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Soil organic carbon and associated soil properties in Enset (*Ensete ventricosum* Welw. Cheesman)-based homegardens in Ethiopia

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ABSTRACT

Enset (*Ensete ventricosum* Welw. Cheesman)-based homegardens have long been practiced as central elements of agricultural land management and food security in south and southwest Ethiopia. In contrast to the homegardens' biodiversity and role in food security, soil quality has received little attention. Objective of this study was to assess soil quality parameters in typical homegardens in comparison with adjacent croplands, both under continuous management for >30 years. The study was undertaken at high (2200–2330 masl), mid (1799–1849 masl), and low (1349–1381 masl) elevation in the central Omo-Gibe basin, southwest Ethiopia. Through interviews of 49 randomly selected farm households, and soil sampling at six paired sites at high and mid elevations, and five paired sites of low elevation, we found that homegardens received the majority of household waste and manure and were less frequently tilled. By contrast, some, but not all, croplands occasionally received inorganic fertilizer. Homegarden soil had significantly greater ($P < 0.05$) soil organic carbon (SOC) concentrations than croplands. At 0–20 cm depth, SOC concentrations in homegardens (22.4–26.4 mg g^{-1} soil) were twice as high as in croplands (11.5–12.7 mg g^{-1} soil). Most likely the lower content of SOC in cropland was due to the limited input of organic matter and intensive tillage. The top 60 cm of homegarden soils stored 21–32 Mg ha^{-1} more SOC than adjacent croplands. Homegardens at high elevation had a significantly greater SOC stock ($P < 0.05$) than at low elevation. Hot water extractable (labile) organic carbon levels at 0–20 cm in homegardens (540–649 μg g^{-1} soil) were three to five times greater than in croplands (106–207 μg g^{-1} soil) and was strongly correlated with the SOC concentration ($R^2 = 0.85$, in homegardens). The fraction of water-stable macro-aggregates (>0.5 mm) was positively correlated with the SOC concentration and significantly greater in homegardens than in cropland. Our results show that traditional homegardens represent a sustainable form of land management and cropping system, enhancing SOC concentration, soil structure and fertility.

1. Introduction

The highlands and midlands of south and southwest Ethiopia are dominated by enset-based farming systems, where the tradition of cultivating and preparing food from enset (*Ensete ventricosum* Welw. Cheesman) has existed for more than 5000 years (Negash and Niehof, 2004; Amede and Diro, 2005). Enset is predominantly grown in homegardens near the homestead, whereas more distant fields are used traditionally for annual crops. Enset, a banana-like perennial plant, is staple and important for food security for more than 20 million people in the region (Borrell et al., 2019). Homegardens occupy about 18 % of smallholders' cultivated land and contribute 25–85 % of the households' food demand (Amede and Diro, 2005). Owing to its drought resistance, enset is also an important source of livestock forage in dry periods (Nurfeta et al., 2008). Enset-based homegardens, valued as climate-resilient systems, with great importance in the face of climate change, have extended gradually to central and western Ethiopia. Enset also grows in other countries in east and central Africa, but has not been domesticated (Borrell et al., 2019).

Although little is known about homegarden soils specifically, long-term land management strongly affects soil organic carbon (SOC) concentration and stock (Ogle et al., 2005; Branca et al., 2013), as well as its labile and recalcitrant fractions (Yu et al., 2017). Quantitative and qualitative aspects of SOC may be used as indicators of soil quality and

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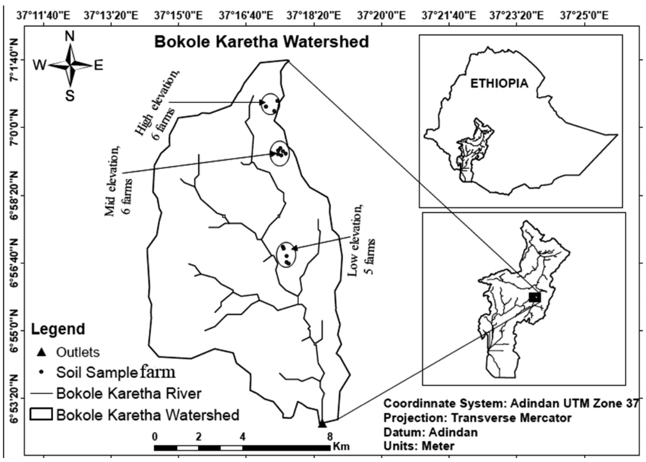

Fig. 1. Location map of the Bokole-Karetha watershed in the Omo-Gibe basin (left), Omo-Gibe basin (right bottom) and Ethiopia (right top).

sustainable productivity (Lal, 2006), but they are superimposed on effects of precipitation (Jobbagy and Jackson, 2000), moisture (Wiesmeier et al., 2013), elevation (Leifeld et al., 2005; Barančíková et al., 2013), and vegetation (Fu et al., 2010). Studies in Europe and North America revealed that intensive tillage reduces SOC (Kasper et al., 2009; Hontoria et al., 2016). By contrast, organic amendments such as livestock manure and household organic waste improve SOC concentration (Nyamangara et al., 2001; Negasa et al., 2017).

Soil organic carbon is important for soil functioning and its sustainable use (Gnanavelrajah et al., 2008; Bajgai et al., 2013). For example, SOC enhances soil aggregation and aggregate stability (Amézketa, 1999; Paul et al., 2013). Soil macro-aggregates (>0.25 mm) increase in response to minimum tillage and organic amendments compared with conventionally tilled fields without organic inputs (Abiven et al., 2009; Loaiza et al., 2018). In conventional cropping, intensive tillage disturbs soil structure, exposes the aggregates to direct solar energy and increases the decomposition process (Paustian et al., 1997; Singh et al., 2011). However, in some cases, the level of soil organic C may not directly be related to the aggregate stability as reported by Devine et al. (2014) for fine-loamy, kaolinitic, thermic soils in the United States, as other factors such as clay minerals and sesquioxides also influence the formation of aggregates (Zhao et al., 2017; Xue et al., 2019). A fraction of soil organic matter is relatively labile, decomposes quickly and contributes significantly to mineralization. Ghani et al. (2003) found hot-water extractable carbon (HWEC) to be a good proxy for labile SOC in cropland soils, forests and pasture of New Zealand.

By contrast to the typical homegardens of southwest Ethiopia, which receive significant amounts of nutrients and organic matter, yet little tillage, croplands further afield receive little fertilizer (be it inorganic or organic) but are ploughed several times per year. The intensity of ploughing differs with elevation, due to type and number of crops grown per year, with two crops per year at mid and low altitude and one at high. The absence of repeated tillage and greater input of organic matter in homegardens compared to cropland has been shown to enhance SOC concentration and stock (Kiflu and Beyene, 2013; Bezabih et al., 2016a). However, the effect of homegardens on associated soil properties such as cation exchange capacity (CEC) (Haileslassie et al., 2006), soil aggregation, aggregate stability and HWEC has been poorly documented. Moreover, the effect of elevation on soil properties in homegardens has received little attention. Understanding the effect of homegardens on soil quality parameters including SOC, aggregate stability and HWEC in different agro-ecological zones is essential for sustainable management. Here, we present an observational study, exploring the effect of land-use history and management on soil quality in both homegardens and cropland further afield at high, mid and low elevations in southwest Ethiopia.

