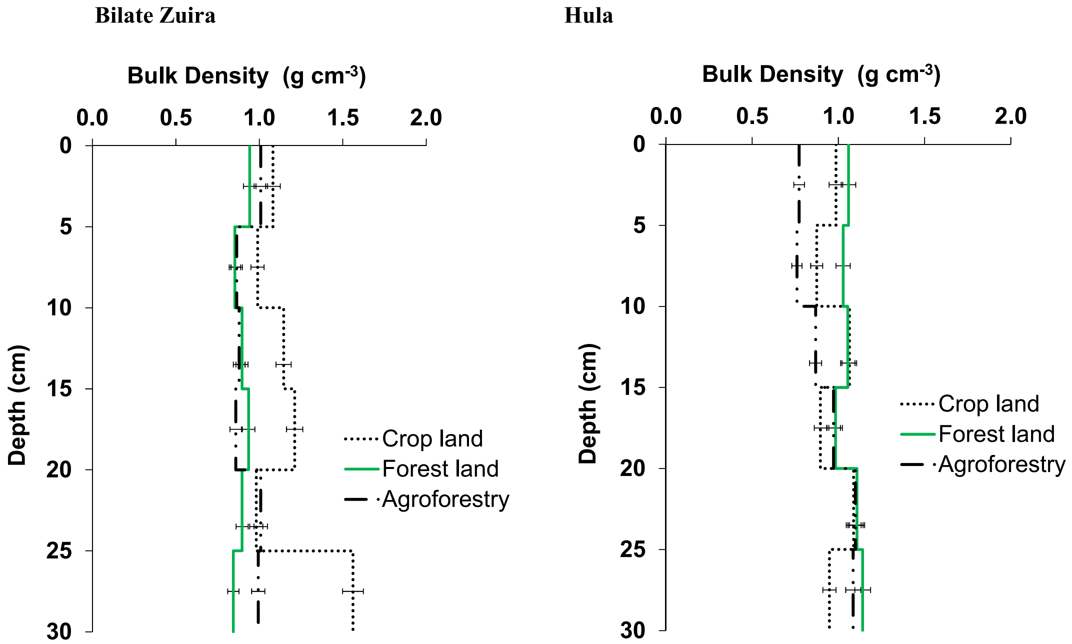

Fig. 3. Soil Bulk density depth distribution in agroforestry, crop and forest land uses at the stud sites. (Left side: for BZ and right side: Hula study sites).

of pH was significantly sensitive only to agro-climate ($p < 0.00001$) but not to LUTs and the interaction effect (Table 3). In agreement, most previous studies indicated that the increase in pH with depth may be attributed to leaching of bases by percolating water and plant uptake [33–35], which definitely related to high rainfall areas (I.e. the agro-climate factor).

In fact, pH is essential for growth conditions for most plants by controlling the solubility of nutrients and toxic metals [36]. Nevertheless, when soil pH is above 7.5, it is often associated with deficiency of heavy metals (Fe, Mn, Cu, Zn) whereas, when the pH is below 5.8, the problems including toxicity related to Al and Mn as well as inhibiting the growth of useful microbes are highly possible [36]. Although our study sites are free from the problems associated with higher pH, the issues related with the lower pH threshold could be the possible threat in Hula (highland) site, where the average pH was nearly 5. Still, homegarden system in Hula has shown relatively higher pH than other LUT, indicating the self-control role of the system probably due to its unique biological compositions.

