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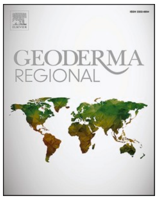

Changes in soil properties with long-term organic inputs due to distance from homestead and farm characteristics in southern Ethiopian farmlands

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ABSTRACT

Traditional farming systems across much of Sub-Saharan Africa have greater organic inputs near to the homestead than in fields further away. This is likely to produce a fertility gradient that impacts production capacity, and so provides an opportunity to explore impacts of organic amendments on soils. Across 198 farm plots in 69 households in Halaba, Southern Ethiopia, we investigated the influence of different organic input systems on soil properties. The study also examined the influence of household and farm characteristics on the adoption of land management practices and its impact on soil properties. Samples were taken from farm plots located close (<30 m), near (30–300 m) and far (>300 m) from the homestead, representing different levels of organic amendments. Soils located close to homesteads had significantly greater soil organic carbon, cation exchange capacity and soil nutrient content compared to soil located near and far from the homestead areas. Soil organic carbon concentrations close to the home were 15%, 27% and 45% greater than farm plots located at far from the home in Andegna Choroko, Asore and Lay Arisho kebeles, respectively. Across all sites, the mean soil organic carbon stock ranged from 20.6 t ha^{-1} to 84.6 t ha^{-1}, depending on the location of the plots with respect to the homestead. Household and farm characteristics also influenced land management practices and soil properties. In some catchments, farm plots managed by female headed households and relatively rich farmers displayed significantly greater soil organic carbon than farm plots managed by male headed and relatively poor households. This was likely due to greater organic inputs in female headed households in areas where men were otherwise engaged in off-farm activities and in wealthier households with greater access to organic manures. Tree cover in farmlands influenced accumulation of soil organic carbon. The results suggest that out-scaling farm management practices that are common around homesteads, such as adding animal manure or household wastes and maintaining tree cover, would help to improve key soil properties and agricultural productivity.

1. Introduction

Soils in Sub-Saharan Africa are some of the most vulnerable to degradation in the world, characterized by low agricultural productivity due to the combined impacts of climate extremes, competition for organic resources and extractive farming practices (Zingore et al., 2015). An essential solution to this degradation is the use of organic inputs. These provide important inputs to soil that provide plant nutrients and help maintain soil carbon stocks, thereby reducing erosion risk and potentially improving water storage to increase drought resistance (Wanga and Zhangb, 2021). Although there are some data on the impact of land management practices on soil organic matter storage and nutrient availability for Sub-Saharan Africa (Tully et al., 2015; Von Fromm et al., 2021), compared to other regions of the world the data are scarce.

With growing population, more intensive and extractive farming practices have contributed to low soil fertility of Sub-Saharan croplands (Lemenih et al., 2005; Muluneh, 2011). Repeated ploughing of soils

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coupled with fewer organic amendments has decreased soil organic carbon (OC), causing substantial negative impacts on soil properties (Getachew et al., 2012; Mganga and Kuzyakov, 2014; Assefa et al., 2020; Fentie et al., 2020; Tiruneh et al., 2021). The croplands of Ethiopia are particularly vulnerable due to the undulating topography, cultivation of steep slopes, conversion of forests and grasslands into agricultural land, and overgrazing, all accentuated by population growth (Deribew and Dalacho, 2019; Wassie, 2020).

Livestock, particularly oxen, are a vital component of mixed crop-livestock agricultural systems in Ethiopia. Livestock serve multiple roles in the livelihood of farmers, including as a source of draught power for farming, food, income, employment opportunities, and manure. Income is closely related to livestock ownership (Shumetie and Mamo, 2019), but the large number of livestock on some farms and free grazing that may affect surrounding land has resulted in overgrazing.

Degradation of soils in Ethiopia is also attributed to the reduced use of organic amendments due to competing uses of crop residues and animal manures for fuel (Amede et al., 2001; Nyssen et al., 2015; Wassie, 2020). This is exacerbated by climate change and extreme weather events, such as the recent El Niño effect, which significantly increased the risk of soil erosion, and soil carbon and nutrient losses (Smith et al., 2019).

Farmers in Ethiopia are aware of the degradation of soils and the associated reduction in agricultural productivity (Assefa and Hans-Rudolf, 2016). As a result, farmers have been using both indigenous and introduced land management practices in attempts to reduce soil degradation (Desta et al., 2021). Commonly employed farm-level soil and crop-based amendments include traditional practices, such as agroforestry home-gardens (Abebe, 2005), contour ploughing, manure application around the homesteads, fallowing, cereal-legume intercropping, crop rotations and incorporation of crop residues (Amede et al., 2001).

The management of soils in Ethiopia creates a gradient characterized by greater inputs of organic amendments close to the home where vegetables and perennial crops are grown, and fewer organic inputs further away in plots that are planted with cereals, such as teff or maize (Laekemariam, 2020). This may be confounded, to some extent, by the placing of homes where soil was initially most fertile, but it does provide a gradient of farming practices to explore the importance and impacts of organic inputs on soil carbon and nutrients. In addition to spatial differences of organic amendments away from the home, household and farm characteristics, such as wealth or gender, may influence organic inputs (Negash et al., 2017). Incorporating such information to understand how different carbon input systems influence soil properties is vital to better planning, designing and implementation of sustainable land use practices (Ashenafi et al., 2010). This understanding needs to extend beyond a biophysical characterization of the soils, to also consider societal and economic choices that affect farm management practices. For instance, farm income and cash availabilty affects the purchase of inorganic fertilizers and organic resource use; richer farmers with greater access to resources are less likely to be cash constrained so more able to invest in inorganic fertilizers and more likely to follow through on plans to use inorganic fertilizer (Duflo et al., 2011; Iticha et al., 2021). Moreover, there is a range of evidence that gender affects farming practices because male and female heads make different management decisions (Croppenstedt et al., 2013; Sheahan and Barrett, 2017; Daadi and Latacz-Lohmann, 2021). So it might be expected that soil properties in female headed households will be different compared to male headed households.

The present study was conducted in Halaba, southern Ethiopia to (a) investigate the influence of different carbon input systems on soil properties and soil nutrient content and (b) assess the influence of household and farm characteristics on land management practices. This study hypothesizes (i) accumulation of soil organic carbon and soil nutrients decreases with increasing distance from homestead, (ii) soil organic carbon is higher in farmlands managed by male than female headed households, (iii) soil organic carbon is higher in farmlands managed by wealthier than poorer households, and (iv) accumulation of soil organic carbon has a positive impact on soil properties that increase soil fertility.

To gain greater understanding of the importance of organic amendments, we measured soil carbon and nutrient storage across 3 kebeles dominated by vitric Andosols (FAO, 1983) but with differences in inherent soil properties and elevation, some differences and also some overlap in cropping practice, and similar climate. The biggest contrasts between the kebeles were soil texture, which was recorded at each of 198 farm plots sampled across 69 household farms (21 in Andegna Choroko, 25 in Asore and 23 in Lay Arisho) in Halaba, southern Ethiopia. From this broad on-farm survey, the heterogeneity driven by local conditions (texture and altitude) was captured. Similar crops were grown by all households, and they all farmed higher-value crops with greater inputs close to their homestead and decreasing inputs with further distance. This gradient in farming practice was obtained by sampling close (<30 m), near (30–300 m) and far (>300 m) from the homestead. The research complements scarce data on the degradation of soils in Sub-Saharan Africa, with an exploration of land management impacts, so it will help to identify, design and plan more sustainable practices.

2. Materials and methods

2.1. Study area

The study was conducted in three kebeles, designated as the smallest administrative units; Andegna Choroko, Lay Arisho, and Asore. These kebeles are located in Halaba Zone, southern Ethiopia (Fig. 1). Andegna Choroko and Asore are nearer to physical market (Halaba Kulito town) than Lay Arisho. The elevation of these kebeles ranges from 1526 to 2237 m, with all having an annual bimodal rainfall pattern. The main rainy season (locally called *Meher*) occurs from June to September and the short rainy season (*Belg*) from April to June.

The annual rainfall for the years 2007 to 2020 varied between 531 and 1212 mm, having a mean value of 943 mm. Over 48% of rainfall occurred in the main rainy season (June–September), with rainfall intensities as high as 140 mm per month. Although data are not available, this rainfall fell erratically with intense periods at sometimes producing visible soil erosion including rills and silted waterways. Run-off from surrounding land up-slope exacerbates erosion in this region. The annual rainfall showed considerable variation between years, with an extreme low of 531 mm in the 2015 El Niño and extreme high of 1212 mm in 2016. The maximum and minimum mean-temperatures in the studied kebeles were 29.3 and 15.0 °C, respectively. The major soils in the studied kebeles are vitric Andosols and chromic Luvisols (FAO, 1983) and the soil textures are dominated by sandy silt loam, sandy loam and clay loam. Soil degradation, manifested by deep gullies, is a serious problem in the studied kebeles, and this is being exacerbated by increased deforestation, mainly attributed to population growth which increases the dependence of local communities on forest resources, and a shift from livestock to crop-based agriculture (Byg et al., 2017).

