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# The impact of household wealth on soil organic carbon and nitrogen stocks in enset (*Ensete ventricosum* (welw.) *cheesman*) based farming systems in southern Ethiopia

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ABSTRACT

Enset [*Ensete ventricosum (welw.) cheesman*] is a multi-purpose perennial crop that is an important keystone species for home garden agroforestry systems in Ethiopia and has great potential to increase resilience to climate change, sequester carbon and reduce net greenhouse gas emissions. Therefore, it could be an important crop to be grown more widely in the future. Carbon sequestration is in part due to application of large amounts of organic matter to enset. However, availability of organic matter for use in enset-based farming systems is likely to be related to wealth status of farmers. Because evidence on the influence of wealth on soil carbon is limited, this study assessed influence of household wealth on soil organic carbon, nitrogen and carbon dioxide emissions from enset-based farming systems in southern Ethiopia. Farmlands managed by resource rich farmers had significantly higher organic carbon in 0–20 cm soil depth (4.6 % and 5.8 %) than those managed by resource-poor farmers (3.7 % and 4.3 %). Total nitrogen followed similar trends. Results suggest that wealth status influences soil properties by determining organic inputs, highlighting the importance of livestock. Resource-poor farmers who do not own livestock should therefore take measures to obtain inputs from other sources, such as compost or vermi-compost.

## 1. Introduction

Enset [*Ensete ventricosum (welw.) cheesman*] is a multi-purpose perennial crop that is a staple/co-staple food for approximately 20 million people in the south-central, south, and southwestern parts of Ethiopia [1]. It is one of the important keystone species for home garden agroforestry system [2]. The traditional perennial crop-based agroforestry systems are known by the combination of two native perennial crops, enset and coffee (*Coffea arabica*) [3], with practices varying from place to place to include other trees with enset and coffee, other trees with enset alone or just coffee combined with enset [4] depending on farmer's interest and management system. Enset has great potential to increase resilience to climate change, sequester carbon and reduce net greenhouse gas emissions and it could be an important crop to be grown more widely in the future. Beyond the benefits of enset production in the home garden system, assessment of its contribution for climate mitigation through below ground carbon storage and removal of carbon dioxide from the atmosphere is important information needed by local decision-makers and international organizations for its wider distribution and use.

Soils are important sinks of atmospheric carbon (C) and provide a significant contribution to climate change mitigation [5]. They hold a large share of the global C; approximately two times the amount held in vegetation and two-thirds more than in the atmosphere [5]. Therefore, maintaining or increasing soil organic C (SOC) through improved soil management practices has received worldwide attention in the context of international policies to mitigate $CO_2$ emission [6,7]. Small changes in SOC can have a big impact on atmospheric [8]. For example, the "4 per 1000" (4p1000) initiative on soil for food security and climate, aims to sequester approximately $3.5 \times 10^9$ t of C (equivalent to $1.3 \times 10^{10}$ t of carbon dioxide ($CO_2$)) in soils globally each year. Recent analysis shows that 25–50 % of the 4p1000 target for soil C sequestration could be met on agricultural lands alone, that is $(0.9–1.85) \times 10^9$ t of C per year on the $1.6 \times 10^7$ $km^2$ of agricultural land [8]. However, if not properly managed, soils can also be a source of $CO_2$ [9]. It is estimated that soils have historically lost 115–154 (average of 135) Gt C due to land use change and unsustainable agricultural practices [10].

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**Abbreviations**

| | |
|---|---|
| 4p1000 | 4 t C per 1000 t soil |
| $CO_2$-eq | carbon dioxide equivalents |
| ETB | Ethiopian Birr |
| GPS | Geographical Positioning System |
| LSD | Least significant difference |
| M3 | Tepid moist mid highlands agroecological zones |
| REF | reference farm with highest C stocks |
| SH3 | Tepid sub-humid mid highlands |
| SNNPRS | Southern Nation Nationalities and People Regional State |
| SOC | soil organic carbon |

Many studies report changes in SOC stocks due to different land use and management practices. For example, Robert [11] suggested that, depending on soil type and environment, conversion of cropland to forest or pasture/paddock can account for an average increase of 0.5 t C $ha^{-1}$ $yr^{-1}$. Restoration of SOC can also be achieved by conversion of cultivated land to forest or grassland [12], restoration of degraded lands with the introduction of resilient trees/shrubs [13], use of organic amendments [14,15], adoption of reduced-tillage in cropping systems or stabilization of C in subsoil [16], conservation tillage [17,18], integrated soil fertility management [19], cover crops [20,21] and management of pastures [22].

Consistent with other parts of the world, studies in Ethiopia have indicated that conversion of arable land to plantation [23], such as establishing exclosures on communal grazing lands [24–27], and use of manures and organic amendments [28] are all practices that increase soil C stocks. In contrast, conversion of native forest to other land uses has been observed to result in a significant decline in SOC stocks across Ethiopia [29]. Of the different land uses and farming systems in Ethiopia, farming of enset is considered to be a key agricultural practice that can increase the accumulation of C in the soils [30]. This may, in part, be due to the common use of organic amendments, such as manures and compost, to support the growth of enset [31]; farmers mostly add organic amendments around the homestead, where the most important crops, such as enset and coffee, are grown to improve financial security. Livestock play an important role in the enset faming system because they provide nutrient recycling [32]. Productivity of enset fields is improved by the long-term application of animal manure. The enset leaves are then used to feed livestock, so maintaining carbon and nutrients within the system [32].