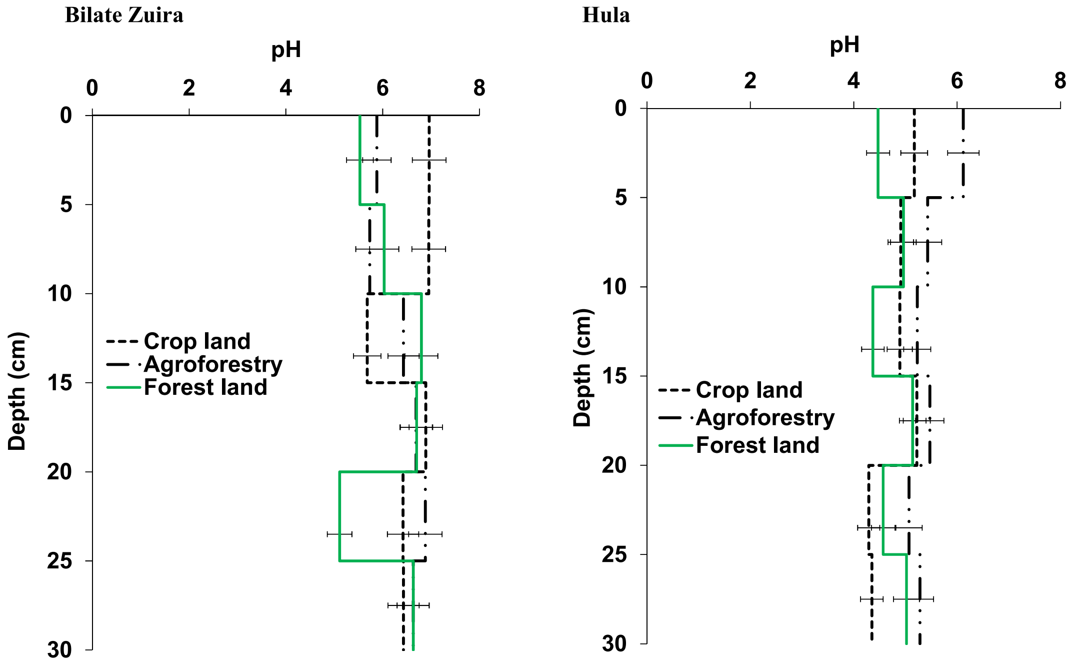

Fig. 4. The depth distribution of pH in soils of agroforestry, crop and forest land uses in the study sites. (Left side: for BZ and right side: for Hula study sites).

3.2.2. *Electrical conductivity (EC) and cation exchanging capacity (CEC)*

The depth distribution of both EC and CEC in the studied sites and LUTs are illustrated in Fig. 5 a and b, respectively. In the respective study sites, the depth distribution of EC roughly followed irregular pattern along the depth where its highest peak was recorded at upper soil surface (0–5) with another but relatively lower peak at the depth of 15–20 cm in soils under crop (3 & 2 mS m^{-1}) and homegarden (1.12 & 0.88 mS m^{-1}) land uses in BZ and Hula districts, respectively (Fig. 5a). In contrast, Hoque et al. [35] and the references therein reported that EC was higher in the top soil and gradually decreased in deeper layers. Moreover, analysis of variance indicated that the depth distribution EC is governed by the agro-climate and the interaction effect but not by LUTs (Tables 2 and 3).

On the other hand, the depth distribution of CEC was hardly vary along the depth (Fig. 5b). Interestingly, higher overall average CEC was recorded in homegardens located at both sites (BZ: 22 ± 1; Hula: 20 ±0 .5 cmol kg^{-1}) than their respective LUTs, reflecting the normalizing role of the system which might be originated from diverse composition of the system. Compared to BZ, high value of CEC was expected in soils of Hula district due to its high clay contents which often provide large surface area for exchanging site, but it was not noted possibly because of the influence of other factors. Nevertheless, the observed CEC values in our study agreed with range (3.1–26.8 cmol kg^{-1}) reported by Dinesh et al. [32]. Also, the Two-way ANOVA analysis did not show any significant differences across the LUTs and agro-climatic districts, collectively implying a slow change of CEC depth distribution pattern despite the difference in land use and agro-climatic characteristics (Fig. 5b).

In general term, both EC and CEC were higher in BZ (1.53 ± 0.5 mS m^{-1}, 20.5 ± 2.6 cmol kg^{-1}) than Hula (0.41 ± 0.3 mS m^{-1}, 19.3 ± 1.8 cmol kg^{-1}) despite receiving low annual rainfall than Hula (Table 1). Nevertheless, this pattern could be associated with the presence of high extractable Na (BZ: 0.12 ± 0.1; Hula: 0.06 ± 0.01 cmol kg^{-1}) and K (BZ: 3.3 ± 2.0; Hula: 0.68 ± 0.5 cmol kg^{-1}) elements (Table 2). Particularly, the significant impact of agro-climate on EC could explain in such that most of the cations form soluble salt by taking organic matter as a temporary store plate for ions which could release up on decomposition and added in to the water suspension and rise the EC of the soil solution during peak soil moisture periods. However, comparing with the results reported by Hoque et al. [35], the salt accumulation due to evaporation via capillary rise of salt containing water generally seems weak in our study sites as evident further by the depth distribution Na and K (discuss below).

3.2.3. *The depth distribution of selected macro and microelements*

3.2.3.1. Extractable macro-elements. The depth distribution of the cation concentrations were higher in soils of BZ than Hula. This is in fact goes along with the pH depth distribution where higher pH was observed in soils of BZ (Fig. 4), indicating higher concentration of alkali (Na, K) and alkaline-earth (Ca) elements which are responsible for higher pH depth distribution than in Hula site. Their depth distribution in soil under different land uses in the studied agro-climatic districts are illustrated in Fig. 6.