Table 1
Characteristics of the high, mid and low elevation zones of the Bokole-Karetha watershed, southwest Ethiopia (year and slope values indicate mean and standard error).

Description	Location in the watershed, elevation zones		
	High elevation	Mid elevation	Low elevation
Elevation, m above sea level (masl)	2200–2330	1799–1849	1349–1381
Major plants in the Homegardens	*Ensete ventricosum*, cabbage, very few *coffee arabica* and other trees	*Ensete ventricosum, Cordia africana, Coffee arabica, Capsicum annum, Musa paradisiaca* L, *Mangifera indica, Persea americana*	*Ensete ventricosum, Cordia africana, Mangifera indica, Coffee arabica, Moringa oleifera, Colocasia esculenta* L., *Musa paradisiaca* L., *Manihot esculenta*
Major annual crops grown in Croplands	*Vicia faba* L., *Eragrostis tef, Hordeum vulgare* L., *Pisum sativum, Triticum aestivum*	*Zea mays* L., *Eragrostis tef, Sorghum bicolor, Phaseolus vulgaris* L., *Arachis hypogaea* L., *Ipomoea batatas, Manihot esculenta, Zingiber officinalis*	*Zea mays* L., *Eragrostis tef, Sorghum bicolor, Phaseolus vulgaris* L., *Arachis hypogaea* L., *Ipomoea batatas*
Dominant aspect of the sampled plots	West	West	West
Years since sampled homegardens were established, mean ± standard error	38 ± 6.67	37.5 ± 5.74	30.8 ± 5.84
Mean slope of sampled plots, degree,	9.6 ± 2.26	7.3 ± 0.95	11.0 ± 1.90

2. Materials and methods

2.1. Site description

The study was conducted in the Bokole-Karetha watershed, southwest Ethiopia, located between 6°55'–7°01'N latitude and 37°15'E–37°20'E longitude (Fig. 1). The watershed is central in the Omo-Gibe River basin which is of crucial environmental, hydrological, political, and socio-economic importance, due to the trans-boundary and trans-regional Omo River and its large hydro-electric dams. The basin covers a diverse agro-ecological area, due to a variable topography, lithology and climate.

The Bokole-Karetha watershed covers an area of 98.4 km^2. The watershed has an undulating landscape, dominated by steep slopes. Its elevation ranges from 950 to 2400 m above sea level (masl). In the upper part of the watershed, the mean annual rainfall is 1886 mm, with less than 30 mm mean monthly rainfall in December and January. The rainy season, commencing in February and lasting until October, allows two cropping periods at mid and low elevations, viz. February–June and July–October. Mean annual minimum and maximum temperatures are 12.2 °C and 21.9 °C, respectively, in the upper and 22.6 °C and 25.5 °C, respectively, in the lower part of the watershed (Wolka and Zeleke, 2017). Dystric Nitosol is the dominant soil type in the watershed (SNNPRS-BoFED, 2004; WRB, 2015).

The Bokole-Karetha watershed is mainly used by smallholder farmers. Homegardens, around the homestead, are dominated by perennials, in particular enset, in addition to fruit trees, but also vegetables are grown (Table 1). Adjacent cropland is mainly used for cereal production.

Combinations of soil and water management, e.g., crop rotation, intercropping, fallow, as well as soil and stone bunds, are practiced in cropland. Inorganic fertilizer is not commonly used. Depending on crop and labor availability, cropland is ploughed 2–3 times per cropping season with '*Ginda*', a common traditional Ethiopian plough drawn by two oxen. Hand hoes are used for weeding and loosening soil under haricot bean, maize and sorghum. Homegardens are infrequently tilled using a hoe to a depth of 20–30 cm between enset plants. Forest and woodland have largely disappeared from the area due to continued deforestation and expansion of agricultural land. Remaining forest patches exist only at very steep slopes, on shallow soils and in riparian areas. Livestock is an important component of the agricultural system in the area.

2.2. Data collection techniques

2.2.1. Socio-economic parameters and crop production data

The Bokole–Karetha watershed was grouped into three agro-ecological areas based on elevation: viz. high, mid and low (Table 1). Elevation and its associated climate constrain farming activities. Reconnaissance field surveys and interviews with key informants (elder farmers and experts of local agriculture and natural resources) were carried out in each elevational zone to acquire qualitative and quantitative data on settlement history and farmers' land management practices during the past 50 years. To this aim, a total of 49 households (22, 16 and 11 from high, mid and low elevations, respectively) representing about 6 % of the total households in the study area, were sampled randomly and interviewed. The survey encompassed household and socio-economic characteristics, land management practices and perceived challenges of managing homegardens and cropland. Since farmers did not record history of their farming practice, the year that homegardens were established was estimated using different reference times that farmers remembered (e.g., change of government).

2.2.2. Soil sampling from homegarden and cropland

In this observational study, we compare soil properties of homegarden with cropland further afield, both belonging to the same farm. Homegarden and cropland on each farm had similar age and similar topographic features. Seventeen farms (6, 6 and 5 farms at high, mid and low elevations, respectively) were selected, all having been managed for more than three decades. In each elevational zone, the selected farms were located less than ~1.2 km apart. For each elevational zone, the selected farms had similar soil type, major crops and land management history. On each farm, homegarden and cropland further afield were in similar landscape position and not hydrologically connected. Soils of both homegarden and cropland were sampled in triplicate at each of the 0–20, 20–40, and 40–60 cm depth, using a soil auger. If sampling by auger was difficult, soil samples were collected from a small 70 cm deep pit. Soil samples were composites consisting of five sub-samples. On each farm, samples for the analysis of bulk density (BD; 406 cm^3 steel rings) and water-stable aggregates were collected from a single pit (that means, not composite) in both homegarden and cropland. The three replicated plots in each homegarden and cropland were about 10 m (5 m at low elevation) apart, but for cropland always between two consecutive bunds (when soil or stone bunds present). In addition, one pit (1.2–1.4 m deep) was dug in homegarden and cropland of each elevational zone to assess the soil profile.

2.2.3. Soil analyses

2.2.3.1. Soil texture and bulk density. The soil texture of the fine earth fraction (<2 mm) was determined following the hydrometer method (Gee and Bauder, 1986). The BD was determined after oven-drying the soil cores at 105 °C to constant weight. To determine the gravel content, soil samples were transferred to a 2 mm sieve and washed until all the soil was removed. The materials retained on the 2 mm sieve were dried at 105 °C and weighed.

2.2.3.2. Water-stable aggregates. Four size fractions of water-stable aggregates (5–2, 2–1, 1–0.5 and 0.5–0.25 mm) were determined by applying a modified method of Grandy and Robertson (2007); Emadi et al. (2009), and Besalatpour et al. (2013). Briefly, soil samples were air-dried for two weeks at room temperature (about 20 °C). The samples were gently broken by hand along natural planes into smaller sizes and sieved using 5 mm mesh. After sample homogenization, 100 g soil was slaked for 15 min in distilled water and transferred to a set of four stacked sieves (2, 1, 0.5, and 0.25 mm). Distilled water was added until the upper sieve was submersed. The stack of four sieves was moved 3 cm up and down 50 times in 2 min. The materials retained by each sieve were transferred to aluminum containers, oven-dried at 105 °C for 24 h and weighed. The proportion of gravel and sand (>0.25 mm) of each of the aggregate size fractions was determined by shaking 5 g in 15 ml sodium hexametaphosphate solution (5 g l^{-1}) for 17 h, followed by passing through the same sieves. The gravel and sand fraction remaining on each sieve was oven-dried at 105 °C for 24 h and weighed. Finally, the percentage of water-stable aggregate was computed by deducting the gravel and sand (>0.25 mm) content.