Haileslassie et al. [33] observed that farmers in the Southern Nation Nationalities and People Regional State (SNNPRS) use higher amounts of organic fertilizers in soil fertility management compared to the other regions in the country. This can be attributed to the large area of enset that typically requires regular applications of manure [34]. However, application of manure varies among socio-economic groups, resulting in a highly variable nutrient balance for enset. Elias [35] observed that the N balance is more positive in the enset-gardens of richer farmers in the highlands, primarily due to more continuous application of manure and less frequent harvesting of enset than is the case for poorer farmers. Although studies exist that compare SOC in different land uses, including enset farms [30,36–39], the contribution of enset farms with different farm structures to improving SOC is not well studied. The factors influencing the N balance [35] are also likely to significantly impact SOC. Therefore, it is important to assess the impact of wealth status of enset farmers on soil C and total nitrogen stocks. It is particularly important to assess changes in soil C stock within the rooting depth of enset in order to understand the impact of enset roots. The present study was therefore, conducted in Lemu and Chaha districts in SNNPRS of Ethiopia to assess the differences in SOC, total nitrogen and the relative emissions of $CO_2$ to the atmosphere among enset farms managed by different socio-economic groups of farmers.

## 2. Materials and methods

### 2.1. Study areas

The study was conducted in two districts, Lemo and Chaha, located in Hadiya and Gurage zones, respectively, SNNPRS (Fig. 1). These two districts were selected as they represent typical enset-based farming systems in the region. Table 1 presents the selected characteristics of the two studied sites.

The soil of both sub-districts, or “kebeles” (the smallest administrative units in Ethiopia), is characterized as well-drained and very deep (>2 m). The soil of Haise kebele (the Lemo site) is a clay loam which was classified as a Lixisol. Yeferezye kebele (the Chaha site) had a clay soil that was classified as a Luvisol [41]. The surface layer (0–20 cm) soil chemical properties of the Haise soil indicated that the soils are moderately to slightly acidic (pH 5.8 to 6.1), having low to medium organic C content (ranging from 1.4 to 2.3 %) and medium to high total nitrogen content (0.11–0.16 %) [42]. At the Yeferezye site, the surface soils (0–20 cm) were strongly acidic (pH 5.1 to 5.4), with a medium organic C content (2.1–2.7 %) and high total nitrogen content (0.18–0.22 %) in accordance with the ratings of [42].

### 2.2. Developing criteria and categorizing farmers into wealth categories

The wealth ranking of farmers engaged in enset farming was conducted with the support of local people who are aware of local assets and relationships with wealth that may not be captured by more general survey data [43]. To develop indicators and categorize households into different wealth categories, four key informants with good knowledge of the local environment were purposely selected from each study site as outlined by Bellon [43]. Key informants are people who are selected on the basis of their experience, position, decision-making capacity, and/or active participation in and knowledge of an area [44]. This approach to developing wealth indicators with key informants has been widely used by previous authors (e.g. Yakob et al. [45]; Kidane et al. [46]; Hargreaves et al. [47]. All the selected informants were interviewed together. First, the informants were asked to define indicators to categorize households into different wealth categories. After identifying the indicators (Tables 2 and 3), the key informants were asked to describe the resource rich, medium-wealth and poor farmers or households based on the predefined indicators (Tables 2 and 3). The key informants of each study site highlighted livestock as important wealth indicators for this study. Livestock are an important asset through which households are able to store their wealth [48,49]. Diversifying livestock ownership is well known to serve as a welfare-improving strategy among smallholders in Ethiopia [50].

Rich farmers earn 10,000 ETB from the sale of “Kocho” and “Bulla”; “Amicho” is a byproduct of the processed enset root, used instead of “Kocho” by poor farmers for household consumption. Off-farm activities carried out by poor farmers include cultivation of land for other farmers, processing or harvesting of enset grown by rich farmers. Poor farmers will often receive “Amicho” as a means of payment for their labor. Resource rich and medium-wealth farmers use the donkeys and carts for transport of water, grain etc.

### 2.3. Selecting experimental farms and site preparation for soil sampling

Before selecting soil sampling sites, the total numbers of households in the study sites were obtained from the district agricultural offices. This was 451 in Haise and 545 in Yeferezye. Key informants categorized all the households into three wealth categories based on the previously developed criteria (Tables 2 and 3). In Haise, 17 (3.8 %) were categorized as rich, 245 (54.3 %) as medium-wealth and 189 (41.9 %) as