Calcium (Ca): The depth distribution of Ca showed somewhat different pattern among land uses and sites. Except in soil under homegarden of Hula where highest peak of extractable Ca at the top soil layer (Fig. 6a), generally it was high in BZ than Hula district (<20 cmol kg^{-1}) as well as its average value was higher in homegarden followed by forestland and cropland. This goes along with the

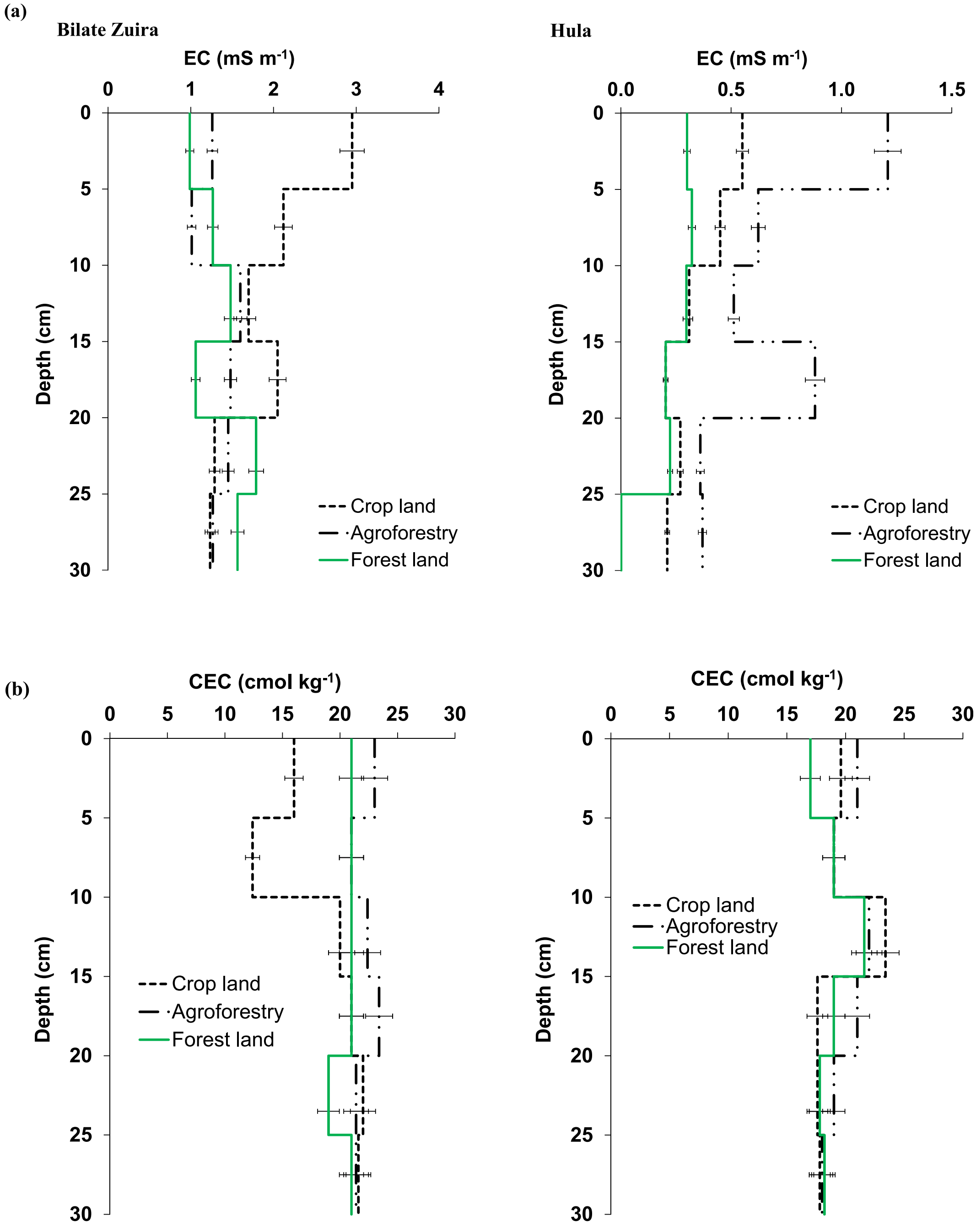

Fig. 5. The depth distribution of EC (a) and CEC (b) in soils of agroforestry, crop and forest land uses in the study sites. (Left side: for BZ and right side: for Hula study sites).

higher EC value as depicted in Fig. 5a, where EC was higher in soils under all land uses of BZ and in soil under homegarden of Hula, indicating in addition to other cations, Ca could take the chief responsibility for higher EC in specified site and land uses. The EER value of Ca was exceptionally higher in forestland (8.4) of Hulla followed by soils under cropland (2.9) of BZ and homegarden (1.3) of Hulla (Table 4), indicating higher Ca amount on top soils with its main input sources are from above ground. The analysis of Two-way ANOVA revealed that the depth distribution of Ca is significantly influenced by both agro-climate and LUTs factors but not by their interaction effect (Table 3).