2.2.3.3. Soil pH, organic carbon and CEC. Soil pH, SOC and CEC were determined in the fine earth fraction (<2 mm). Soil pH was measured in a soil to water ratio of 2.5 (10 g soil in 25 ml distilled water) using a digital pH meter. The SOC concentration was determined following the Walkley-Black method (Sahrawat, 1982; De Vos et al., 2007). The stock of SOC was computed using Eq. (1):

$$SOC = \sum_{i=1}^{n} SOCi * \rho fi * Di * \left(1 - \frac{GVi}{100}\right) * 10 \tag{1}$$

Where *SOC* is total soil organic carbon stock (Mg ha^{-1}), *SOCi* is the SOC concentration of fine earth in soil layer *i* (kg of SOC per Mg^{-1} of soil), ρf_i the soil bulk density of the fine earth fraction in layer *i* (Mg m^{-3}), *Di* the thickness of layer *i* (m), *GVi* volumetric fraction of gravel >2 mm (%) in layer *i*, multiplied by 10 to correct the unit. The ρfi was calculated using Eq. (2) (Don et al., 2007; Rytter, 2012).

$$\rho fi = \frac{Ms - Mr}{Vs - \frac{Mr}{\rho s}} \tag{2}$$

where ρfi is density of the fine earth fraction in layer *i* (Mg m^{-3}), *Ms* is mass of sampled soil (Mg), *Mr* mass of gravel and stone materials (Mg), *vs* volume of sampled soil (m^3), ρs density of stone (Mg m^{-3}). The volume of gravel materials >2 mm was computed from mass and assumed density of 2.65 Mg m^{-3} (Poeplau and Don, 2013; McClean et al., 2015).

Exchangeable base cations (Ca^{2+}, Mg^{2+}, Na^{+}, K^{+}) were determined following extraction with 1 M ammonium acetate (NH4OAc) buffered at pH 7. Extractable acidity was determined by back-titration with 0.05 M sodium hydroxide to pH 7. The sum of exchangeable base cations and exchangeable acidity was assumed equal to the cation exchange capacity (CEC) (Schollenberger and Simon, 1945).

2.2.3.4. Hot-water extractable carbon (HWEC). The HWEC was determined following the procedure by Ghani et al. (2003). Briefly, 5 g air dried fine earth (<2 mm) was added to a 50 ml centrifuge tube to which 30 ml deionized water was added. The tubes were shaken using a vortex shaker for 1 min and placed in a water bath for 16 h at 80 °C. Then, the tubes were centrifuged at 1960*g* for 15 min and filtered (0.45 µm). The dissolved organic carbon (DOC) was analyzed using a total organic carbon analyzer (TOC-V CPN, Shimadzu).

Table 2
Respondents socio-economic characteristics and land management practices at high, mid and low elevational zones of homegardens (HomeG) and croplands further afield (CropL) in the Bokole-Karetha watershed, southwest Ethiopia (%; mean ± standard error).

Socio-economic characteristics and land management		Elevational zone High, n = 22	Mid, n = 16	Low, n = 11	Significance
Education level	illiterate, %	36.4	50	41.7	ns
	grade1–4, %	13.64	12,5	41.67	ns
	grade5–8, %	31.82	12,5	16.67	ns
	grade>8, %	18.18	12.5	0.0	ns
Family members (mean number)		8.27 ± 0.51	8.38 ± 0.83	8.17 ± 0.37	ns
Livestock owned (mean TLU)		3.78 ± 0.32	3.47 ± 0.39	3.08 ± 0.32	ns
Land owned	HomeG, ha	0.29 ± 0.04a	0.10 ± 0.02b	0.09 ± 0.01b	s
	CropL, ha	0.75 ± 0.12	0.84 ± 0.17	0.63 ± 0.07	ns
Estimated years since the current HomeG established		52.09 ± 7.98	34.0 ± 3.32	44.5 ± 6.49	ns
Generations used the same HomeG, number		2.45 ± 0.34a	1.31 ± 0.14b	3.33 ± 0.48a	s
Estimated amount of household waste and manure added per week on HomeG, m^3*		0.64 ± 0.07	0.54 ± 0.08	0.49 ± 0.02	ns
Changed location of home and HomeG so far	yes, %	18.18	18.75	8.33	ns
	no, %	81.82	81.25	91.67	ns
Changed HomeG area in past 10 years	yes, %	27.27	87.5	75	ns
	no, %	72.73	12.5	25	s
Ploughing frequency in HomeG,	every year, %	4.55	31.27	36.4	s
	every 2 years, %	18.18	18.75	63.61	s
	every 3–5 years, %	77.27	50	0	s
Plots where household waste and manure applied	HomeG, %	100	100	100	ns
	CropL, %	0	0	0	ns
Used inorganic fertilizer in CropL in the past 5 years	yes, %	75	72.71	27.32	s
	no, %	25	45.52	54.45	ns
Perceived challenges on HomG	soil erosion, %	10.53	18.18	18.18	ns
	enset disease, %	23.81	81.82	81.82	ns
	soil fertility decline, %	13.33	18.18	33.33	ns
Perceived challenges on CropL	soil erosion, %	64.7	62.5	54.5	ns
	land shortage, %	82.4	75	81.6	ns
	soil fertility decline, %	94.1	56.3	36.4	s

Note: TLU, tropical livestock unit; s, significant difference ($P < 0.05$) between elevations; ns, not significant ($P > 0.05$) between elevations; mean and standard error of a continuous variable that followed by different small letters indicate significant difference between elevations; *, amount of household waste and manure was estimated from respondents traditional basket used to transport it.

2.3. Statistical analyses

The farmers' response to the interviews was subjected to descriptive statistics, chi-square and analysis of variance (ANOVA). Average values of soil properties were determined for homegardens and cropland based on six (at high and mid elevations) or five farms (at low elevation). Differences between homegardens and croplands were analyzed using the paired *t*-test at each elevation and soil depth. Differences in soil properties with elevation were analyzed with one-way ANOVA for each of the management practices and soil depths separately. The least significance difference (LSD) was applied to determine differences between means. The relationships between SOC and selected soil properties were analyzed for homegardens and cropland separately with a linear regression model. Statistical analyses were conducted using SPSS 21.0 (IBM Co., Armonk, NY, USA) and R 3.6.2 (R core Team, Vienna, Austria).

3. Results and discussion

3.1. Socio-economic characteristics and land management practices

Homegardens accounted for 31 % of the total cultivated land at high elevation, whereas this was 10 % at mid and low elevation (Table 2). This has been attributed to the higher productivity (Tsegaye and Struik, 2003) and lower incidence of pests and diseases (Wolde et al., 2016) of enset at higher elevation. Enset disease was perceived a challenge by 24 % of the respondents at high elevation, while this was 83 % at mid and low elevations (Table 2). Although enset is more drought tolerant than many other crops, the low survival of enset seedlings during the dry season was perceived as a serious challenge for homegardens at low elevation.