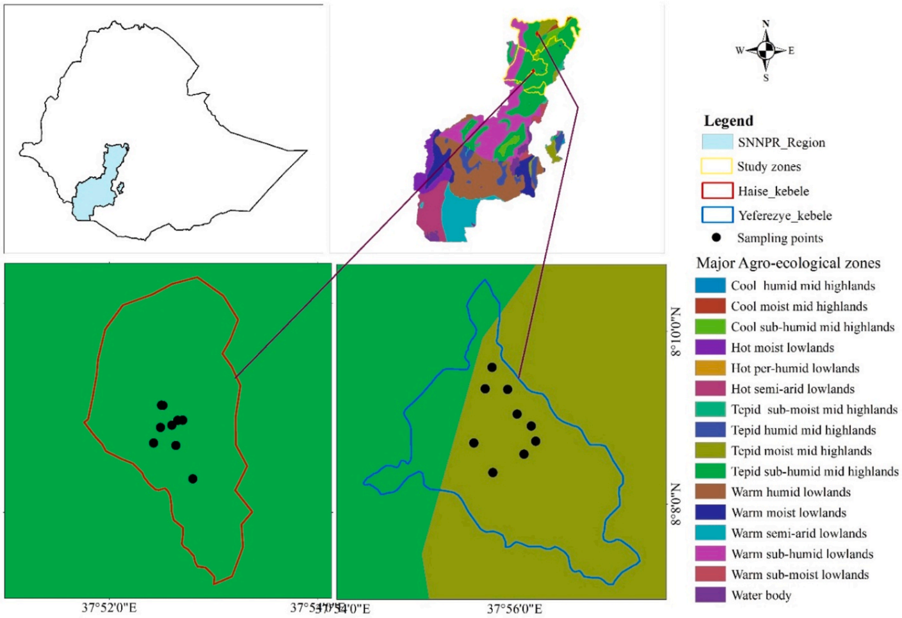

**Fig. 1.** Location map of the study areas and major agro-ecological zones.

**Table 1**
Selected characteristics of the study districts in southern Ethiopia.

| Major site characteristics | | Study districts | Chaha |
|---|---|---|---|
| | | Lemo | |
| Area (ha) | | 35437 | 55963 |
| Elevation (m) | | 1923–2753 | 1020–2840 |
| Location | Latitude (N) | 7.408672°–7.690042° | 8.003532°–8.260656° |
| | Longitude (E) | 37.725919°–37.975591° | 37.597370°–38.067466° |
| Weather | Average annual Rainfall (mm/year) | 744.8–1543.4 | 681–1610.8 |
| | Average annual temperature (°C) | 11–23 | 11.7–20.6 |
| Major Agroecological zone (AEZs) | | Tepid sub-humid mid highlands (SH3) and some partly cool sub humid mid highlands (SH4) | Warm sub-humid lowlands (SH2), Tepid sub-humid mid highlands (SH3) and Tepid moist mid highlands (M3) |
| Major crops | | Enset, wheat, barely, potato, faba beans, oats, coffee and peas | Enset, khat, teff, maize, barley, coffee, wheat, field peas, fababean and vegetables |
| Major land cover class (LULC) (% total land area) | | Annual crop land (63 %)<br>Perennial crops (23 %)<br>Wet land (8.7 %)<br>open shrub land (3 %)<br>Moderate forest (1.5 %) | Annual crop land (74 %)<br>Open grass land (8 %)<br>Sparse forest (7 %)<br>Moderate forest (6 %)<br>Dense Forest (3 %) |

Note: the long-term (30 years, 1991–2020) climatic data were obtained from Ethiopian Meteorological Institute (EMI)[; Agroecological classification was based on [40]; Elevation was estimated using the United States Geological Survey Digital Elevation Model (USGS DEM); the land use and land cover data were obtained from the Geospatial Institute of Ethiopia.

resource-poor, whereas in Yeferezye, 177 (32.5 %) were categorized as rich, 154 (28.2 %) as medium-wealth and 214 (39.3 %) as resource poor.

To avoid external factors such as slope, landscape position or previous land use affecting the results of the study, households with enset fields established in the lower and upper slope positions of the study sites and farms with enset established less than 30 years ago were excluded. Three representative farms were then randomly selected from each wealth category of each kebele, giving a total of eighteen farms (2 locations × 3 wealth categories × 3 farms). Based on the key informant discussions and preliminary observations, it was noted that management was similar in all wealth categories except for differences in the amount of manure and crop residue added to the soil. Therefore, three samples from each wealth groups was considered sufficient to represent differences in these study sites; this limited sample size was also necessary because of the amount of work required to adequately sample working farms. All sampling locations were geo-referenced using a Geographical Positioning System (GPS) (Table 4).

### 2.3.1. *Soil sampling*

From the 18 selected farms, a total of 108 composite soil samples at 0–20 cm and 20–40 cm depths were collected using a soil auger (18 farms × 3 replicates × 2 depths = 108). These sampling depths were considered to cover soil layers that are significantly affected by the management practices of enset farming, particularly tillage and rooting depth [51,52]. Enset has a large root system and thick root cords with 89–96 % of roots found in the upper 40 cm soil layer [53], suggesting sampling down to a depth of 40 cm is crucial.

At each farm, soil samples were collected from three replicate sampling points (Fig. 2b), and at each sampling point, 8–10 sub-samples (24–30 sub-samples from each farm) were collected and pooled together into one composite sample to reduce the spatial variability. Similarly, at each location, core samples were collected to determine the bulk density of the soil. According to FAO [54], a soil core sampler of known volume with a diameter between 5 and 10 cm should be used for determination of bulk density. In this study, a circular cylinder metal core sampler with a diameter of 5.5 cm and a height of 4 cm was used.

### 2.3.2. *Soil sample preparation and laboratory analysis*

The collected soil samples were prepared for physiochemical analyses following standard procedures. The samples were weighed in sealed bags in the laboratory. Soil lumps were broken up by hand and then air dried at room temperature. The samples were passed through a 2 mm sieve to prepare them for determination of soil pH. They were further sieved through a 0.5 mm mesh to determine SOC and total nitrogen.