About 80% of the population in the study area are smallholder farmers with on average <1 ha of land per household under mixed crop-livestock farming system. Farming close to the homestead is dominated by perennials, such as khat (*Catha edulis*), coffee (*Coffea arabica*), fruit and shade trees integrated with root crops and sometimes cereals (maize- *Zea mays*). By contrast, farming far from the homestead areas is dominated by cultivation of annual crops, such as maize, teff (*Eragrostis tef*), sorghum (*Sorghum bicolor*), haricot beans (*Phaseolus vulgaris*), millet (*Elusine coracana*) and pepper (*Capsicum* sp.).

2.2. Experimental design

Prior to setting up sampling plots to examine soil properties and

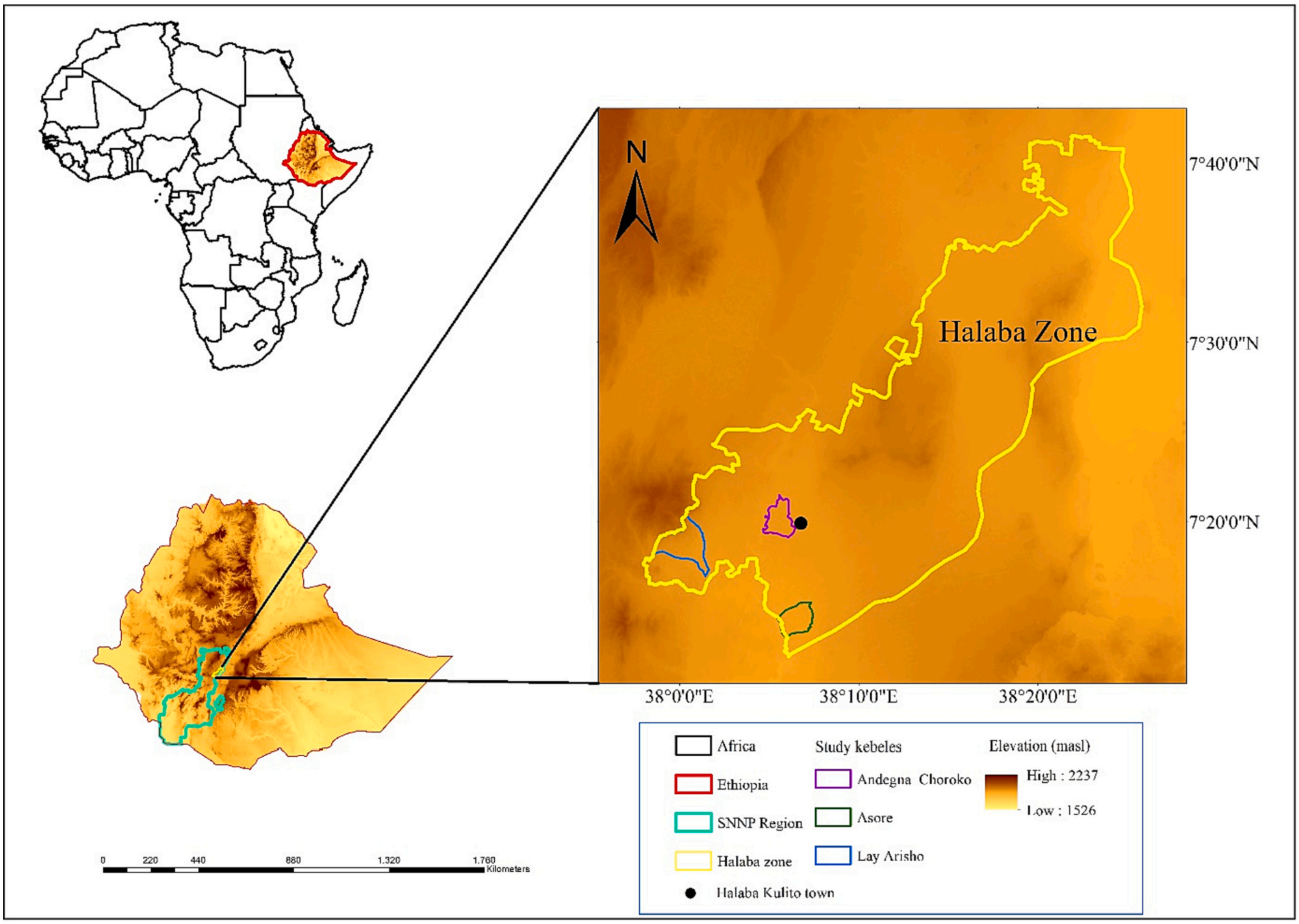


Fig. 1. Location of the study kebeles.

nutrients under different carbon inputs systems, three farm plots were identified in each household. The criterion used to identify the farm plots was distance from the home. The farm plots selected were located close to the homestead (<30 m), near to the homestead (30 to 300 m away) and far from the homestead (> 300 m away) (Table 1). The study surveyed 63, 71 and 64 farm plots from Andegna Choroko, Asore and Lay Arisho kebeles, respectively. Supplementary material 1 shows the common landscape features of the sampled farm plots. There are diverse farming practices with some overlap in these three kebeles and soil properties differ, reflective of broader socio-economic and biophysical conditions of the Halaba zone. These soils are moisture stressed and experience severe land degradation. Moreover, the kebeles are central to agricultural advisory activities in the region, providing some efforts to manage natural resources including soils through interventions such as changed cropping practices, agroforestry and organic inputs. The study considered each of the farm plots at different locations in reference to the homestead as treatments or factors and the number of surveyed plots in each treatment as replicates.

Households were categorized into three different wealth groups (i.e., poor, middle and wealthy). The grouping of the households into three wealth groups employed a participatory wealth ranking exercise in that wealth categories were defined jointly with the community leader and key informants. Both physical and non-material assets were used as criteria (Table 2). This allowed the study to examine the influence of household characteristics on soil properties.

2.3. *Soil sampling and data collection*

Soil samples were collected from three sampling points from each plot and then mixed to form one composite soil sample. These were taken at depths of 0- to 20- and 20- to 50-cm. During the entire study, a total of 396 composite soil samples were collected. One soil core sample was also taken from each plot for bulk density determination. Data on farm characteristics, such as farm size, vegetation cover, vegetation canopy cover, slope, landform and elevation were collected from each farm plot by using an Open Data Kit (ODK) data recording system on smartphones. The ODK interface was designed to have several pages to input sampling point characteristics, with the software (ODK Collect, XLSForm and ODK Aggregate) obtained from https://opendatakit.org/software/odk/. The approach was developed based on a structured sampling protocol. We used the Braun-Blanquest vegetation rating scale (Braun-Blanquet, 1928) from 0 (bare) to 5 (> 75%) to assess the vegetation cover. Vegetation canopy was also recorded in the field on a scale from 0 (none) to 4 (full cover). Data on household characteristics collected included wealth status, sex, age, livestock holding expressed in tropical livestock unit (TLU) and active labour in the household.

2.4. *Laboratory analysis*

The collected soil samples were air dried and labelled with identification codes provided by the ODK software and then shipped to the James Hutton Institute (Aberdeen, UK) for analysis. Table 3 presents the standard procedures used for soil laboratory analyses.

Table 1

Fertility zones (carbon input systems), their characteristics and major plants grown in Halaba zone, southern Ethiopia. The plants present across the sites are coffee (*Coffea arabica)*, khat (*Catha edulis*), maize (*Zea mays), Teff (Eragrostis tef), sorghum* (*Sorghum bicolor), finger millet (Eleusine coracana)*, pepper (*Capsicum annuum)*, common beans (*Phaseolus vulgaris),* enset (*Ensete ventricosum)*, Eucalyptus (*Eucalyptus camaldulensis*), pencil cactus (*Euphorbia tirucalli*), and various shade trees (*Cordia africana*, *Acacia spp*, *Croton macrostachus*, *Ficus sur, Albizia spp*).

Location of farm plots from Homestead	Characteristics	Major plants grown		
		Andegna Choroko	Asore	Lay Arisho
Close (< 30 m)	House location where herbaceous and perennial crops are grown. Greater use of organic (farmyard manure) and household waste such as ash.	Coffee, fruit trees, khat and maize at relatively high density.	Maize, khat, fruit trees, coffee, and shade trees dominant. Root crops and vegetables (e.g., cabbage). Indigenous and exotic woody species.	Diverse crops - cereals-maize, sorghum, common bean, vegetables, cabbage, shade trees, coffee, fruit trees, khat and enset
Near (30–300 m)	Fields relatively close to the house, where farmers likely apply more organic and inorganic fertilizers compared to Far fields.	Khat and maize dominant. Trees at boundary.	Khat and maize dominant. Trees and pencil cactus at the boundary.	Khat and maize dominant. Peppers, coffee, and fruit trees are also grown. Eucalyptus trees at boundary.
Far (> 300 m)	Fields furthest from house. They tend to receive less organic inputs than Close and Near.	Maize, cabbage, pepper, sorghum, khat and some indigenous scattered trees.	Maize and common beans dominant. Teff, sorghum, and finger millet. Some scattered trees.	Dominated by maize. Some intercropped maize with cabbage. Some scattered trees.