Homegardens were perceived to be more important for household food security than cropland, especially at high and mid elevations (96 and 56 % of respondents, respectively). The majority of the respondents (~70 %) favor expanding homegardens, especially at high elevation. This is contrary to other areas of Ethiopia where enset-based homegardens are declining, due to expansion of cash crops such as *Coffee arabica* and *Chata edulis* (Woldeyes et al., 2016; Teklu et al., 2018).

As shown by Amede and Diro (2005), farmers apply all household waste and manure at homegardens, especially in young-aged enset stands. In contrast, inorganic fertilizer is not commonly used in homegardens. In addition, the enset-based homegardens are hoed periodically (once every 2–5 years at mid and high elevation and every 1–2 years at low) and receive regular pruning of the enset leaves. More than 90 % of enset pruning as well as residues of harvest (e.g., scrapings of leaf sheet and corm (Atlabachew and Singh, 2008; Andeta et al., 2019)) is returned to the soil as mulch. Thus, homegardens are islands of fertility and farmers rarely change their location. By contrast, farmers in Kenya change homestead location, which is not enset-based homegarden, every 10–15 years to use fertile soil for crop cultivation (Tittonell et al., 2005).

Management of cropland differs from that of homegardens. A major proportion of the aboveground residue from croplands is consumed by livestock and about 73–83 % of the farmers do not practice fallow, partly due to land shortage. In addition, farmers plough cropland three times per cropping season to prepare seed beds. As a result, the majority of the farmers perceived soil erosion (55–65 %) and soil fertility decline (36–94 %) problems. This confirms earlier studies in the Delta and Arsamma watersheds, Ethiopia, which reported soil fertility decline in cropland compared to enset-based homegarden and coffee-based agroforestry (Bezabih et al., 2016b; Guteta and Abegaz, 2016). Also, in Tanzania, farmers perceived soil fertility decline due to frequent ploughing of cropland (Malley et al., 2006).

Table 3
Sand, clay, silt, bulk density (BD), (n = 6 at high and mid elevation; n = 5 at low elevation), pH (n = 4) and cation exchange capacity (CEC, n = 4) at 0–20, 20–40 and 40–60 cm soil at high, mid and low elevations of homegardens (HomeG) and croplands further afield (CropL) in the Bokole-Karetha watershed, southwest Ethiopia (mean ± standard error).

	Sand, %		Clay, %		Silt, %		Bulk density, g cm^{-3}		pH (H_2O,1:2.5)		CEC, cmol kg^{-1}	
Elevation	HomeG	CropL	HomeG	CropL	HomeG	CropL	HomeG	CropL	HomeG	CropL	HomeG	CropL
0–20												
high	38.0 ± 4.1aA	28.6 ± 2.1aA	27.3 ± 2.8aA	36.4 ± 2.2bA	34.7 ± 4.3aA	35.1 ± 1.7aA	0.97 ± 0.01aA	1.25 ± 0.03bA	6.88 ± 0.06aA	5.91 ± 0.10bA	40.2 ± 2.10aA	30.8 ± 1.45bA
mid	33.2 ± 2.4aA	23.4 ± 1.9bA	27.9 ± 2.0aA	43.8 ± 2.4bB	38.9 ± 1.3aA	32.7 ± 1.4bA	1.05 ± 0.02aAB	1.32 ± 0.02bB	7.37 ± 0.05aB	6.35 ± 0.05bB	32.7 ± 1.00aB	20.8 ± 0.60bB
low	38.6 ± 2.9aA	37.7 ± 2.4aB	32.7 ± 1.8aA	31.4 ± 2.5aA	28.7 ± 2.2aA	30.9 ± 1.9aA	1.10 ± 0.04aB	1.42 ± 0.02bC	7.35 ± 0.06aB	7.10 ± 0.03aC	44.8 ± 3.90aA	35.2 ± 3.25bA
20–40												
high	31.3 ± 2.0aA	29.5 ± 2.4aA	33.2 ± 1.7aA	35.7 ± 3.2aA	35.5 ± 2.0aA	34.9 ± 1.6aA	1.15 ± 0.03aA	1.27 ± 0.02bA	6.43 ± 0.04aA	5.82 ± 0.08bA		
mid	27.9 ± 3.6aA	21.6 ± 1.8aB	37.8 ± 3.8aA	45.9 ± 2.8bB	34.3 ± 2.7aA	32.6 ± 1.4aA	1.21 ± 0.03aA	1.27 ± 0.01aA	7.01 ± 0.03aB	6.25 ± 0.03bB		
low	31.3 ± 1.4aA	36.9 ± 2.0bC	39.8 ± 1.5aA	36.4 ± 1.2bA	29.0 ± 1.4aA	26.7 ± 2.2aB	1.25 ± 0.04aA	1.44 ± 0.03bB	7.45 ± 0.04aC	6.90 ± 0.01bC		
40–60												
high	28.2 ± 0.8aA	26.6 ± 2.5aA	34.9 ± 2.1aA	39.7 ± 3.2aA	37.0 ± 1.6aA	33.8 ± 1.4aA	1.24 ± 0.03aA	1.29 ± 0.02aA	6.38 ± 0.07aA	5.92 ± 0.08bA		
mid	28.1 ± 2.8aA	21.8 ± 1.9bA	40.5 ± 3.5aA	48.4 ± 4.0bB	31.4 ± 2.7aA	29.8 ± 2.2aA	1.23 ± 0.03aA	1.27 ± 0.02bA	6.79 ± 0.03aB	6.29 ± 0.02bB		
low	31.4 ± 1.6aA	37.9 ± 2.6bB	39.2 ± 2. aA	34.5 ± 1.3aA	29.3 ± 2.1aA	27.6 ± 1.9aA	1.23 ± 0.03aA	1.42 ± 0.03bB	7.38 ± 0.06aC	6.85 ± 0.05bC		

Note: mean and standard error followed by different small letters indicate significant difference ($P < 0.05$) between homegarden (HomeG) and cropland (CropL). Different capital letters indicate significant differences ($P < 0.05$) between the three elevations. Number of samples (n):one sample per farm (homegarden/cropland) was considered for sand, clay and silt fractions; for bulk density, the average of three replicates per farm (homegarden/cropland) was considered; For CEC and pH, one sample per farm and four farms (homegarden/cropland) were considered. Total number of farms (homegarden/cropland) were six at upper and middle and five at lower elevation.

Table 4
Fine earth density (n = 6 in high and mid, n = 5 in low elevation), soil organic carbon (SOC, n = 6 in high and mid, n = 5 in low elevation), hot water extractable carbon (HWEC, n = 4), and HWEC% of SOC (n = 4) at 0–20, 20–40 and 40–60 cm soil at high, mid and low elevation of homegardens (HomeG) and croplands further afield (CropL) in the Bokole-Karetha watershed, southwest Ethiopia (mean ± standard error).