Core and gravimetric methods were used to determine the soil bulk

**Table 2**
Indicators and description of wealth categories from the perspective of local communities in Haise, Lemo study site, southern Ethiopia.

| Indicators | Rich | Middle | Poor |
|---|---|---|---|
| Enset farm | Cultivate >0.25 ha of enset farm; harvest or process up to 40 enset annually; possess "Kocho", throughout the year, and earn up to ETB 10,000 per year | Cultivate 0.125 ha of enset farm; process 10–15 enset annually; do not own "Kocho" throughout the year; all products of enset used for household consumption. | Cultivate <0.0.0625 ha of enset farm; process up to 5 enset annually and/or only use "Amicho"; engage in off-farm activities; do not sale and earn money from the sale of products and byproducts of enset |
| Total farmland | >1.5 ha | 1 ha | 0.1–0.375 ha |
| Number of oxen | Pair of oxen | 1 ox | None |
| Number of dairy cows | 6 highbred cows | 2-3 cows (1 highbred + 2 local) | None to 1 local cow |
| Number of Donkey + cart | 2 donkeys + 2 carts | 1 donkey + 1 cart | None |
| House | 4 houses | 2 houses | 1 house |
| Eucalyptus plantation | 0.125 ha | 0.0625 ha | No |
| Agricultural inputs (improved seed and fertilizers) without getting credit | Can purchase seed and fertilizers without getting credit; use up to 400 kg of fertilizers and to 100 kg of wheat & 500 kg of potato seed; use improved barley, teff & maize seed | Can purchase seed and fertilizers using credit; use up to 200 kg of fertilizers and 50 kg of wheat and 200 kg potato seed | Can purchase fertilizers using credit; use up to 100 kg of fertilizers; do not use improved seeds |
| Producing different crops (potato, wheat, maize, barley and teff) | Cultivate diverse crops (wheat, potato, barley, maize, teff_ | Cultivate wheat & potato | Some resource poor farmers intercrop maize with enset or cultivate maize on small area adjacent to enset farms. |
| | Sell 2000 kg potato/year | Sell 1000 kg potato/year | No sell, but engaged in off-farm activities, particularly on farms of rich farmers to meet their other demands. |
| | Sell 1000 kg wheat/year | 400–500 kg wheat/year | No sell, but engage in off-farm activities |
| Rent farmland from the poor | Cultivate up to 1 ha of land by renting from other farmers | Engage in share cropping (cultivate up to 0.5 ha). | Do not engage in share cropping and renting farms |

Note: "Kocho" is the fermented product from chopped and grated corm and pseudo-stem of enset; "Bulla" is flour made from dehydrated product of the juice from the decortication of the pseudo-stem and grating of corm; "Amicho is the stripped corm of younger plants of enset, boiled and consumed.

density and moisture content, respectively [55]. The wet and dry weights of samples were measured, and bulk density, $\rho$ (g cm$^{-3}$), and gravimetric water content, $\theta_{\mathrm{d}}$ (%), were computed using equations (1) and (2), respectively [51].

$$\rho = W_{\mathrm{d}}/V \tag{1}$$

where $W_{\mathrm{d}}$ is the weight of oven dry soil (g) and $V$ is the volume of soil (cm$^{3}$)

**Table 3**
Indicators and description of wealth categories from the perspective of local communities in Yeferezeye, Chaha study site, southern Ethiopia.

| Indicators | Rich | Middle | Poor |
|---|---|---|---|
| Enset farm | Cultivate >0.5 ha of enset farm; harvest or process up to 50 enset annually; possess "Kocho" throughout the year; store "Kocho", for about 2 years, and earn up to 100–1500 ETB of enset fiber | Cultivate >0.25 ha of enset farm; process 25–30 enset annually; own ''Kocho'' throughout the year; and earn up to 750 ETB of enset fiber | Cultivate 0.125 ha of enset farm; process up to 10 enset annually; own ''Kocho'' for 6 months; earn up to 200 ETB of enset fiber |
| Total farmland | 5–6 ha | 2–3 ha | 0.5 ha |
| Number of cattle | 5-6 out of which 2 dairy cows and all local breeds | 3 out of which 1 dairy cow local breeds | 1 local breed |
| Goat and poultry | 6 goat and 5 chicken | 2 goat and 3 chicken | 0-1 goat and 2 chicken |
| House | 3 (1 with metal roof, 1 traditional hut and 1 kitchen with metal roof) | 2 (1 with metal roof, 1 traditional hut) | 1 house (very small with metal roof or small hut) |
| Khat | Sells 20000 ETB annually | Sells 10000 ETB annually | Sells 2000 ETB annually |
| Eucalyptus plantation | 0.5 ha (sells up to 35,000 ETB/5 years = 7000/year | 0.25 ha (sells up to 20,000 ETB/5 years = 4000/year | 0–0.0625 ha (sells up to 5000 ETB/5 years = 1000/year |
| Coffee | Cover annual consumption | Cover 6 month consumption/year | May use coffee from own farm for 1 month/year |
| Avocado | Sells 1500 ETB annually | Sells 750 ETB annually | Sells 300–500 ETB annually |
| Producing different crops (potato, wheat and teff) | Cultivate diverse crops (wheat, potato & teff); use improve seeds for wheat, potato and teff; can use up to 200 kg of fertilizers | Cultivate wheat & potato; use improve seeds for wheat and potato; use up to 100 kg of fertilizers | Cultivate wheat; may/may not use improve seeds; not able to use fertilizer or get credit from the rich |
| Gesho | Sells up to 1500 ETB annually | Sells up to 800 ETB annually | Sells <250 ETB annually |
| Off farm activity (pottery) | Sell 1000 ETB/week | Sell up to 1000 ETB/week | Sell upto 250 ETB/week |