Sodium (Na): Na concentration along the depth varied in a narrow range from 0.04 to 0.25 cmol kg^{-1}. Except in soil under cropland of BZ where Na suddenly peaked at the depth of 10–15 (0.25 cmol kg^{-1}) and gradually decreased back, its depth distribution was nearly in similar pattern across land uses and sites (Fig. 6b). Excluding the cropland soil of BZ (0.63), the EER values were higher

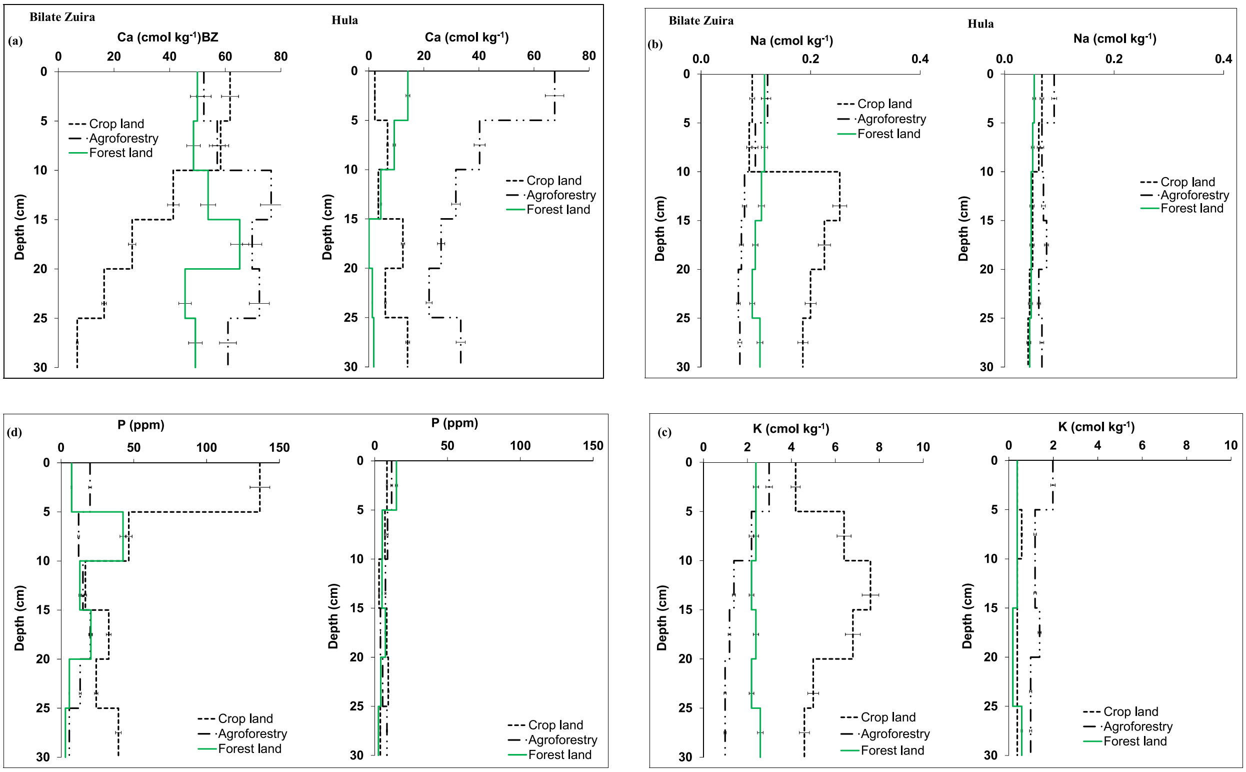

Fig. 6. The depth distribution of (a) Calcium [Ca], (b) Sodium [Na], (c) Potassium [K] and (d) Phosphorus [P] in soils of agroforestry, crop and forest land uses in the study sites. (Left side: for BZ and right side: for Hula study sites).

Table 4
Elemental Enrichment Ratio (CER), which refers to the proportion of amount of chemical element in the upper surface to subsurface soil of the studied land uses.

No.	Chemical elements	Study sites					
		Hulla (Highland)			Bilate Zuria (Lowland)		
		Cropland	Homegarden	Forestland	Cropland	Homegarden	Forestland
1	OC	1.33	0.70	1.79	1.57	0.80	1.80
2	Ca	0.38	1.28	8.38	2.92	0.88	0.95
3	Na	1.29	0.84	1.05	0.63	1.37	1.15
4	K	1.15	0.99	1.15	0.96	2.05	0.98
5	P	0.83	1.17	1.80	1.71	1.21	2.04
6	Mn	1.32	0.89	1.32	1.18	1.57	5.67
7	Fe	1.29	1.06	1.61	1.29	2.02	2.32
8	Cu	1.10	1.26	1.48	4.26	4.86	0.98
9	Zn	2.54	1.69	2.40	2.62	1.85	2.02

than 1, indicating it tends to stay in the surface soil similar to that of Ca (Table 4). Further, the Two-way ANOVA revealed that depth distribution of Na was significantly affected by agro-climate, LUTs and their interaction effect (Table 3).