Elevation	Fine earth density, g cm^{-3}		Soil organic carbon, mg g^{-1}		HWEC, μg g^{-1} soil		HWEC, % of SOC	
	HomeG	CropL	HomeG	CropL	HomeG	CropL	HomeG	CropL
0–20								
high	0.94 ± 0.01aA	1.22 ± 0.02bA	26.21 ± 1.57aA	12.5 ± 0.41bA	648.50 ± 70.22aA	180.50 ± 12.61bA	2.46 ± 0.13aA	1.43 ± 0.10bA
mid	0.99 ± 0.02aA	1.27 ± 0.01bA	22.43 ± 0.83aA	11.5 ± 0.95bA	582.00 ± 48.18aA	104.50 ± 15.27bB	2.57 ± 0.13aA	1.11 ± 0.16bAB
low	0.91 ± 0.04aA	1.12 ± 0.03bB	26.4 ± 2.24aA	12.68 ± 1.25bA	539.50 ± 80.83aA	206.50 ± 27.11bA	1.94 ± 0.15aB	1.55 ± 0.16bAC
20–40								
high	1.11 ± 0.04aA	1.25 ± 0.02bA	14.0 ± 0.78aA	9.0 ± 0.77bA	303.50 ± 34.99aA	101.00 ± 13.15bA	2.32 ± 0.17aA	1.10 ± 0.08bA
mid	1.21 ± 0.03aA	1.27 ± 0.01aA	12.93 ± 0.71aA	8.74 ± 0.51bA	221.50 ± 21.82aA	47.50 ± 4.98bB	1.69 ± 0.12aA	0.65 ± 0.07bB
low	1.05 ± 0.04aA	1.17 ± 0.03aB	14.17 ± 1.55aA	9.55 ± 1.0bA	262.00 ± 4.59aA	112.00 ± 13.69bA	2.10 ± 0.47aA	1.13 ± 0.10bAC
40–60								
high	1.22 ± 0.03aA	1.27 ± 0.02aA	11.51 ± 0.92aA	8.04 ± 0.77bA	163.50 ± 30.95aA	64.00 ± 8.24bA	1.39 ± 0.15aA	0.85 ± 0.06bA
mid	1.18 ± 0.02aA	1.24 ± 0.02aA	8.81 ± 0.54aB	7.94 ± 0.83aA	129.50 ± 8.69aA	28.50 ± 3.85bB	1.46 ± 0.13aA	0.43 ± 0.05bB
low	1.00 ± 0.05aB	1.14 ± 0.04aB	8.79 ± 0.79aB	8.27 ± 0.61aA	159.50 ± 22.20aA	70.50 ± 6.61bA	2.01 ± 0.26aB	0.92 ± 0.07bAC

Note: mean and standard error followed by different small letters indicate significantly differennce ($P < 0.05$) of fine earth density, SOC concentrations, HWEC, HWEC % of SOC in between homegarden (HomeG) and cropland (CropL). Different capital letters indicate significant differences between the three elevations ($P < 0.05$). Number of samples (n): for fine earth density and SOC, average values of three replicates per farm (homegarden/cropland) (six farms at upper and middle and five at lower elevations); for HWEC, average values of three replicates on four farms (homegarden/cropland).

3.2. Texture, pH and bulk density

Soil texture differed between homegarden and cropland in only a few cases (Table 3). Specifically, at mid and high elevations, surface soils of the homegarden had significantly smaller ($P < 0.05$) clay and greater sand content than cropland. The clay content of cropland at mid elevation was significantly greater (43.8–48.4 %) than that at low and high (31.4–39.7 %) elevations. Soils at low elevation had more sand than those at mid and high elevations. The soil texture data at each of the three elevations suggests that any difference in soil quality between the two forms of land management is not due to preferential selection of inherently clay-rich patches as homegardens.

As expected, the soil pH in homegarden was higher, often significantly ($P < 0.05$), than in cropland (Table 3). Probably this is due to the addition of ash, other household waste and manure (Negasa et al., 2017). Other studies comparing soil pH of homegardens and croplands on Nitisols of southern Ethiopia (Kiflu and Beyene, 2013; Bajigo and Tadesse, 2016) and Burkina Faso (Bationo et al., 2007) also reported greater soil pH in homegardens. Soil pH decreased significantly with elevation in both homegarden and cropland. Most likely this is due to increased leaching of base cations at higher elevations resulting from greater precipitation (Wolka and Zeleke, 2017). A study in the Kilimanjaro area of Tanzania also reported decreasing pH with elevation (Pabst et al., 2013).

Soil BD as well as the density of the fine earth fraction (*ρfi*) of homegardens was significantly smaller ($P < 0.05$) than that of croplands

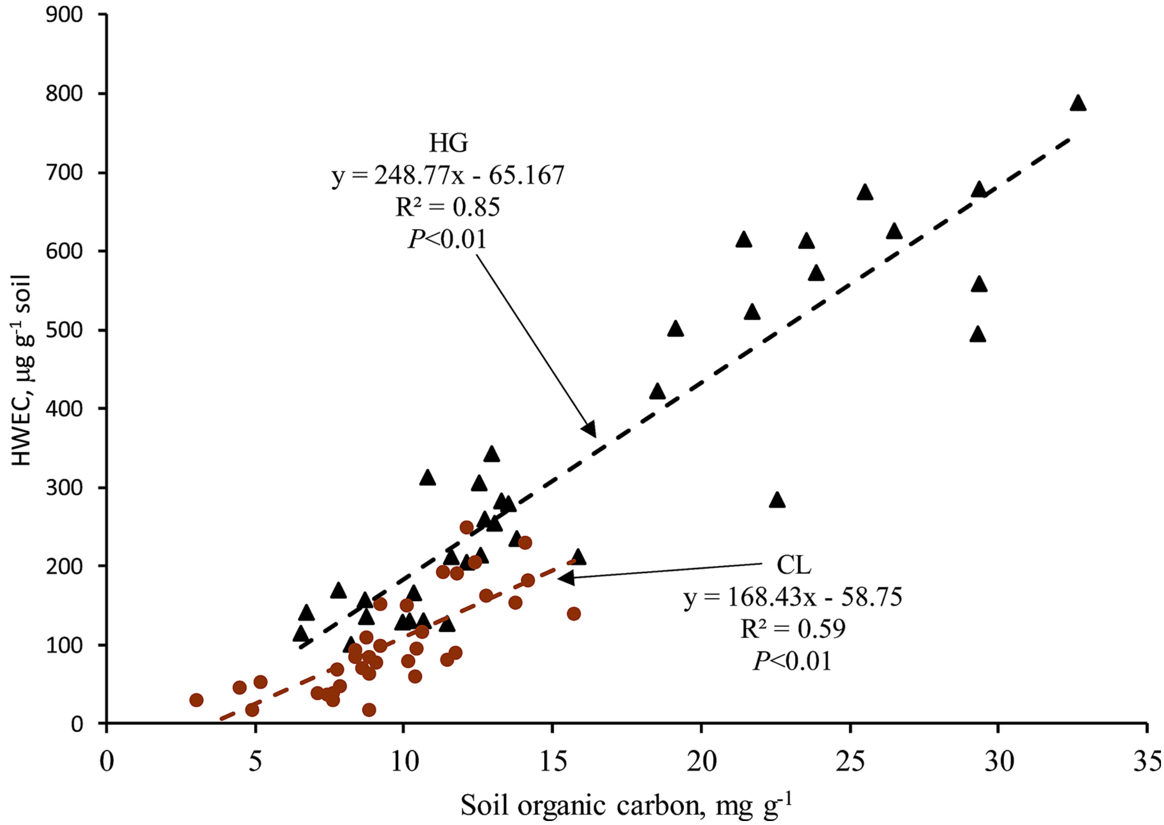

Fig. 2. Relationship between soil organic carbon and hot water extractable carbon (HWEC) at homegardens (HG) and croplands (CL) soils of the Bokole-Karetha watershed, southwest Ethiopia. Note: n = 36 or (average of 3 replicates) * 4 farms (homegarden/cropland)* 3 elevational zones * 3 depths. The SOC of these farms, replicates, depths and elevational zones were included in this regression (n = 36).

at 0–20 and 20–40 cm depths (Tables 3 and 4). This is due to the higher SOC concentration in homegardens (see below). The SOC content had a negative relationship with the fine soil density and the relationship was significant in homegardens (R^2 = 0.3, $P < 0.01$; Fig. S1).