2.5. Data analysis

All statistical analyses were performed using R (R CoreTeam, 2013) at a significance level α of 0.05. Analysis of variance tested the significance of differences in soil properties among treatments. Prior to analysis, model selection and validation were done. Normality and homoscedasticity were tested using the Komolgorov– Smirnov test (R Core Team, 2013) and Levene's test. In addition, all data were inspected visually using q-q plots. A Tukey HSD's post hoc test was used to separate the means at $P < 0.05$.

3. Results

3.1. Soil properties as affected by sites and location from home

We detected significant differences ($P < 0.05$) between sites in most of the soil properties (Tables 4, 5 and 6). For instance, the 0- to 20-cm depth, farmlands in Lay Arisho (higher elevation site) displayed significantly greater soil OC concentration and CEC than Andegna Choroko and Asore, while Andegna Choroko showed significantly greater soil OC concentration and CEC than Asore (Fig. 2 and Table 5). Among the study sites, farmlands in Asore displayed significantly higher bulk density (Table 4).

Table 3

Selected soil properties and methods for laboratory analyses.

Parameter	Methods	Source
pH	1: 2.5 soil: water ratio	Black (1965)
Organic carbon (g/100 g)	Walkley - Black wet oxidation ($L < 2.0$ g/100 g)	Walkley and Black (1934)
CEC (meq. Per 100 g soil)	Summation of exchangeable cations (Ca^{++}, Mg^{++}, Na^{+}, K^{+}, and Al^{+++}	Chapman (1965)
Nitrate N (ppm)	1:2.5 $CaSO_4$ extraction ($L < 2$ ppm; M = 2–20 ppm; $H > 20$ ppm)	Keeney and Nelson (1982)
Olsen P (ppm)	$L < 16$ ppm; H = 16–20 ppm; $VH > 20$ ppm	Olsen et al. (1954)
Available K (ppm)	1 M ammonium acetate extraction ($L < 140$ ppm)	Chapman (1965)
Soil texture	Laser diffraction and calculated on a ternary diagram	Vitton and Sadler (1997)

Note: C = Carbon, SOM = soil organic matter, CEC = cation exchange capacity, N = nitrogen, P = phosphorus, K = potassium, L = low, M = medium, H = high, VH = very high (EthioSIS, 2016).

Table 2

Criteria used by community leaders and key informants to classify households in-to three wealth categories.

Indicators	Andegna Choroko			Asore			Layegnaw Arisho		
	Wealthy	Middle	Poor	Wealthy	Middle	Poor	Wealthy	Middle	Poor
Natural Capital									
Land holding (ha)	>1.5	0.5–1.5	<0.5	>3	1–3	<1	3	1–3	<1
Livestock holding (number)									
Ox	>2	<2	≤ 1	>4	1	0	4	0	0
Cow	NC	NC	NC	>2	1	0	>4	<3	0
Shoat	>5	3–5	0	>10	3–10	1	>5	3–5	<2
Housing condition									
House roof type	CS	GR	GR	CS	GR	GR	CS	GR	GR
House in urban area	Yes	No	No	Yes	No	No	Yes	No	No
Separate animal stall	Yes	No	No	Yes	No	No	Yes	No	No
Financial Capital									
Children in school	Yes (Private)	Yes (Public)	No	NC	NC	NC	Yes (Public)	No	No
Cash crops	Yes	No	No	Yes	No	No	Yes	No	No
Saving account	NC	NC	NC	Yes	No	No	NC	NC	NC
Investment Agricultural inputs	Yes (In cash)	Yes (Via credit)	No	NC	NC	NC	NC	NC	NC
Non-farm livelihoods	Yes	No	No	NC	NC	NC	NC	NC	NC
Crops yield attained	H	M	L	NC	NC	NC	H	M	L

Note: CS = Corrugate sheet, GR = Grass roof, NC = Not taken as a criterion, H = High, M = Medium, L = Low.

Table 4
Mean (± SE) of soil bulk density and texture in the 0- to 20-cm depth of different carbon input systems and kebeles. Note: N is the number of samples; "Close" is <30 m, "Near" is 30–300 m and "Far" is >300 m. Mean values with different letters in the same column are statistically different at α 0.05. NS not significant at the $p = 0.05$ level and asterisk indicating the level of significance $*p < 0.05$, $**p < 0.01$, $***p < 0.001$. *p < 0.05, **p < 0.01, ***p < 0.001.

		N	Slope (%)	Elevation (masl)	Bulk density (g cm^{-3})	Proportion (%)			Dominant textural Class
						Sand	Silt	Clay	
Andegna Choroko	Close	20	3.6^{a}	1781 ± 10^{a}	1.1 ± 0.0^{a}	37.4 ± 1.6^{a}	50.2 ± 1.2^{a}	12.4 ± 0.5^{a}	Silt loam
	Near	22	2.7^{a}	1782 ± 9.0^{a}	1.1 ± 0.0^{a}	35.2 ± 1.4^{a}	51.5 ± 1.0^{a}	13.3 ± 0.5^{a}	Silt loam
	Far	21	2.0^{a}	1781 ± 9.7^{a}	1.0 ± 0.0^{a}	34.5 ± 1.5^{a}	51.2 ± 0.9^{a}	14.4 ± 0.7^{a}	Silt loam
	F-value		NS	NS	NS	NS	NS	NS	
Asore	Close	25	3.7^{a}	1742 ± 6.0^{a}	1.2 ± 0.0^{a}	47.5 ± 0.9^{a}	43.5 ± 0.7^{a}	9.0 ± 0.3^{a}	Loam
	Near	23	1.8^{a}	1742 ± 6.1^{a}	1.2 ± 0.0^{a}	47.9 ± 1.5^{a}	42.6 ± 1.2^{a}	9.5 ± 0.4^{a}	Loam
	Far	23	2.2^{a}	1743 ± 6.0^{a}	1.3 ± 0.0^{a}	48.5 ± 1.9^{a}	41.9 ± 1.5^{a}	9.6 ± 0.5^{a}	Loam
	F-value		NS	NS	NS	NS	NS	NS	
Lay Arisho	Close	23	6^{a}	1868 ± 11^{a}	1.0 ± 0.0^{b}	39.2 ± 2.2^{a}	48.5 ± 1.7^{a}	12.3 ± 0.8^{c}	Loam
	Near	20	5^{a}	1867 ± 12^{a}	1.1 ± 0.0^{ab}	32.5 ± 1.1^{b}	51.2 ± 1.1^{a}	16.3 ± 0.7^{b}	Silt loam
	Far	21	4^{a}	1869 ± 12^{a}	1.1 ± 0.0^{a}	30.1 ± 1.2^{b}	49.9 ± 0.9^{a}	20.0 ± 1.3^{a}	Silt loam
	F-value		NS	NS	3.5*	71.3***	NS	15.2***	
	Adegna Choroko	63	2.6^{b}	1781 ± 6.0^{b}	1.1 ± 0.0^{b}	35.7 ± 0.8^{b}	51 ± 0.6^{a}	13.3 ± 0.3^{a}	Silt loam
Site[1]	Asore	71	2.6^{b}	1742 ± 3.4^{c}	1.2 ± 0.0^{a}	47.8 ± 0.8^{a}	43 ± 0.6^{b}	9.2 ± 0.2^{b}	Loam
	Lay Arisho	64	5.2^{a}	1868 ± 7.0^{a}	1.1 ± 0.0^{b}	34.0 ± 1.1^{b}	50 ± 0.7^{a}	16.0 ± 0.7^{a}	Silt loam
	F-value		6.1**	147.8***	26.8***	71.3***	46.2***	46.2***	

[1] Site refers to compilation of data based on the aggregated data for each kebele (i.e., without considering fertility zones), N = sample size.

Table 5
Statistical analysis of selected soil properties in the 0- to 20-cm depth of different carbon input systems (home, near, far) and kebeles (Andegna Choroko, Asore, Lay Arisho). Note: CIS = carbon input systems, KE = kebeles, OC = organic carbon, CEC = cation exchange capacity, nitrate-N, P = phosphorus and K = available potassium; Values reported are the F-values from the ANOVA and asterisk indicating the level of significance. NS not significant at the $p = 0.05$ level and *p < 0.05, **p < 0.01, ***p < 0.001.