Potassium (K): The concentration K declined gradually from top to bottom in soil under the homegarden located at both sites unlike in other LUTs. In forestland of both sites, the depth distribution of K was nearly uniform from top to bottom with EER value of nearly 1 (Table 4). The maximum concentration K was observed at the depth of 10–15 cm (7.6 cmol kg^{-1}) and slowly decreased in both sides in soil under cropland of the BZ district (Fig. 6c). Except in homegarden of BZ (EER = 2.1), where its amount in surface soil was twice that of the subsurface, the EER values were nearly 1, indicating uniform distribution between the top and subsoil. Like Na, Two-way ANOVA analysis showed that it was significantly affected because of the difference in agro-climate, LUTs and their interaction effect (Table 3).

Phosphorus (P): In BZ, P was gradually decreased from top to bottom in soil under homegarden whereas irregularly distributed in soil under crop and forestlands. The highest peak of P was observed in the upper soil layer (0–5 cm) of cropland (136.6 ppm) with three other small peaks at depths of 5–10 cm (46.5 ppm), 15–20 cm (32.8 ppm) and 25–30 cm (39.4 ppm). In forestland of the same site, the concentration P was the highest at the depth of 5–10 cm (42.6 ppm). On the other hand, in Hula site, P was high in the upper soil layer and decreased irregularly across the LUTs (Fig. 6d). The EER values were higher in forestland located in both sites (Hull: 1.8, BZ: 2.0), indicating the top soil is rich in P (Table 3). Besides, Two-way ANOVA confirmed that there was a significant differences because of only agro-climate ($p = 0.005$) factor (Table 3), showing higher in lowland (BZ) than highland (Hula).

The global ranking order of macro-chemical elements evaluated based on the median topsoil concentration factor (i.e 0–20 cm to that of 0–100 cm) in their vertical distribution from upper soil to the bottom profile was set as $P > K > Ca > Mg > Na{=\!=}Cl = SO_4$ [37]. Except some irregularities like the depth distribution of Ca, our findings generally agreed with the global trends. As indicated in Fig. 6d, P was highly concentrated in the top soil while that of Na was less responsive to depth except in soil under cropland (Fig. 6b) of the BZ. In agreement with the results by Jobbagy and Jackson [37], a general higher concentration of P and K on top soil layers (shallower distribution) could be associated with plant cycling role on the elements such as via litterfall quickly uptake as the plants demands in higher amount, which ultimately define such a soil profile. Another reason could be fertilization (principally P) input particularly in the cropland soils. Lower extractable P in Hula district could be associated with high clay content causing its fixation. Related to K, Tian et al. [15] reported that clay content is the key factor influencing the distribution of available K as it provides high adsorption capacity. In agreement, our result from Hula district where clay content dominates (Fig. 3), showed very low extractable K across the LUTs compared to that in BZ (Table 2), highlighting strong fixation of the element by clay.

3.2.3.2. Extractable micro-elements. Unlike to macro-elements, the distribution of the microelements across the different land uses and agro-climate districts showed consistently higher in the cold area (Hula) and in soils under forest or homegarden. The depth distribution spectrum of the elements are shown in Fig. 7.

Manganese (Mn): The concentration of Mn sharply declined below 10 cm by peaking (30 mg kg^{-1}) at the upper soil surface (0–5 cm) in soil under forestland while peaked at 0–5 cm with 16.7 mg kg^{-1} in homegarden and at 0–5 cm with 29.3 mg kg^{-1}in cropland; re-emerged at the depth of 15–20 cm in the BZ district (Fig. 7a). In Hula district, Mn was almost uniformly distributed up to the upper 15 cm (maximum at the top: 54.6 mg kg^{-1}) in homegarden and after a brief decline, it re-emerged below 20 cm depth (~50 mg kg^{-1}). The highest average Mn was recorded in Hula across all land uses than BZ, in which the highest was recorded in homegarden followed by forestland and cropland (Table 3). Regarding to EER (Table 4), the highest value was observed in soil under forestland (5.7) followed by homegarden (1.6) located in lowland (BZ), but nearly 1 in cropland of the lowland and in all land use types of highland, indicating the main input sources are possible from aboveground biomass. Moreover, according to the analysis of Two-way ANOVA, the depth distribution of Mn was significantly differ due to agro-climate and the interaction effect of agro-climate and LUTs but not by LUTs alone (Table 3).