3.3. SOC concentration, HWEC and CEC

At all elevations, the SOC concentration in the fine earth fraction of the upper 20 cm was significantly greater ($P < 0.05$) in homegardens

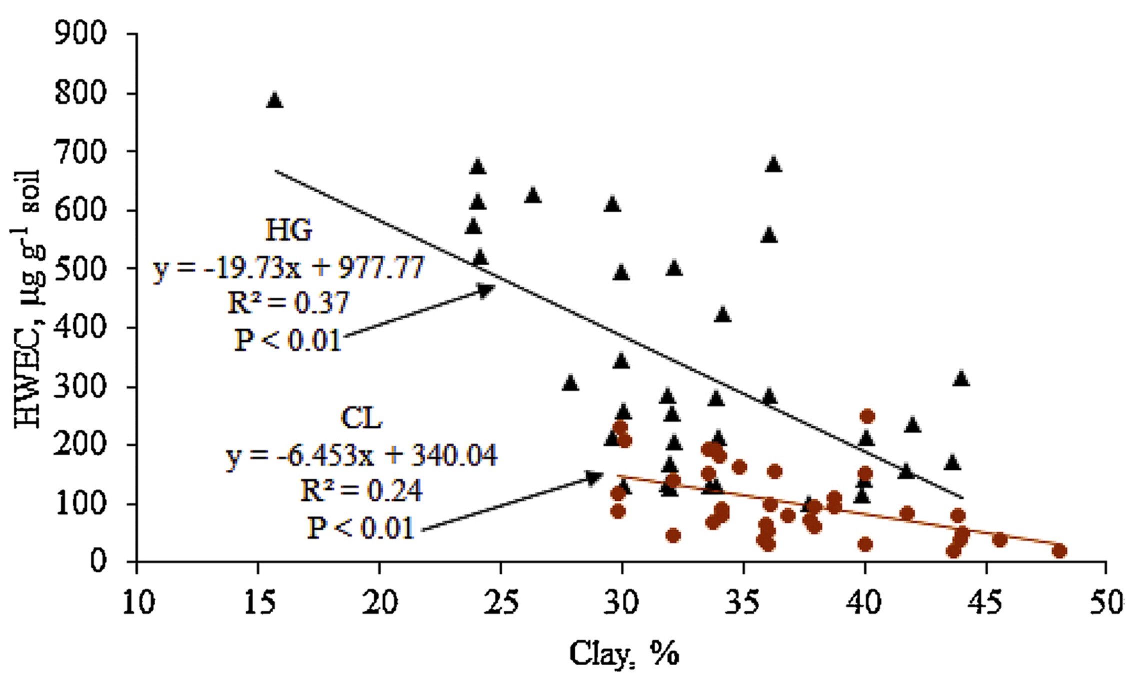

Fig. 3. Relationship between the contents of clay and hot water extractable carbon (HWEC) at homegardens (HG) and croplands (CL) soil of the Bokole-Karetha watershed, southwest Ethiopia. Note: in clay fraction, n = 36 or (average of 3 replicates) *4 farms (homegarden/cropland)* 3 elevational zone * 3 depths.

(22.4–26.4 mg g^{-1} soil) than in cropland (11.5–12.7 mg g^{-1} soil). Also, at 20–40 cm depth, but not at 40–60 cm, the SOC concentration was significantly greater in homegardens ($P < 0.05$; Table 4). In addition to the larger organic inputs (manure, household waste and tree litter), in homegardens the permanent vegetation cover (Table 1) helped preventing soil erosion, thus limiting loss of organic topsoil (Tsegaye and Struik, 2001). Cropland, on the other hand, received little, if any organic input due to crop residue harvesting and roaming livestock and may experience significant SOC losses due to frequent soil tillage and erosion (Table 2). The difference in SOC concentration is supported by the darker color of the soil in homegardens compared to the cropland further afield (e.g., at mid elevation 10YR 2/2 and 10R 3/3, respectively, Table S1; Fig. S2). Earlier studies elsewhere in Ethiopia also reported higher SOC content in enset-based homegardens than in cropland (Bezabih et al., 2016a). Similarly, coffee-enset-tree agroforestry had higher SOC content than khat, sugarcane or cropland (Kim et al., 2016; Negasa et al., 2017). Increased SOC concentrations were reported in Kenya and Uganda for homegardens without enset (Tittonell et al., 2013).

By contrast to the study at the Kilimanjaro, Tanzania (Pabst et al., 2013), the Bokole-Karetha watershed did not show significantly different SOC concentration in the surface soil with elevation, neither in homegardens nor in croplands despite the noticeable difference in temperature and precipitation (Wolka and Zeleke, 2017). Perhaps the lack of significant differences in SOC concentration with elevation was due to interlinked processes affected by land management practices and climatic conditions. For instance, higher biomass production at low elevation may be offset by a higher decomposition rate (Alvarez and Lavado, 1998).

The labile C, assessed using HWEC values, showed a strong relationship with the SOC concentration in homegardens ($R^2 = 0.85$, $P < 0.01$) and cropland ($R^2 = 0.59$, $P < 0.01$; Fig. 2). Hot water extractable carbon was significantly greater ($P < 0.05$) in homegardens than cropland in all soil layers and at all elevations (Table 4). Studies in China reported the strong influence of land use type on the labile fraction of SOC, where cultivated land showed less HWEC than non-cultivated land (Jinbo et al., 2006; Yu et al., 2017). The higher ratio of HWEC to SOC is an important indicator of the quality of homegarden soils as HWEC has a short turnover time, quickly releases plant nutrients and is a major energy source for soil microbes (Sparling et al., 1998; Ghani et al., 2003). As in other studies, we found that the HWEC and its proportion in SOC decreased with increasing depth (Chodak et al., 2003; Jinbo et al., 2006).

Soils at mid elevation had less HWEC ($P < 0.05$) than those at high and low elevations. The amount of HWEC was negatively related to the soil's clay content, which was significantly greater ($P < 0.05$) at mid elevation both in cropland and homegarden (Fig. 3). The negative relationships between clay and HWEC could be due to physical protection of particulate organic carbon by the clay fractions (Franzluebbers and Arshad, 1997). As expected, in homegardens and cropland at the three elevations, the HWEC and its proportion of SOC decreased with increasing depth, with few exceptions (Table 4), due to decreasing SOC with increasing depth.