Soil properties	Carbon input system (CIS)	Kebele (KE)	CIS X KE
OC (g/100 g)	38.36***	69.30***	8.65***
OC (t ha^{-1})	32.17***	49.44***	6.20***
pH (H_2O)	46.87***	3.99*	NS
CEC (meq/100 g)	31.67***	84.20***	2.69*
Nitrate-N (ppm)	21.41***	NS	NS
P (ppm)	54.58***	NS	3.33*
K (ppm)	85.32***	NS	NS

To get better understanding on the difference in soil properties, similar carbon input systems at different sites were compared and the results indicated that farmlands located in the same fertility zones displayed differences in some of the soil properties (Figs. 2, 3 and 4). For example, in the 0- to 20-cm depth, farmlands located close to homestead in Lay Arisho kebele displayed significantly greater OC concentration and CEC than farmlands near to the homestead in Andegna Choroko and Asore, while the values in Andegna Choroko were significantly greater than Asore (Fig. 2). Farmlands located far from the homestead in Lay Arisho had significantly less soil P compared to the same fertility zones in Andegna Choroko and Asore (Fig. 3). Farmlands located far from the homestead in Asore had signficanlty higher soil K compared to the same fertility zones in Andegna Choroko and Lay Arisho (Fig. 4).

In the 0- to 20-cm and 20- to 50-cm depths, significant differences were found between the three distances from the home within a farm in most of soil properties (Figs. 2, 3, 4 and Tables 5, 6). For example, in the 0- to 20-cm soil depth of all the studied kebeles, farm plots close to the home (or high carbon input system) displayed significantly greater soil OC concentration (Fig. 2 and Table 5) and stock (Fig. 5), and soil nitrate N content (Fig. 2 and Table 5) compared to the values in near and far

Table 6
Mean (± standard error) of selected soil properties in the 20- to 50-cm of different carbon input systems and kebeles. Note: OC = organic carbon, CEC = cation exchange capacity, nitrate-N, P = phosphorus and K = available potassium; "Close" is <30 m, "Near" is 30–300 m and "Far" is >300 m. Mean values with different letters are statistically different at α 0.05. NS not significant at the $p = 0.05$ level and asterisk indicating the level of significance *p < 0.05, **p < 0.01, ***p < 0.001. *p < 0.05, **p < 0.01, ***p < 0.001.

			OC (g/100 g)	pH (H2O)	CEC	Soil nutrients		
		Sample size				Nitrate-N (ppm)	P (ppm)	K (ppm)
Andegna Choroko	Close	20	1.49 ± 0.1^{a}	7.11 ± 0.1^{a}	15.6 ± 0.4^{a}	23.0 ± 3.8^{a}	18.9 ± 3.5^{a}	1028 ± 76^{a}
	Near	22	1.38 ± 0.1^{a}	6.74 ± 0.1^{b}	14.4 ± 0.3^{ab}	13.7 ± 1.1^{b}	9.38 ± 2.3^{b}	660 ± 50^{b}
	Far	21	1.39 ± 0.0^{a}	6.58 ± 0.1^{b}	13.5 ± 0.4^{b}	14.4 ± 1.4^{b}	6.14 ± 0.7^{b}	508 ± 36^{b}
	F-value		NS	9.7***	7.6**	4.5*	16.6***	22.5***
Asore	Close	25	1.05 ± 0.1^{a}	7.15 ± 0.1^{a}	14.0 ± 0.5^{a}	23.8 ± 2.8^{a}	17.0 ± 2.7^{a}	1047 ± 54^{a}
	Near	23	0.94 ± 0.0^{a}	7.05 ± 0.1^{a}	13.1 ± 0.3^{a}	12.2 ± 2.1^{b}	9.26 ± 2.3^{b}	786 ± 46^{b}
	Far	23	0.03 ± 0.0^{a}	6.95 ± 0.1^{a}	13.3 ± 0.6^{a}	10.8 ± 1.5^{b}	8.61 ± 1.2^{b}	718 ± 35^{b}
	F-value		NS	NS	NS	10.5***	5.3**	14.4***
Lay Arisho	Close	23	1.72 ± 0.1^{a}	7.28 ± 0.1^{a}	18.7 ± 0.9^{a}	28.8 ± 5.3^{a}	21.0 ± 2.3^{a}	1090 ± 96^{a}
	Near	20	1.31 ± 0.1^{b}	6.94 ± 0.1^{ab}	16.4 ± 0.7^{ab}	12.5 ± 1.4^{b}	6.84 ± 0.9^{b}	615 ± 59^{b}
	Far	21	1.17 ± 0.1^{b}	6.73 ± 0.2^{b}	16.2 ± 0.6^{b}	10.2 ± 1.3^{b}	4.0 ± 0.5^{b}	454 ± 39^{b}
	F-value		8.6***	6.2**	3.5*	8.5***	18.5***	21.9***
Site	Adegna Choroko	63	1.4 ± 0.0^{a}	6.8 ± 0.1^{b}	14.5 ± 0.2^{b}	17.0 ± 2.6^{a}	11.5 ± 1.2^{a}	732 ± 42^{a}
	Asore	71	1.0 ± 0.0^{b}	7.1 ± 0.1^{a}	13.5 ± 0.3^{b}	15.8 ± 3.0^{a}	11.4 ± 1.4^{a}	856 ± 31^{a}
	Lay Arisho	62	1.4 ± 0.1^{a}	7.0 ± 0.1^{b}	17.2 ± 0.5^{a}	17.8 ± 3.0^{a}	12.4 ± 1.6^{a}	428 ± 54^{a}
	F-value		38.4***	4.2*	32.5***	NS	NS	NS

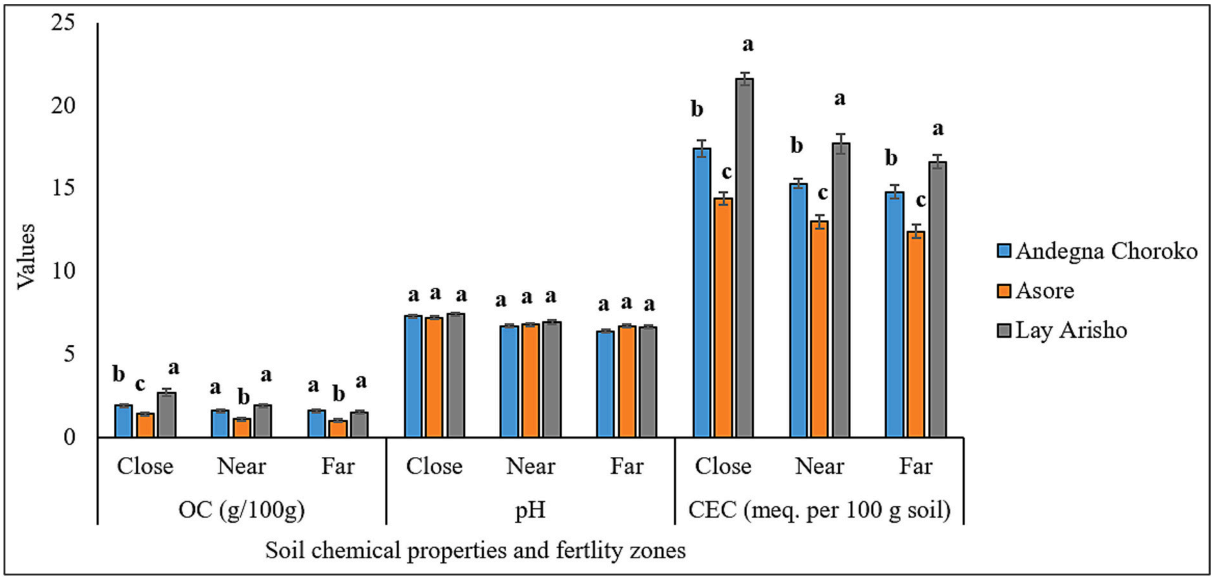


Fig. 2. Soil OC (g/100 g), pH and CEC (0-20cn depth) of farm fields at similar fertility zones in study kebeles.

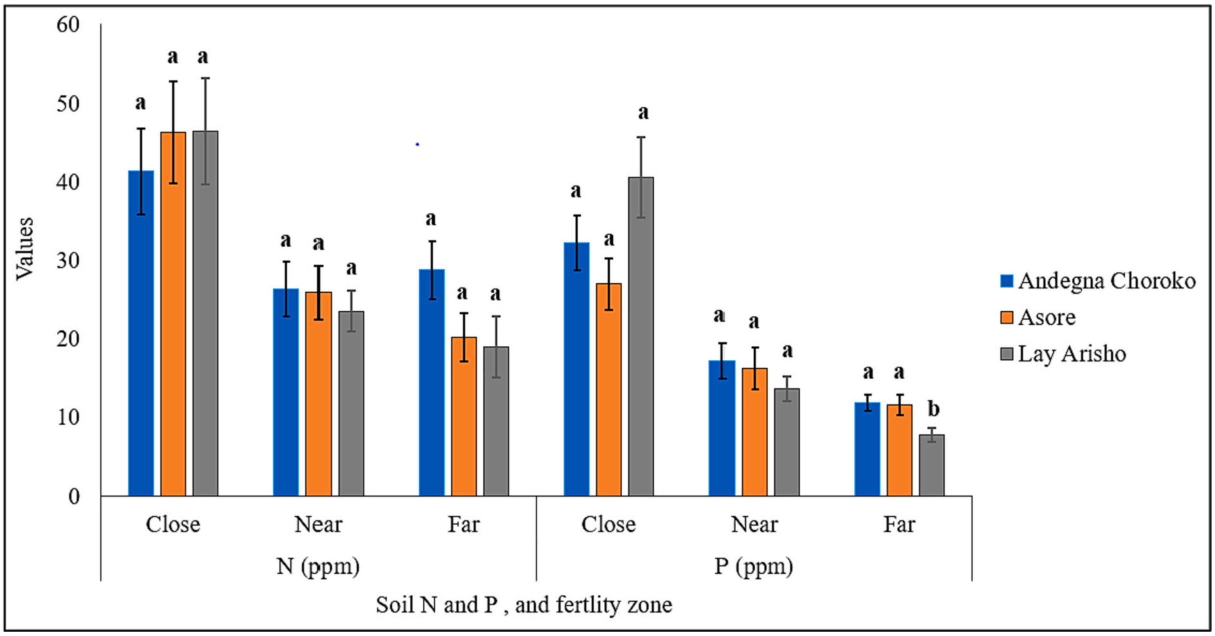


Fig. 3. Soil nitrate-N and P (0-20cn depth) of farm fields at similar fertility zones in study kebeles.