Note: "Kocho" is the fermented product from chopped and grated corm and pseudo-stem of enset. All economic groups use processed enset products for household consumption and some rich farmers may use for market; poor farmers not able to afford fertilizers themselves, but get credit (fertilizers) from the rich farmers to return as wheat at a lower price during harvesting.

$$\theta_{\mathrm{d}} = 100 \times (W_{\mathrm{t}} - W_{\mathrm{d}})/W_{\mathrm{d}} \tag{2}$$

where $W_{\mathrm{t}}$ is weight of field moist soil (g) and $W_{\mathrm{d}}$ is the weight of oven dry soil (g).

The SOC content was determined using the wet digestion method described by Walkley and Black [56]. Total N was determined using the Kjeldahl wet digestion and distillation method as described by Van Reeuwijk [57]. Soil pH was determined using a pH meter in the supernatant suspension of a 1:2.5 soil to water (10 g soil: 25 ml distilled water) extract as outlined by Sahlemedhin and Taye [58].

### 2.3.3. *Determination of soil organic carbon and nitrogen stocks*

The SOC and nitrogen stocks were calculated using the following formula [59].

$$M_{\mathrm{C,soil}} = P_{\mathrm{OC}} \times \rho \times d \tag{3}$$

$$M_{\mathrm{N,soil}} = P_{\mathrm{N}} \times \rho \times d \tag{4}$$

**Table 4**
Summary of experimental sites description.

| Haise-Lemo | | | | Yeferezye-Chaha | | | |
|---|---|---|---|---|---|---|---|
| No. farms | Wealth status | Latitude | Longitude | No. farms | Wealth status | Latitude | Longitude |
| 1 | Rich | 07.48284 | 037.87867 | 1 | Rich | 08.15167 | 037.93441 |
| 2 | Rich | 07.47871 | 037.87816 | 2 | Rich | 08.14595 | 037.93465 |
| 3 | Rich | 07.47317 | 037.88073 | 3 | Rich | 08.15657 | 037.93267 |
| 4 | Middle | 07.48256 | 037.87914 | 4 | Middle | 08.14389 | 037.92668 |
| 5 | Middle | 07.48152 | 037.87577 | 5 | Middle | 08.14397 | 037.93624 |
| 6 | Middle | 07.48171 | 037.87752 | 6 | Middle | 08.14915 | 037.93744 |
| 7 | Poor | 07.47902 | 037.87459 | 7 | Poor | 08.14664 | 037.93835 |
| 8 | Poor | 07.48500 | 037.87613 | 8 | Poor | 08.15907 | 037.92177 |
| 9 | Poor | 07.48501 | 037.87574 | 9 | Poor | 08.13671 | 037.92556 |

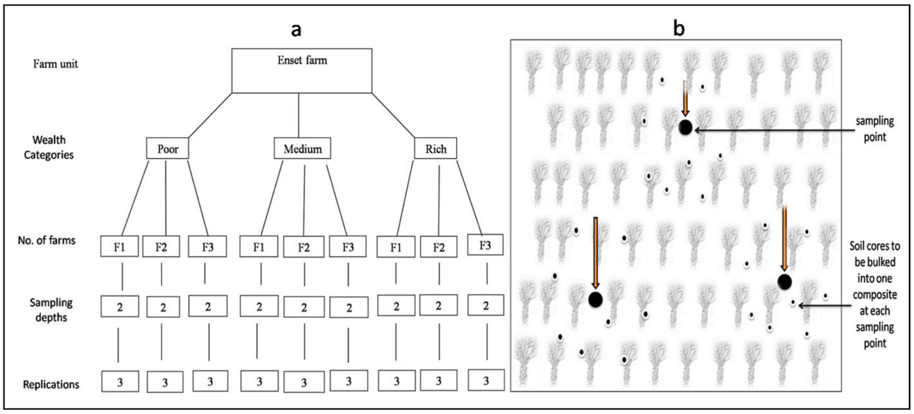

**Fig. 2.** (a) Experimental design and (b) layout of soil sampling in each Kebele.

where $M_{C,soil}$ and $M_{N,soil}$ are the stocks of SOC and N in the soil respectively (both in t $ha^{-1}$), $P_{OC}$ and $P_N$ are the concentrations of SOC and N (g per 100 g soil by weight), $\rho$ is the bulk density (g $cm^{-3}$), and $d$ is the soil depth (cm).

### 2.3.4. Impact of carbon dioxide in the atmosphere

To understand the impact of C stored in the soil on $CO_2$ in the atmosphere, the captured soil C was converted into $CO_2$ equivalents ($CO_2$-eq) by multiplying the C stock by a factor of 44/12 = 3.67 (mole mass $CO_2$ per mole mass C) [60]. This means that 1 t of soil C corresponds to 3.67 tons of $CO_2$ captured from the atmosphere.

$$M_{CO2} = M_{C,soil} \times 3.67 \quad (5)$$

where $M_{CO2}$ is the $CO_2$-eq corresponding to the stock of SOC and $M_{C,soil}$ is the stock of SOC, both in t $ha^{-1}$.