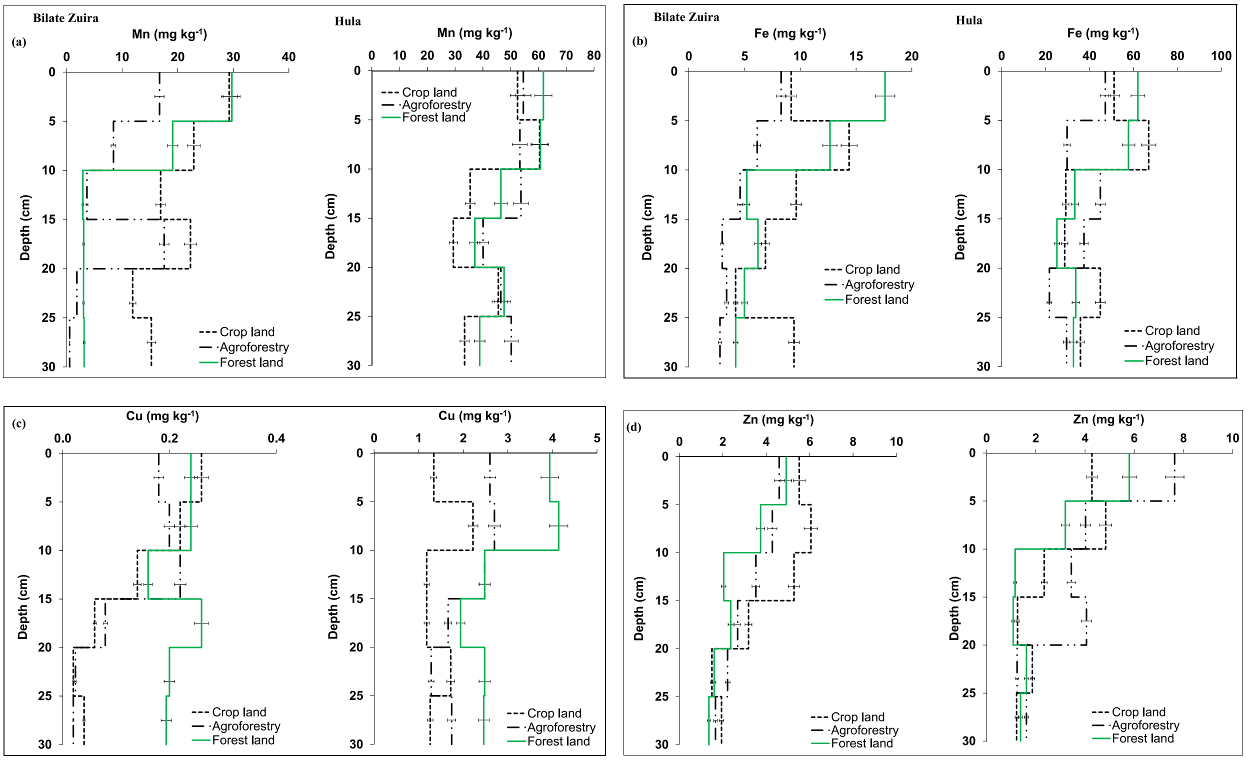

Fig. 7. The depth distribution of (a) Manganese [Mn], (b) Iron [Fe], (c) Copper [Cu] and (d) Zinc [Zn] in soils of agroforestry, crop and forest land uses in the study sites. (Left side: for BZ and right side: for Hula study sites).

Iron (Fe): The depth distribution of Fe has shown similar pattern in both sites with their corresponding LUTs (Fig. 7b). Typically, higher Fe content was recorded in Hula (21–67 mg kg^{-1}) than BZ (3–18 mg kg^{-1}), indicating the effect of location with its entire bio-geo-physical characteristics. In support of this, the Two-way ANOVA indicated that the depth distribution of Fe was significantly affected only by agro-climate factor (Table 3). The EER values showed that Fe is more available on surface soil (Table 4) specially twice higher in homegarden (2) and forest (2.3) land uses located in lowland (BZ). In agreement, Sharma and Singh [38] reported high surface availability of Fe than in the subsurface, implies that Fe is more mobile in soil mainly governed by its redox potential and strong bond formation like with SOC. Nevertheless, similar to that of Mn, the highest mean Fe concentration was recorded in Hula than BZ with the lowest in homegarden (35.1 ± 9.9 mg kg^{-1}) and the highest in cropland (42.8 ± 14.8 mg kg^{-1}).

Copper (Cu): Higher concentration of extractable Cu was obtained in the upper 10 cm (~4 mg kg^{-1}) soil under forestland of Hula. Its distribution pattern in cropland located in BZ showed a general decreasing trend with the highest at the depth of 0–5 cm (0.26 mg kg^{-1}) unlike its counterpart of the Hula district where it peaked at different depth (e.g. 5–10 cm with 2.2 mg kg^{-1} & 20–25 cm with 1.7 mg kg^{-1}). The depth distribution of Cu in homegarden located in Hula district showed somehow decreasing trend along the depth (Fig. 7c). Similarly, Barona et al. [39] and Mengel et al. [40] have reported that Cu has strong affinity to soil organic matter than other