farm plots (i.e., the relatively lower carbon input systems). Also, at both depths, the soils of the studied sites displayed a pH close to neutral (Fig. 2 and Table 6) and the pH was higher in farm plots located close to homestead areas compared to the values in farm plots located near and far from homestead areas. The value of OC stock in the 0- to 20-cm depth of farm plots close to the home ranged from 29.0 to 50.6 t ha^{-1} with a mean value of 39.1 t ha^{-1} in Andegna Choroko, 20.6 to 51.2 t ha^{-1} with a mean value of 32.4 t ha^{-1} in Asore and 26.1 to 84.6 t ha^{-1} with a mean value of 55 t ha^{-1} in Lay Arisho (Fig. 5).

At Lay Arisho kebele, farm plots located close to homesteads had significantly lower bulk density than plots located far from home. Soils close to home had greater sand content than near and far from home farm plots, whereas farm plots located far from home had greater clay content (Table 4). Relatively higher slopes were recorded at farm plots located close to homesteads than plots located near and far from home (Table 4).

The mean difference of soil chemical properties among the three farm plots, close, near and far, displayed a consistent pattern (Figs. 6 a -f). In all cases, the mean difference in soil properties between close and far farm plots were significantly greater when compared to the mean differences in soil properties between near and far farm plots ($P < 0.01$). For example, the mean difference in OC stock between close and far was 10.7 t ha^{-1}, while it was 7.7 t ha^{-1} between close and near, and 2.8 t ha^{-1} between near and far farm plots (Fig. 6 a).

3.2. *Influence of household and farm characteristics on soil properties*

To evaluate the influence of household and farm characteristics on selected soil properties, the whole farmlands were considered. The analysis of variance indicated that some of the household and farm characteristics significantly ($P < 0.05$) influenced soil properties, agreeing to some extent with household and farm characteristics that

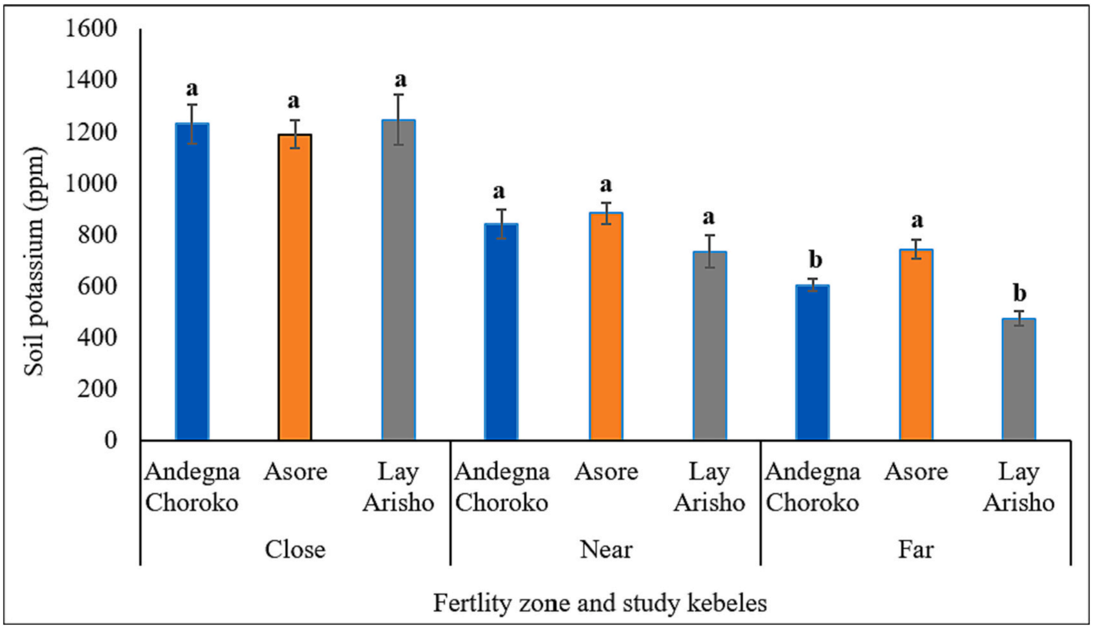


Fig. 4. Soil K (0-20cn depth) of farm fields at similar fertility zones in study kebeles.

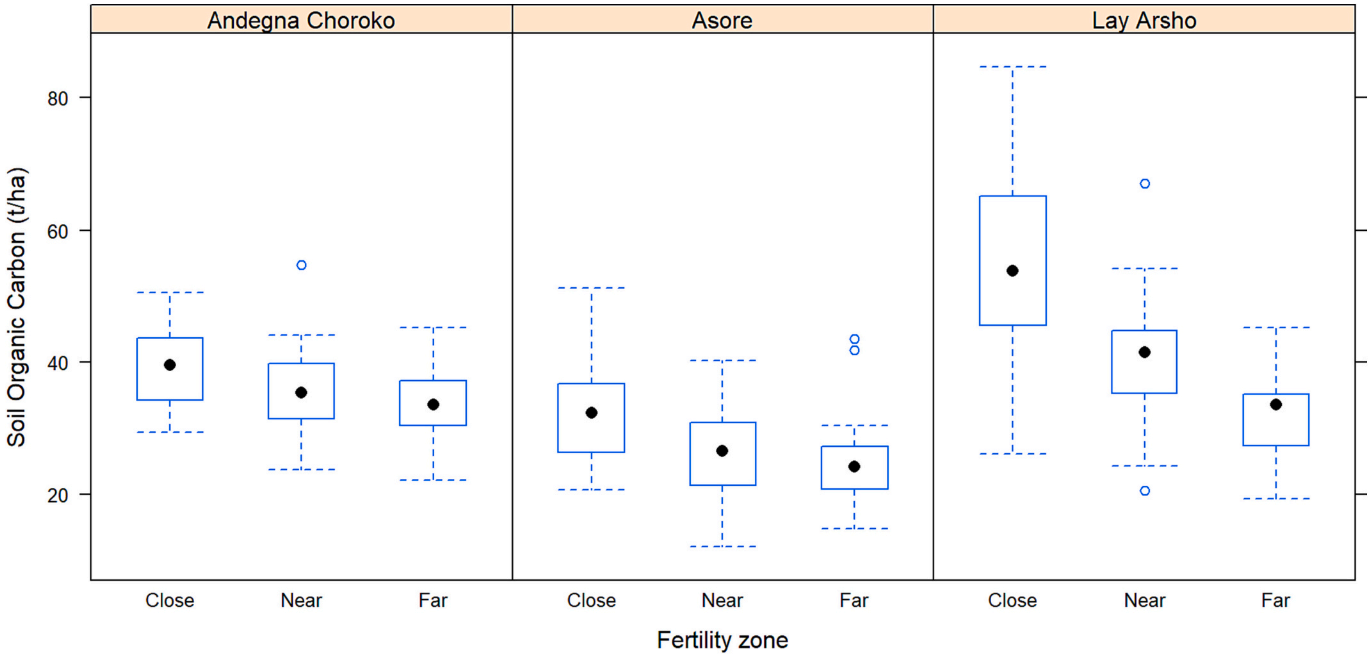


Fig. 5. Soil organic carbon stock (t ha^{-1}, 0-20 cm depth) at three fertility zones or carbon input systems. Note: "Close" is <30 m, "Near" is 30–300 m and "Far" is >300 m.

may influence the amount of carbon that can be added to the soil (Table 7). For example, soil OC varied significantly with gender (being male or female headed households) and wealth at Andegna Choroko and Lay Arisho, respectively (Table 7). Farmlands managed by female headed households at Asore had significantly greater pH, CEC, K and soil P than farmlands managed by male headed households (Table 7). At one of the three sites (i.e., Lay Arisho), farmlands managed by rich farmers displayed significantly greater soil OC content and soil pH than farmlands managed by middle income farmers (Table 7). However, non-significant results were observed in soil OC for the remaining two sites (i.e., Andegna Choroko and Lay Arisho).