Following the approach adopted by Ref. [30], the impact of wealth category on $CO_2$ emitted from enset farms was estimated with respect to the emissions from the farm with highest C stocks, which was taken as the reference (REF). The difference between $CO_2$ emissions in each farm and the REF farm ($\Delta M_{CO2}$, t $ha^{-1}$) was calculated as

$$\Delta M_{CO2} = M_{CO2,REF} - M_{CO2,farm} \quad (6)$$

where $M_{CO2,REF}$ and $M_{CO2,farm}$ are the $CO_2$-eq corresponding to the stock of SOC on the reference farm and the given farm, respectively (both in t $ha^{-1}$).

Note that while direct measurements of $CO_2$ emissions would indicate the release of $CO_2$ by autotrophic and heterotrophic respiration, they omit uptake of $CO_2$ by the plant and soil, and so provide no direct indication of the impact on climate. Such measurements are also difficult to integrate over time. By contrast, calculating $CO_2$ emissions from the difference in SOC directly accounts for all net exchange of C with the atmosphere by respiration, photosynthesis and other processes. In a dry soil, such as studied here, net exchange of C can be equated to net $CO_2$ emissions.

### 2.4. Statistical analysis

Prior to conducting statistical analyses, the normality of data was tested using the Shapiro–Wilk normality test [61]. The ANOVA PROC-GLM procedure was used to evaluate the significance of the difference in bulk density, soil moisture content, soil pH, SOC, soil total nitrogen and C sequestration ($CO_2$-eq). All collected data were analyzed using the SAS (9.3 version) software package [62]. The significance of differences in mean values were tested using the least significant difference (LSD) at $P \leq 0.05$ [63]. All graphs were created using Sigma Plot version 15.0 procedures.

## 3. Results

### 3.1. Soil physical properties

The results indicated that the impact on soil physical properties of wealth of farmers managing enset farms varied with site. For example, in the 0–20 and 20–40 cm soil depths, significant ($p < 0.05$) differences in soil bulk density were detected between farms managed by different wealth categories at Haise, while the differences were insignificant at Yeferezye (Table 5). Similarly, the differences in soil moisture contents were significant at Haise but not significant at Yeferezye site (Fig. 3).

Soils of resource poor farmers displayed significantly higher bulk density ($p < 0.05$) than soils managed by resource rich and medium-wealth farmers (Table 5). In contrast to bulk density, soils of resource rich and medium-wealth farmers showed significantly higher moisture content in the 0–20 cm depth than those of resources poor farmers (Fig. 3). However, in the lower depth (20–40 cm) there was no statistical difference in the moisture contents of soils managed by farmers of

**Table 5**
Soil bulk density, pH and soil texture as influenced by wealth status of farmers in enset farms.

| Soil depth (cm) | Parameters | Unit | Haise | | | Yeferezye | | |
|---|---|---|---|---|---|---|---|---|
| | | | Wealth categories | | | Wealth categories | | |
| | | | Rich | Medium | Poor | Rich | Medium | Poor |
| 0–20 | Sand | % | 39 ± 2 | 37 ± 2 | 39 ± 1 | 34 ± 4 | 25 ± 3 | 24 ± 3 |
| | Silt | % | 41 ± 2 | 42 ± 1 | 40 ± 1 | 35 ± 3 | 42 ± 1 | 43 ± 3 |
| | Clay | % | 20 ± 1 | 21 ± 1 | 22 ± 1 | 31 ± 1 | 34 ± 3 | 34 ± 1 |
| | Texture | | Loam | Loam | Loam | Clay Loam | Clay Loam | Clay Loam |
| | Bulk density | g $cm^{-3}$ | 1.05 ± 0.02b | 1.04 ± 0.01b | 1.11 ± 0.02a | 0.94 ± 0.02 | 0.98 ± 0.02 | 1.03 ± 0.02 |
| | pH | – | 7.0 ± 0.2 | 6.9 ± 0.2 | 7.0 ± 0.2 | 7.0 ± 0.2 | 6.8 ± 0.2 | 7.1 ± 0.2 |
| 20–40 | Sand | % | 37 ± 1 | 36 ± 1 | 39 ± 2 | 31 ± 3 | 24 ± 3 | 22 ± 3 |
| | Silt | % | 40 ± 1 | 42 ± 1 | 38 ± 1 | 34 ± 3 | 34 ± 1 | 42 ± 2 |
| | Clay | % | 23 ± 1 | 23 ± 1 | 23 ± 1 | 34 ± 3 | 38 ± 3 | 37 ± 2 |
| | Texture | | Loam | Loam | Loam | Clay Loam | Clay Loam | Clay Loam |
| | Bulk density | g $cm^{-3}$ | 1.05 ± 0.02b | 1.05 ± 0.03b | 1.13 ± 0.02a | 0.98 ± 0.01 | 0.99 ± 0.03 | 1.02 ± 0.03 |
| | pH | – | 6.9 ± 0.3 | 6.6 ± 0.2 | 6.7 ± 0.2 | 6.6 ± 0.3 | 6.4 ± 0.3 | 6.8 ± 0.2 |