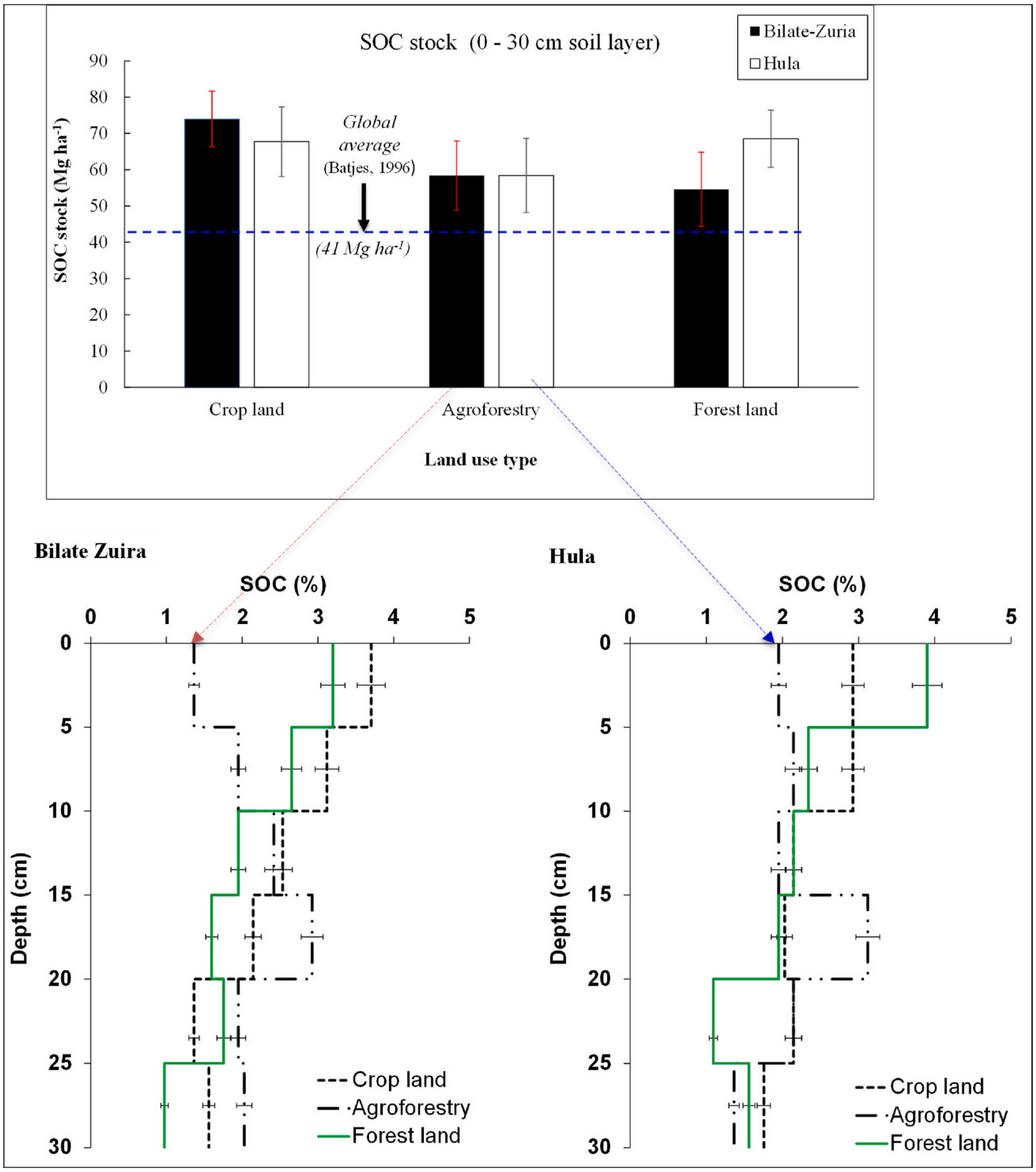

Fig. 8. The SOC stock (Mg ha^{-1}) across the studied land uses and districts (inset); the broken horizontal line indicates the global average level [41]. Below: the depth distribution of SOC concentration (%) in soils under homegarden, crop and forestland uses in the studied sites (below left side: for BZ and right side: for Hula study sites).

divalent cations, implying its concentration in the upper soil horizon. The higher Cu content observed in Hula district could be associated with the higher clay content along the depth as compare to that of the BZ (Figs. 3 and 7c). However, based on the EER values (Table 4), the amount of Cu in surface soil was four to five times higher than subsoil of homegarden and cropland uses located in lowland (BZ), implying it is strongly influenced by site and associated land use types. In agreement, according to the analysis of Two-way ANOVA, the depth distribution of Cu was also significantly affected by agro-climate, LUTs and their interaction effects (Table 3).

Zinc (Zn): The maximum concentration of Zn in cropland of both sites was recorded at depth of 5–10 cm (BZ: 6.1 mg kg^{-1}; Hula: 4.8 mg kg^{-1}) but it showed a general declining pattern along the depth (Fig. 7d). Dinesh et al. [32] reported that Zn showed irregular depth distribution pattern with increasing depth. Unlike them, our findings revealed that relatively regular Zn depth distribution with higher in the top (with EER value of >1.5 across the LUT and study sites, Table 4) and lower in the deeper soil horizon, which could be associated with turnover processes by plant residues. Moreover, such difference may be originated from the advantage of using fine soil sampling resolution which provides the chance to examine fine differences along the depth [10] unlike to that of coarse horizon which would more likely to overlook such differences. According to the analysis of Two-way ANOVA, the depth distribution of Zn was not significantly affected by the main factors and their interactions. However, the higher mean Zn concentration was observed in BZ than Hula, where the highest in homegarden followed by crop and forest land use types (Table 2).