Also, farmlands managed by female headed households in Andegna Choroko displayed significantly greater soil OC stock than farmlands managed by male headed households (Fig. 7 b). In Lay Arisho, farmlands managed by rich farmers showed significantly greater soil OC stock than farmlands managed by middle income and poor farmers (Fig. 7 a). Furthermore, soils in farmlands with higher vegetation canopy cover (5–25%) showed significantly greater soil OC stocks at Lay Arisho and Asore kebeles (Fig. 8). Other household characteristics (livestock number and active household labour) and farm characteristics (farm size, vegetation cover, elevation, distance to urban market, and slope and landform of the field) did not significantly influence soil properties (Supplementary table 1).

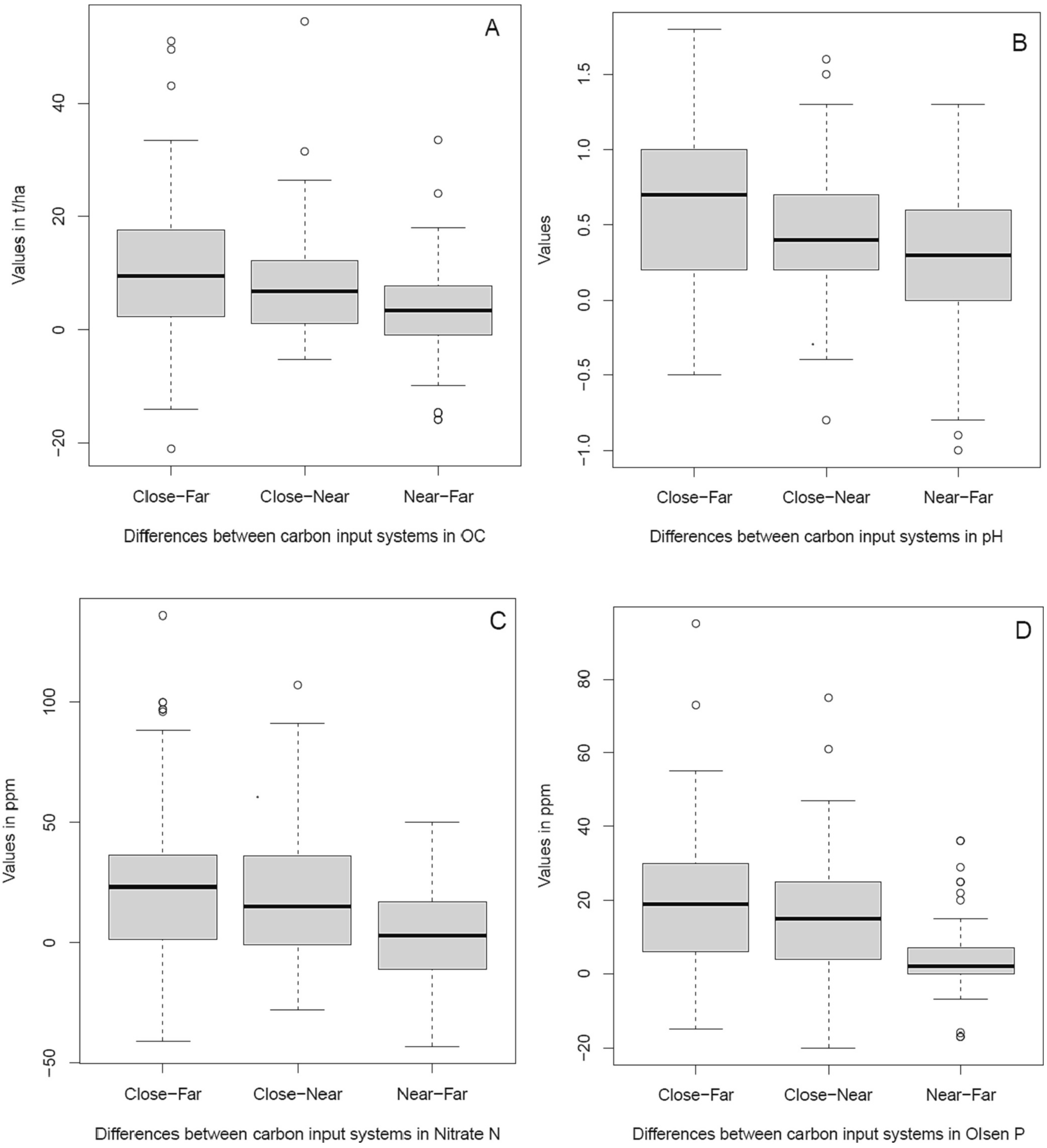


Fig. 6. Differences in selected soil properties (0-20 cm depth) between different carbon input systems: (a) soil organic stock, (b) soil pH, (c) Nitrate-N, (d) Olsen P, (e) cation exchange capacity (CEC) and (f) average K. Note: "Close" is <30 m, "Near" is 30–300 m and "Far" is >300 m.

4. Discussion

From a broad survey of three kebeles in Southern Ethiopia, we found a clear trend of declining topsoil organic matter with distance from the home. These trends were affected by different carbon input systems and household characteristics, which also affected other key soil properties. The consistently higher OC content of soils located close to homesteads (Fig. 2) and their higher OC stock (Fig. 5) across all the studied kebeles can be attributed to the application of farmyard manure, household waste and increased carbon inputs through litter fall and root turnover from perennial and annual crops (Hao et al., 2003; Shukla et al., 2006; Liu et al., 2018; Ichinose et al., 2020). Continuous organic inputs from farmyard manure and litter fall ascribed to the long years of soil amendment is likely to have played an important role in the maintenance of soil OC levels, which in turn improved soil quality and productivity (Laekemariam, 2020). In addition, higher vegetation cover

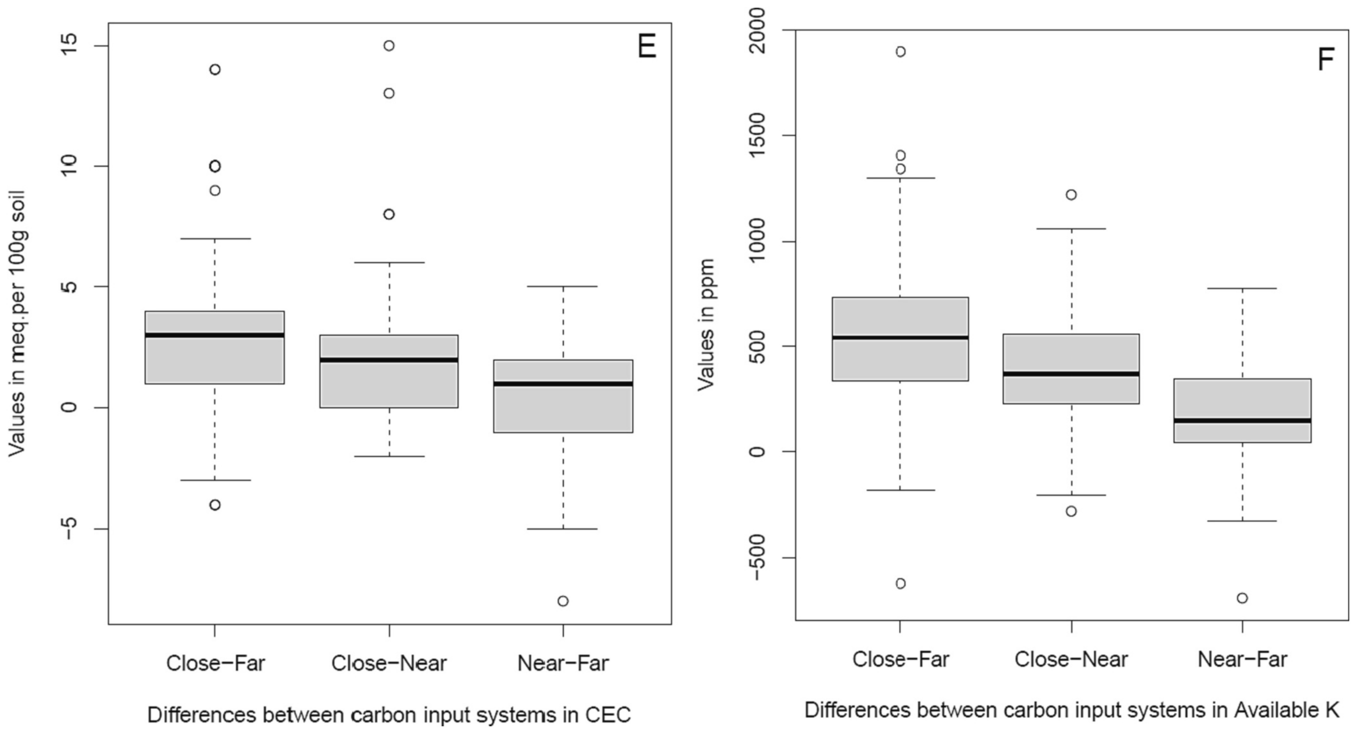


Fig. 6. (*continued*).