The soil's CEC at 0–20 cm depth in homegardens (40.2, 32.7, 44.8 $cmol_c$ kg^{-1} at high, mid and low elevation, respectively) was significantly greater ($P < 0.05$) than in croplands (30.8, 20.8, 35.2 $cmol_c$ kg^{-1}, respectively; Table 3; Table S2). Probably, this is due to the important concentration of SOC as the relationship between CEC and SOC was significant ($P < 0.05$) both in homegarden ($R^2 = 0.58$, $P < 0.01$) and cropland ($R^2 = 0.35$, $P < 0.05$; Fig. S3). Also, previous studies reported greater CEC for enset-based homegardens of Gununo watershed, southern Ethiopia (Bajigo and Tadesse, 2016) and non-enset-based homegardens in Uganda and Kenya (Tittonell et al., 2013). The CEC increase with the concentration of soil organic matter and thus SOC was also reported for Mollisols and Ultisols in Argintina (Peinemann et al., 2000) and Acrisols of Zambia (Martinsen et al., 2017). The relationship between CEC and clay was not significant ($P > 0.05$) in homegardens and cropland. Martinsen et al. (2017) also reported a weak relationship between clay and CEC in the eastern province of Zambia. This suggests that in the study area the SOC is more important to affect the level of CEC than clay content.

Table 5
Percent of water-stable aggregate at 0–20 and 20–40 cm soil depths at high, mid and low elevation of homegardens (HomeG) and croplands further afield (CropL) in the Bokole-Karetha watershed, southwest Ethiopia (mean ± standard error, n = 4).

Elevation	Elevation zone	Water-stable aggregates, %			
		2–5mm	1–2 mm	0.5–1mm	0.25–0.5 mm
High					
0–20	HomeG	4.88 ± 0.87a	12.27 ± 1.41a	19.73 ± 1.59a	29.88 ± 2.30a
	CropL	4.28 ± 2.24a	6.87 ± 1.85b	8.51 ± 1.70b	22.22 ± 2.16b
20–40	HomeG	4.07 ± 0.94a	10.22 ± 0.91a	23.11 ± 1.85a	26.14 ± 2.79a
	CropL	4.02 ± 0.99a	11.25 ± 1.74a	19.20 ± 3.84a	26.19 ± 3.90a
Mid					
0–20	HomeG	4.55 ± 1.26a	10.81 ± 1.91a	19.93 ± 2.45a	29.15 ± 2.14a
	CropL	2.79 ± 1.18b	5.88 ± 1.15b	12.56 ± 1.77b	28.84 ± 2.42a
20–40	HomeG	1.95 ± 0.43a	5.87 ± 0.65a	18.03 ± 0.81a	31.33 ± 3.18a
	CropL	1.93 ± 0.21a	7.79 ± 1.36a	18.21 ± 3.43a	29.99 ± 0.98a
Low					
0–20	HomeG	5.12 ± 0.65a	9.58 ± 1.54a	21.48 ± 5.11a	25.57 ± 2.46a
	CropL	7.70 ± 1.49b	8.38 ± 1.13a	13.92 ± 3.33b	22.70 ± 2.21a
20–40	HomeG	1.66 ± 0.16a	5.60 ± 0.97a	16.43 ± 1.87a	33.72 ± 2.69a
	CropL	3.67 ± 0.16b	10.21 ± 0.85b	18.35 ± 1.03a	22.25 ± 0.21b

Note: mean and standard error followed by different small letters show significant difference ($P < 0.05$) between homegarden (HomeG) and croplands further afield (CropL). Number of samples (n): average of three replicates per farm (homegarden/cropland) in four farms.

3.4. Water-stable aggregates and SOC stock

In the upper 20 cm of the soil, water-stable macro-aggregates (>0.25 mm) were more abundant in homegardens than in croplands mainly at high and mid elevations (Table 5; Table S3). The fraction of water-stable aggregates of 2–5, 1–2 and 0.5–1 mm at 0–20 cm soil depth was positively correlated ($P < 0.05$) with the concentration of SOC in homegardens, but not in cropland (Fig. 4). Probably, the smaller content of water-stable aggregates in cropland is due to low organic matter input and frequent disturbance resulting from ploughing. Our findings confirm previous studies reporting fewer macro-aggregates in cropland compared to other less disturbed land uses (Liu et al., 2014) and positive effects of cattle manure and other organic matter input on aggregate stability (Nyamangara et al., 2001; Wagner et al., 2007; Karami et al., 2012). The higher content of water-stable aggregates as found in homegardens are known to protect and facilitate storage of SOC (Andruschkewitsch et al., 2014; Wang et al., 2014) through physical stabilization, which also decreases erodibility (An et al., 2010; Annabi et al., 2011, 2017). The majority of the farmers that were interviewed also perceived less erosion in the homegardens. Earlier, Barthes and Roose (2002) and Cantón et al. (2009) reported that the abundance of macro-aggregates (>0.25 mm) indicates soil quality and plays an important role in tolerating soil erosion.