Generally, the average concentrations of the macro-elements (Ca, Na, K and P) was found to be higher in lowlands while the microelements (Mn, Cu, Fe and Zn) was higher in highlands. Nevertheless, the observed variation of the depth distribution of macro- and micro-elements as well as other physicochemical properties at various degree indicate the influences of the LUTs and all suite of site characteristics including active biogeochemistry turnovers involving both deposition and bio-pumping (flora, soil fauna and roots) effects.

3.3. The depth distribution of SOC

The depth distribution of organic carbon concentration along the depth was not significantly different among the LUTs as well as between the studied agro-climate districts ($P = 0.943$, Table 3). The SOC stocks in our study sites for the studied depth (0–30 cm) ranged from 55 to 74 Mg ha^{-1} (Fig. 8), which are generally higher than that of the global average (41 Mg ha^{-1}) reported by Batjes [41]. Comparing to similar land use types, higher SOC stocks were reported from Enset (122 Mg ha^{-1}), Enset-Coffee (120 Mg ha^{-1}) and Fruit-Coffee (115 Mg ha^{-1}) based agroforestry systems from neighboring Gedio Zone [18]. Also, in terms of SOC stock (kg ha^{-1}) with in the observed depth, Two-way ANOVA analysis showed that there was no significant difference of SOC between the two sites as well as among land use types ($P = 0.9431$).

The depth distribution of SOC uniquely showed an increasing trend in the soil profiles under homegarden agroforestry systems located in both sites than the other two LUTs. This is also confirmed by lower EER values in homegadren of both sites (Hulla: 0.7; BZ: 0.8), while it was exceeding 1 in the rest (Table 4). In fact, a similar pattern was reported by Rumpel et al. [42] that up to 75% organic carbon present in the mineral soils under beech and spruce forests were found below the A-horizon. Hence, the observed SOC depth distribution under homegarden agroforestry in our study sites implied that it is well protected and located in soil horizons of less susceptible for any possible carbon emission drivers. This makes the system unique and has a paramount important in terms of climate change. Therefore, homegarden land use types should be encourage in response to combat climate challenges [43] while boosting the livelihood of the community irrespective of the agro-climatic differences. So, community can get double benefits of practicing homegarden agroforestry systems by improving and diversifying their all-round livelihood needs at the same time protecting the emission of carbon by buried it in deeper soil horizon and stored in perennial plant biomass like trees in the system.

4. Conclusions

The present study identified that the depth distributions of soil texture (only the sand and the clay contents), pH, EC, Ca, Na, K, P, Mn, Fe and Cu were significantly affected by the agro-climate factors, while BD, Ca, Na, K and Cu by the land use types. The significant interaction effects (combination of agro-climate and land use types) was only manifested on the depth distribution BD, EC, Na, K, Mn and Cu, reflecting the influence of land use type, site, parent material and bio-recycling related processes. Hence, our initial hypothesis is rejected because the presented study prevails that most of vertical distributions of selected physicochemical properties among different land use type located in contrasting agroclimatic sites are not similar.

Very interestingly, the study discovered that the depth distribution of SOC in soils under homegarden in both sites followed a reverse distribution order unlike to other land use types. This slows down the biogeochemical cycling segment of the carbon linking to the atmospheric pool. Besides, due to the nature of species composition, homegarden possesses unique stratification of plant nutrient along the soil depth, which provides the opportunity to utilize them depending on the nature of plant root architecture. Collectively, agroforestry systems are being adopted for the multi-functional roles and expanded as climate-smart agriculture package. Connected to this, IPCC [44] has recently recognized and included it as part of climate change mitigation strategy due to its capacity to store carbon both deep in soil horizons (supported by result of this study) and in perennial plant biomass at the same time improving all-round livelihood needs of the practicing community. Despite the need of further investigation, the study gives a general understanding of the effects of LUTs and AgCs on the depth distribution of critical soil physicochemical parameters by highlighting the significance as well as the need of expanding indigenous homegarden practices as a tool for soil fertility management and climate change mitigation strategies. Given the current tendency of transforming homegarden agroforestry to monoculture types owing to economical drivers, such information definitely helps to make rational decision for managing soils under homegarden for the long-term supply as well as formulating sound soil fertility management plans.

Author contribution statement

M.T. Teramage: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data; Wrote the paper.

Mengistu T. Teramage: Ambachew Demissie: Abate Feyissa: Tadesse Ababu: Yadessa Gonfa: Getachew Sime: Conceived and designed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data.

Meto Asfaw: Conceived and designed the experiments; Performed the experiments; Analyzed and interpreted the data; Contributed reagents, materials, analysis tools or data.

Data availability statement

Data will be made available on request.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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