Table 7

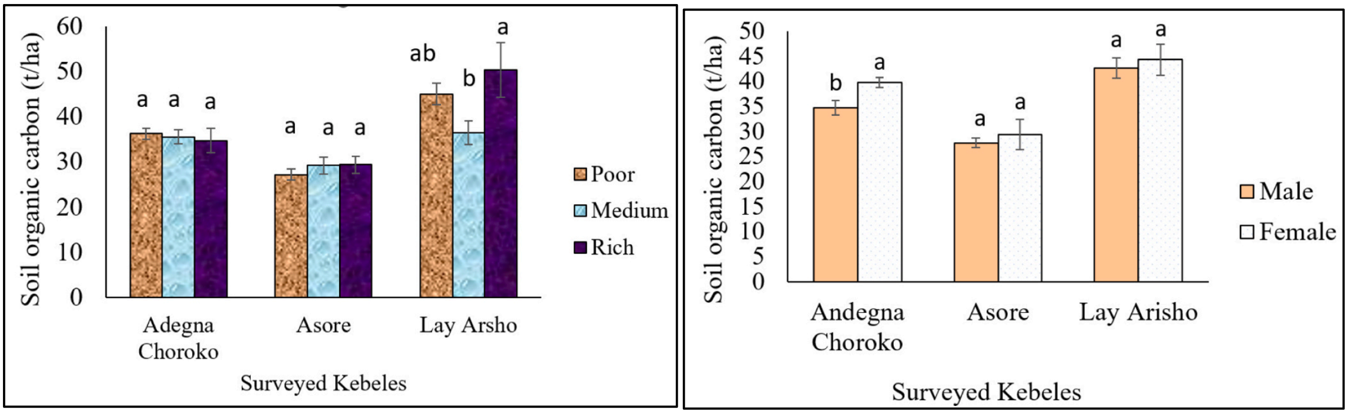
Soil properties in the 0- to 20-cm depth of farmlands managed by female and male headed households and by households categorized under different wealth categories. Note: OC = organic carbon, CEC = cation exchange capacity, nitrate-N, P = phosphorus and K = available potassium. Mean values with different letters in the same column are statistically different at α 0.05. NS not significant at the p = 0.05 level and asterisk indicating the level of significance *p < 0.05, **p < 0.01, ***p < 0.001.

	Gender of household head							
Sites	Gender		OC (g/100 g)	pH	CEC	Soil nutrients		
		N				Nitrate-N (ppm)	P (ppm)	K (ppm)
Andegna Choroko	Male	48	1.6 ± 0.1^{b}	6.8 ± 0.1^{a}	15.7 ± 0.3^{a}	31 ± 2.9^{a}	20 ± 2.1^{a}	888 ± 53^{a}
	Female	15	1.9 ± 0.1^{a}	6.7 ± 0.1^{a}	16.0 ± 0.4^{a}	36 ± 5.4^{a}	21 ± 3.5^{a}	881 ± 94^{a}
	F-value		5.1*	NS	NS	NS	NS	NS
Asore	Male	57	1.2 ± 0.0^{a}	6.8 ± 0.1^{b}	13.1 ± 0.2^{b}	30 ± 3.2^{a}	16.2 ± 1.5^{b}	911 ± 36^{b}
	Female	14	1.3 ± 0.1^{a}	7.2 ± 0.1^{a}	14.4 ± 0.7^{a}	37 ± 8.2^{a}	27.9 ± 5.2^{a}	1094 ± 91^{a}
	F-value		NS	0.002	0.02	NS	0.004	0.03
Lay Arisho	Male	58	2.0 ± 0.1^{a}	7.0 ± 0.1^{a}	18.5 ± 0.5^{a}	29.6 ± 3.4^{a}	20.8 ± 2.8^{a}	828 ± 62^{a}
	Female	6	2.2 ± 0.2^{a}	7.2 ± 0.2^{a}	20.3 ± 0.8^{a}	33.8 ± 5.5^{a}	24.0 ± 6.2^{a}	821 ± 141^{a}
	F-value		NS	NS	NS	NS	NS	NS
	Wealth status of the household							
	Wealth	N	OC (%)	pH	CEC	N	P	K
Andegna Choroko	Poor	30	1.8 ± 0.1^{a}	6.9 ± 0.1^{a}	16.2 ± 0.4^{a}	32.7 ± 4.2^{a}	22.1 ± 2.9^{a}	934 ± 72^{a}
	Middle	24	1.6 ± 0.1^{a}	6.8 ± 0.1^{a}	15.6 ± 0.4^{a}	27.7 ± 3.2^{a}	19.7 ± 2.7^{a}	870 ± 73^{a}
	Rich	9	1.6 ± 0.1^{a}	6.6 ± 0.2^{a}	15.1 ± 0.6^{a}	40.6 ± 6.6^{a}	14.8 ± 2.8^{a}	771 ± 85^{a}
	F-value		NS	NS	NS	NS	NS	NS
Asore	Poor	37	1.1 ± 0.1^{a}	6.9 ± 0.1^{a}	13.3 ± 0.3^{a}	27.4 ± 4.2^{a}	19.1 ± 2.8^{a}	942 ± 52^{a}
	Middle	25	1.2 ± 0.1^{a}	6.9 ± 0.1^{a}	13.3 ± 0.4^{a}	34.6 ± 5.5^{a}	17.0 ± 2.0^{a}	934 ± 58^{a}
	Rich	9	1.4 ± 0.1^{a}	6.9 ± 0.1^{a}	13.8 ± 0.6^{a}	37.6 ± 5.6^{a}	20.0 ± 3.7^{a}	1004 ± 73^{a}
	F-value		NS	NS	NS	NS	NS	NS
Lay Arisho	Poor	34	2.2 ± 0.1^{a}	7.1 ± 0.1^{ab}	19.4 ± 0.7	34.2 ± 4.8^{a}	23.9 ± 4.1^{a}	855 ± 80^{a}
	Middle	22	1.7 ± 0.1^{b}	6.8 ± 0.1^{b}	17.1 ± 0.7	22.5 ± 3.6^{a}	14.8 ± 3.1^{a}	698 ± 91^{a}
	Rich	8	2.3 ± 0.3^{a}	7.4 ± 0.2^{a}	19.6 ± 1.4	31.4 ± 8.5^{a}	25.8 ± 6.3^{a}	1048 ± 172^{a}
	F-value		3.7*	3.5*	NS	NS	NS	NS

Note: N = sample size.

reduces soil erosion and the loss of OC and soil nutrients (Tsegaye and Struik, 2001). By contrast, cereal based mono-cropping farming systems with minimal addition of organic inputs and repeated ploughing dominates in farm plots located near and far from homestead areas (Negasa et al., 2017; Wolka et al., 2021). This leads to deterioration of the physical, chemical and biological condition of the soil (Lagomarsino et al., 2011; Singh et al., 2011), further reducing the accumulation of soil OC (Mganga and Kuzyakov, 2014; Yusoff et al., 2017). Similarly, other studies reported higher soil OC and nutrients in farm plots located close to homesteads compared to fields away from the dwellings (Elias et al., 1998; Samake et al., 2005).

The increase in soil OC with elevation might be attributed to the lower mineralization rate at the higher altitude (Bangroo et al., 2017). Other studies reported higher SOC with increasing elevation (Elias et al., 1998; Krishnan et al., 2007; Sheikh et al., 2009; Bargali and Bargali, 2020). The lower soil P in farmlands located far from homesteads in Lay



(a)

(b)

Fig. 7. Soil organic carbon stock (0-20 cm depth) of farmlands: (a) farmlands managed by male and female headed households, (b) farmlands managed by different wealth categories of farmers.

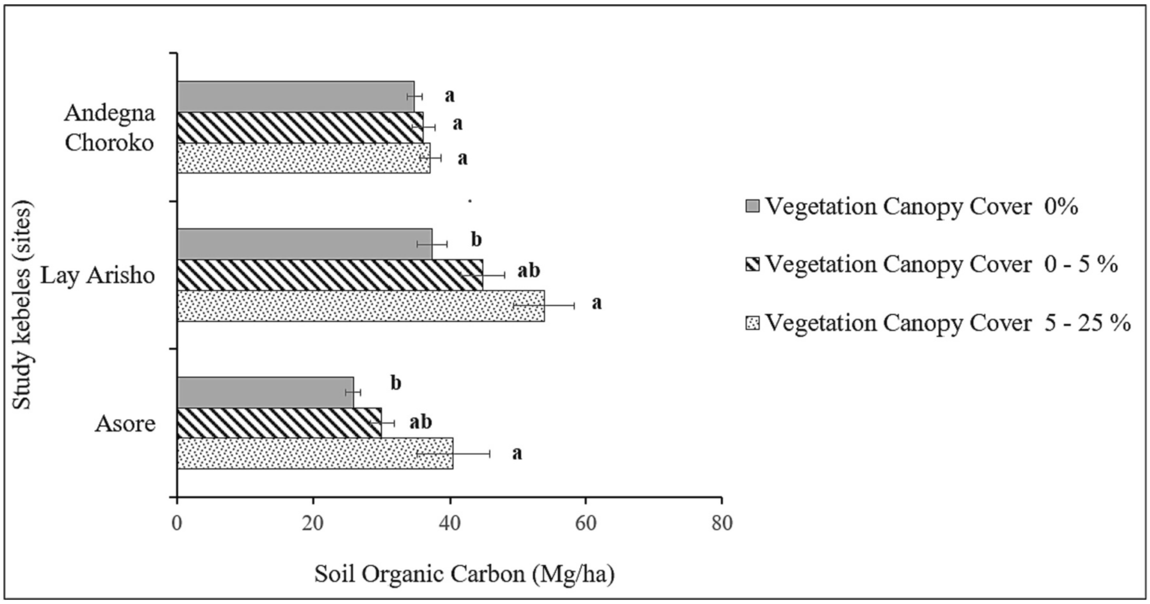


Fig. 8. Soil organic carbon (0-20 cm depth) of farmlands with different vegetation canopy cover.