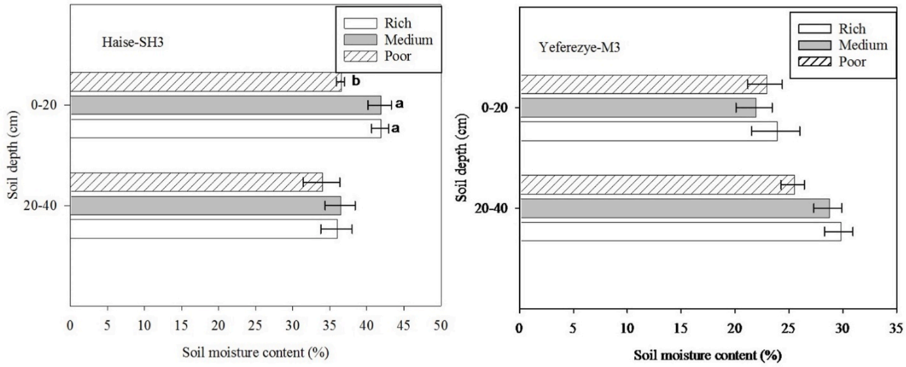

**Fig. 3.** Average (n = 9, ±) soil moisture content in relation to wealth categories. Error bars represent standard error. Values represented by different letter indicate significant differences among wealth categories. SH3 represent Tepid sub-humid mid highlands and M3 represent Tepid moist mid highlands agro ecological zones.

different categories. Differences between the wealth categories in soil texture were non-significant in 0–20 and 20–40 cm soil depths (Table 5).

### *3.2. Soil organic carbon and total nitrogen concentrations*

In the 0–20 cm and 20–40 cm soil depths, significant differences ($p < 0.05$) in SOC were observed between farms managed by different wealth categories in Haise and Yeferezye (Fig. 4). At both sites, soils of resource rich farmers had significantly higher SOC compared to soils managed by medium-wealth and resource poor farmers in the 0–20 cm depth. Soils of medium-wealth and resource rich farmers showed significantly higher SOC than soils of resource poor farmers at 20–40 cm in both locations.

Comparing the two study sites, higher SOC was measured in the soils of the Yeferzye site, ranging from 4.3 % ± 0.2 %–5.8 % ± 0.2 % in the 0–20 cm layer and 3.7 % ± 0.3 %–4.8 % ± 0.2 % at 20–40 cm, whereas at the Haise site, SOC of 3.7 % ± 0.05 %–4.6 % ± 0.2 % was recorded in the 0–20 cm layer and 2.5 % ± 0.1 %–3.5 % ± 0.2 % at 20–40 cm. At the Haise site, the average SOC content from 0 to 40 cm in soils managed by resource rich, medium-wealth and poor farmers were 3.9 % ± 0.1 %, 3.7 % ± 0.1 % and 3.1 % ± 0.1 %, respectively, while the respective SOC contents were 5.3 % ± 0.2 %, 4.7 % ± 0.1 % and 4.0 % ± 0.1 % at Yeferezye. At both sites, SOC content decreased in the order of rich > medium-wealth > poor. Total nitrogen followed a similar trend to SOC in both sites. However, the differences in total nitrogen between the soils of the different wealth categories were not statistically significant (Fig. 4).

### *3.3. Soil organic carbon and nitrogen stocks*

In both study sites (Haise and Yeferezye) significant differences were observed in SOC stocks at each soil depth. Soil organic C stocks ranged from 82 ± 3 to 98 ± 4 t $ha^{-1}$ at Haise and 89 ± 4 to 108 ± 5 t $ha^{-1}$ in the Yeferezye sites (Fig. 5), which is equivalent to removal of $CO_2$-eq from the atmosphere of 300 ± 9 to 360 ± 20 t $ha^{-1}$ at Haise and 330 ± 20 to 400 ± 20 t $ha^{-1}$ at Yeferezye (Fig. 6). Soils managed by resource rich farmers displayed significantly higher SOC stocks compared to the values in soils managed by medium-wealth and resource poor farmers in the 0–20 cm depth at both sites (Fig. 5). The contents of SOC stock in soils managed by rich farmers were higher by 16.3 % at Haise and 18.0 % at Yeferezye sites compared to the soils managed by resource poor farmers. The average value of the SOC stock was higher (96 t $ha^{-1}$ ≈ 350 $CO_2$-eq t $ha^{-1}$) at Yeferzye than at Haise (87 t $ha^{-1}$ ≈ 320 $CO_2$-eq t $ha^{-1}$).

Soils managed by medium-wealth and resource rich farmers showed significantly higher SOC stocks than those managed by resource poor farmers at 20–40 cm depths in both locations (Fig. 5). However, higher SOC stock, ranging from 75 ± 6 to 95 ± 3 t $ha^{-1}$, was recorded at the Yeferezye site than at the Haise site which ranged from 57 ± 3 to 73 ± 3 t $ha^{-1}$ SOC. The differences in SOC stocks between soils managed by resource rich and poor farmers were 20.6 % and 16.3 % in Yeferezye and Haise sites, respectively.