The content of water-stable aggregates in homegardens, did not

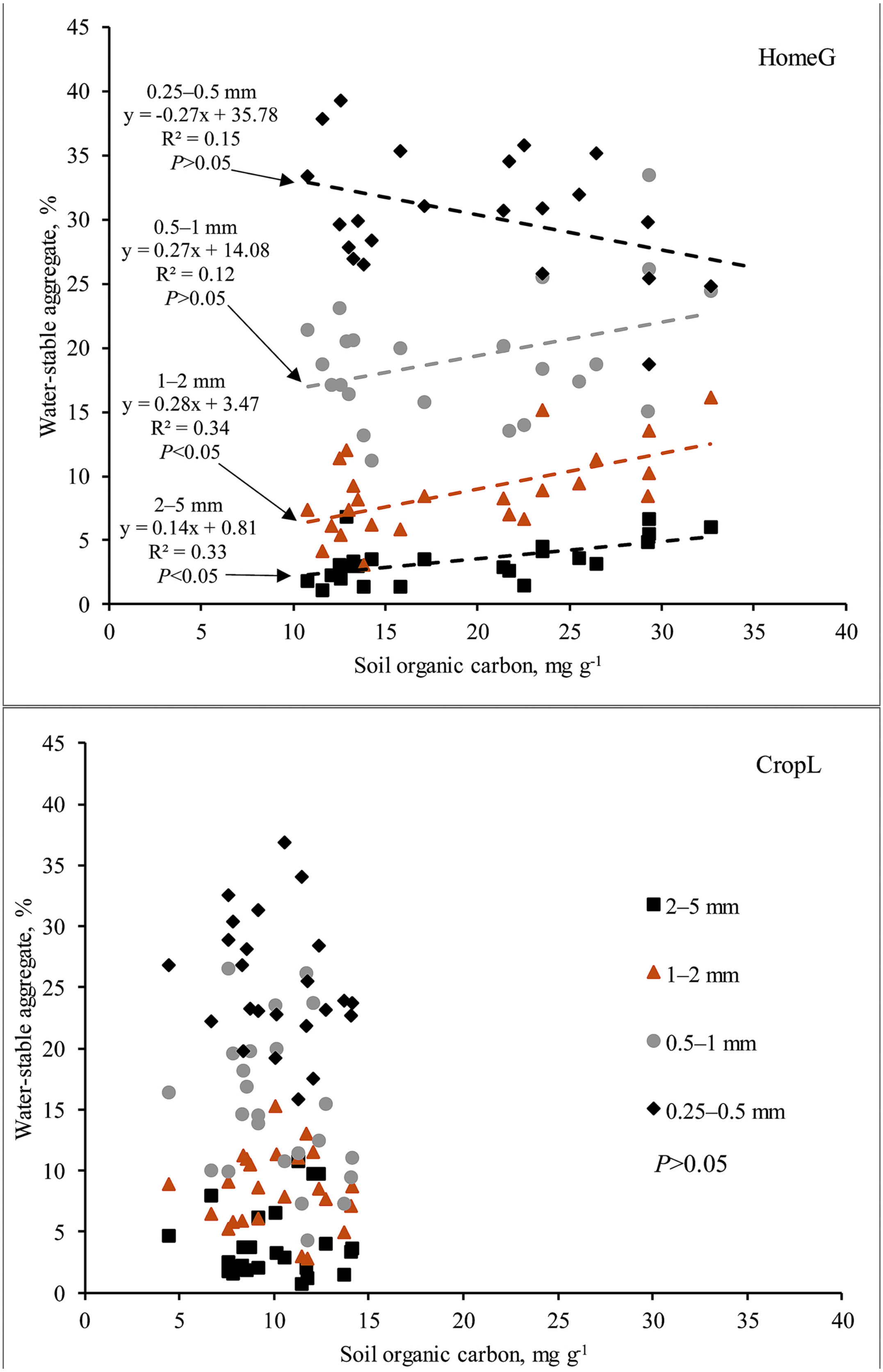

Fig. 4. Relationship between soil organic carbon concentrations and water-stable aggregates (2–5, 1–2, 0.5–1 and 0.25–0.5 mm) at 0–20 and 20–40 cm homegardens (HomeG, top) and croplands (CropL, bottom) soil of the Bokole-Karetha watershed, southwest Ethiopia. Note: n = 24 or (average of 3 replicates per homegarden/ cropland) *4 farms considered* 3 elevational zone * 2 depths).

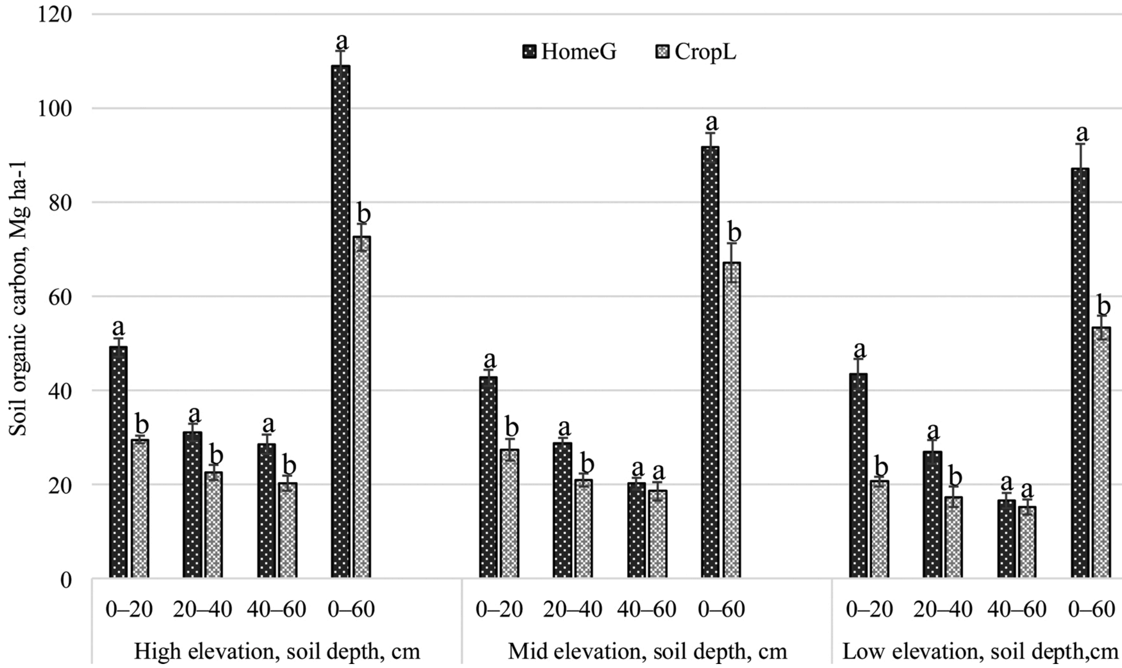

Fig. 5. Soil organic carbon stocks (Mean ± standard error, n = 6 at high and mid, 5 at low elevations) at homegarden (HomeG) and croplands further afield (CropL) in high, mid and low elevation areas of the Bokole-Karetha watershed, southwest Ethiopia. Bars and SE shown with different small letters indicate significant difference ($P < 0.05$) between HomeG and CropL. Note: n is average of 3 replicates per farm.

differ significantly between elevations. By contrast, cropland at low elevation had significantly greater contents of water-stable aggregates ($P < 0.05$) than at high and mid elevations (Table S3). Regarding the soil depths, in homegardens, the 2–5 mm and 1–2 mm water-stable aggregates at 0–20 cm soil depth were significantly greater ($P < 0.05$) than at 20–40 cm depth (especially at mid and low elevations), due to higher SOC in the topsoil. As in previous studies, cropland had considerably greater 1–2 mm and 0.5–1 mm water-stable aggregates at 20–40 cm soil depth than in the upper 20 cm, probably due to breaking soil aggregates caused by ploughing (Álvaro-Fuentes et al., 2008; Paul et al., 2013; Kabiri et al., 2015).

The SOC stock in the upper 20 cm of homegarden soils (42–50 Mg ha^{-1}) was 34–70 % greater than that of croplands (22–30 Mg ha^{-1}), but differences were smaller at 20–40 and 40–60 cm depth (Fig. 5). The relative share of the 0–20 cm soil to the total SOC stock was greater in homegardens than in cropland (about 50 % and 40 %, respectively, Table S4), which is due to the greater input of organic waste and manure in homegardens. The total SOC stock in the upper 60 cm of the soil was greater in homegardens (107.6, 91.7, 87.9 Mg ha^{-1} at high, mid and low elevations, respectively) than in croplands (70.7, 69.0, 56.4 Mg ha^{-1} at high, mid and low elevations, respectively). Homegardens at high elevation stored significantly ($P < 0.05$) greater SOC than at low elevation, partly due to high SOC concentration and density of the fine earth fraction in the sub-soil. The SOC stock (0–60 cm soil depth) in homegardens of the Bokole-Karetha watershed was smaller than values reported for older-aged coffee-tree-enset based agroforestry systems in the Gedeo area, Ethiopia, (109–253 Mg ha^{-1}; Negash and Starr, 2015). However, our results were higher than estimates for other forms of homegardens with diverse species in India, ~60–66 Mg ha^{-1} (Saha et al., 2009).

4. Conclusion

In southwest Ethiopia, enset-based homegardens receive most of the household waste and manure while only some croplands further afield receive small amounts of inorganic fertilizers. The homegardens are less frequently ploughed, while the croplands are ploughed on average three times per crop growing season. At 0–20 cm layer, SOC concentrations of homegardens, managed on average for more than three decades, were almost twice as high as those in croplands. The upper 60 cm soil of the homegardens stored greater SOC (88–108 Mg ha^{-1}) than adjacent croplands (56–71 Mg ha^{-1}). The labile soil carbon fraction (HWEC) was significantly greater in homegardens and was positively correlated with SOC concentration. The homegardens topsoil possessed greater percentage of water-stable aggregates making them more resistant to water erosion. It can be concluded that land management practices of enset in homegardens, important for food security, has highly contributed to the enhanced soil properties. This observational study showed that the homegardens management practice appeared sustainable and should be promoted to increase food security.

Declaration of Competing Interest

The authors report no declarations of interest.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.still.2020.104791.

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