Arisho (a site exhibiting higher elevation), compared to the same fertility zones in Andegna Choroko and Asore, could be explained by the influence of elevation on availability of soil P (Vincent et al., 2014). Various global studies also reported that soil P availability decrease with increasing elevation (Reich and Oleksyn, 2004; Soethe et al., 2008; Vincent et al., 2014; Mou et al., 2020).

In general, the surveyed farmlands across the kebeles had low soil OC, moderate CEC, and high to very high K (EthioSIS, 2016). Low organic carbon and CEC is typical in many Sub-Saharan African soils due to climate and soil driven rapid turnover of organic carbon, soil erosion and resource poor, extractive farming practices (Kiflu and Beyene, 2013; Laekemariam, 2020; Kebebew et al., 2022). Soils in this region have inherently high K due to their volcanic origin and genesis (EthioSIS, 2016).

The relatively more alkaline soil pH values in farmlands located close to homestead areas (Fig. 2 and Table 6) was probably due to the addition of ash, which is common practice in southern Ethiopia (Bationo et al., 2007; Kiflu and Beyene, 2013; Bajigo and Tadesse, 2016; Negasa et al., 2017; Salim et al., 2018; Wolka et al., 2021). There was likely to have been a positive impact on plant growth, which in turn enhances carbon inputs to the soils. Such increases in carbon inputs improve OC and other associated soil properties.

The significant difference in CEC among the studied soils could be due to differences in OC. This is also supported by a strong and significant correlation between soil OC and CEC in all sites (Fig. 9). Previous studies also reported greater CEC for home garden soils of southern Ethiopia (Wolka et al., 2021), but also in Uganda and Kenya (Tittonell et al., 2013) and on the east coast of Peninsular, Malaysia (Yusoff et al., 2017). Similarly, the continuous addition of manure, compost, and ash to the soils around the homesteads contributed to greater P (>20 ppm), (Miheretu and Yimer, 2018) and K values (Ovung et al., 2021; Dori et al., 2022).

The lower bulk density at farm plots close to homestead areas of Lay Arisho kebele could be due to the continuous application of farmyard manure, household waste and increased carbon inputs through litter fall and root turnover from perennial and annual crops. The contribution of vegetation to reduced soil bulk density was reported by Santos et al. (2021). On the other hand, higher soil bulk density at farm plots far from

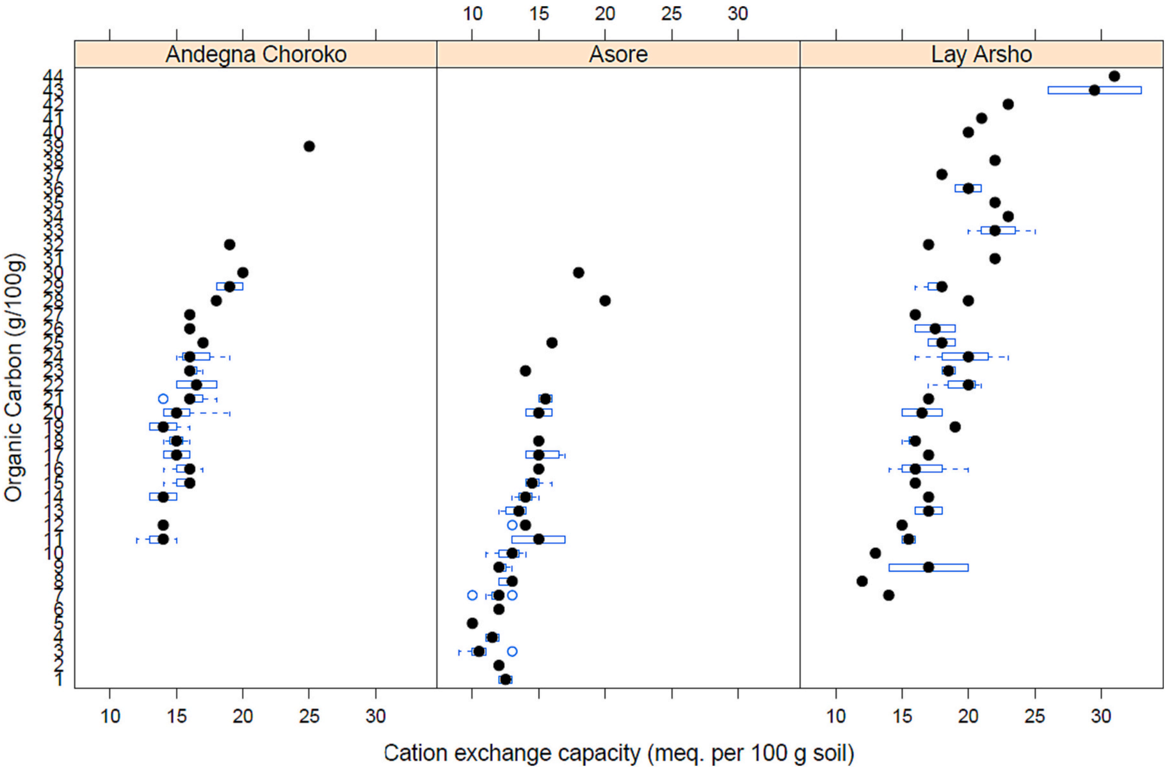


Fig. 9. Relationship between soil organic carbon (OC) and cation exchange capacity (CEC) of surface soil (0-20 cm) in the studied kebeles.

the homestead was probably due to continuous tillage, which in turn lowered soil OC and the stability of the soil against physical degradation (Strudley et al., 2008; Negasa et al., 2017). Studies conducted in Ethiopia and elsewhere in the world also reported negative association between soil bulk density and soil OC (Wang et al., 2020; Seifu et al., 2021). The significantly higher sand and lower clay content at farm plots close to homestead in Lay Arisho could be partly ascribed to the difference in slope of farm plots. Farm plots close to the homestead displayed relatively steep (higher) slope compared to farm plots located near and far from homestead areas. This, in turn, would be expected to increase soil erosion and removal of fine particles from the surface soil. Other studies (Li and Lindstrom, 2001; Wubie and Assen, 2020) reported a linear decrease in clay content and a corresponding increase of sand content in the steeper slope.

Greater utilization of farmyard manure and household waste by female-headed households than male-headed households at Andegna Choroko and Asore could explain the higher soil OC in farmlands managed by female headed households (Daadi and Latacz-Lohmann, 2021). The proximity of the Andegna Choroko and Asore kebele to an urban market could encourage male headed household to engage in non-farm business (Emeru et al., 2022), leading to less utilization of farmyard manure and household waste. This result is inconsistent with Abebe and Debebe (2019) who in the Amhara region, Northwestern Ethiopia reported male-headed households were more likely to use organic fertilizers than female-headed households. The significantly higher soil OC content in farmlands managed by rich farmers compared to middle income farmers in Lay Arisho kebele could be attributed to their larger livestock holdings, thereby providing better access to animal manure to be applied to farmlands (Daadi and Latacz-Lohmann, 2021). Interestingly, lower income farms had similar OC content to rich farms, and more than middle income farms. Poor farmers depend heavily on organic resources to restore soil fertility, as they do not have capacity to purchase inorganic fertilizers, so this might help restore soil organic carbon. In line with this, Mekuria et al. (2022) indicated that household wealth was one of the factors influencing the implementation and the sustainable use of organic soil amendments, such as the addition of manure.

5. Conclusions

Under traditional Ethiopian farming practices, fields close to homesteads have the greatest soil carbon and nutrients, with levels decreasing at further distances. The results also suggest that soil properties varied with farm and household characteristics, such as elevation, wealth, and gender. This, in turn, suggest that improving agricultural productivity through the planning, design and implementation of soil management practices need to consider differences in household and farm characteristics. Out-scaling farm management practices that are common around homesteads would help improve key soil properties and agricultural productivity. Further research is needed to investigate the carbon and nutrient balance under different carbon input systems.

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.

Data availability

Data will be made available on request.

Acknowledgements

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.geodrs.2023.e00710.

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