Soils managed by rich and medium-wealth farmers presented significantly higher SOC stocks in 0–40 cm depth compared to those of resource poor farmers in Haise, whereas only soils managed by rich farmers showed significantly higher SOC stocks compared to those of poor farmers in Yeferezye site. The order of SOC stocks and SOC

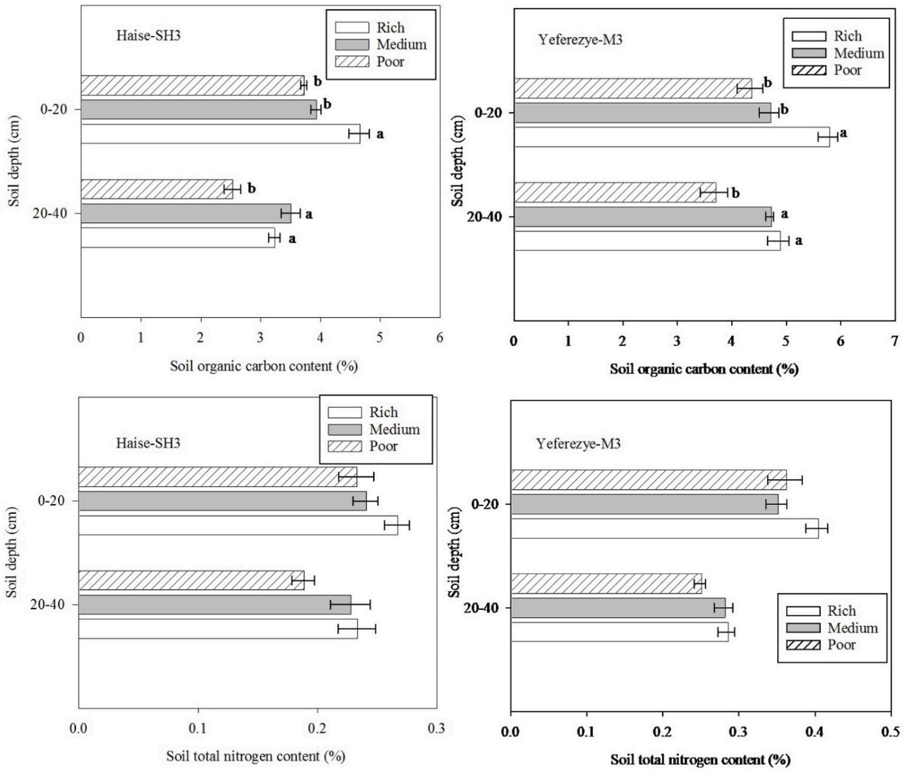

**Fig. 4.** Average (n = 9, ±) soil organic carbon and soil total nitrogen content in relation to wealth categories. Error bars represent standard error. Values represented by different letters indicate significant differences. SH3 represent Tepid sub-humid mid highlands and M3 represent Tepid moist mid highlands agro ecological zones.

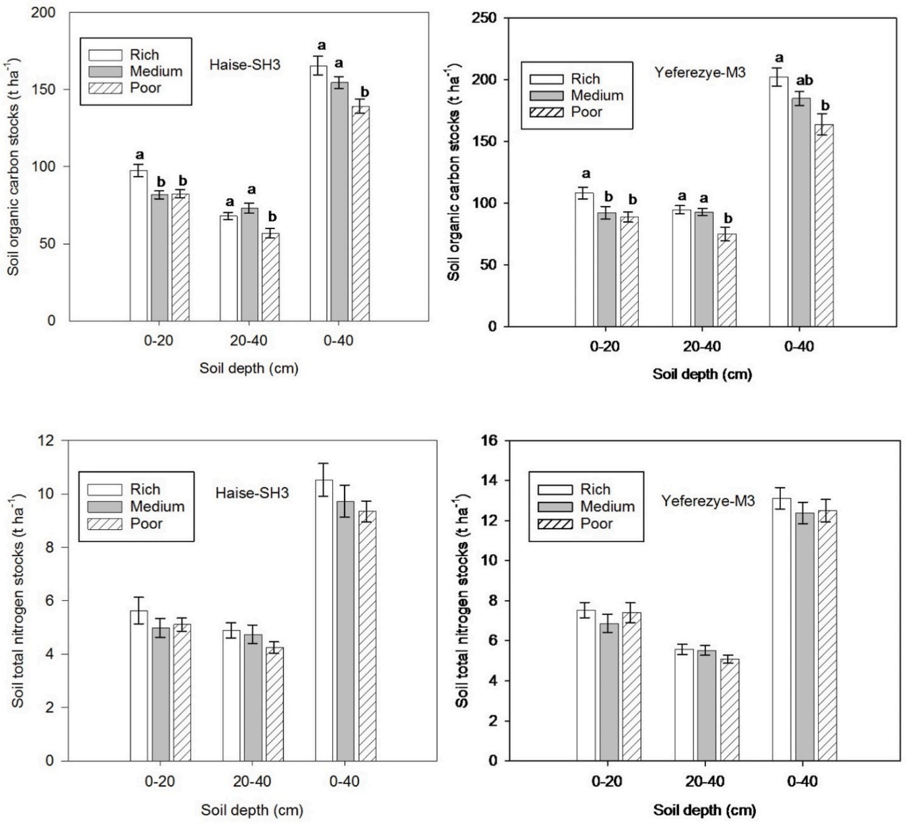

**Fig. 5.** Average (n = 9, ±) SOC and soil total N stocks in relation to wealth categories. Error bars represent standard error. Values represented by different letters indicate significant differences. SH3 represent Tepid sub-humid mid highlands and M3 represent Tepid moist mid highlands agro ecological zones.

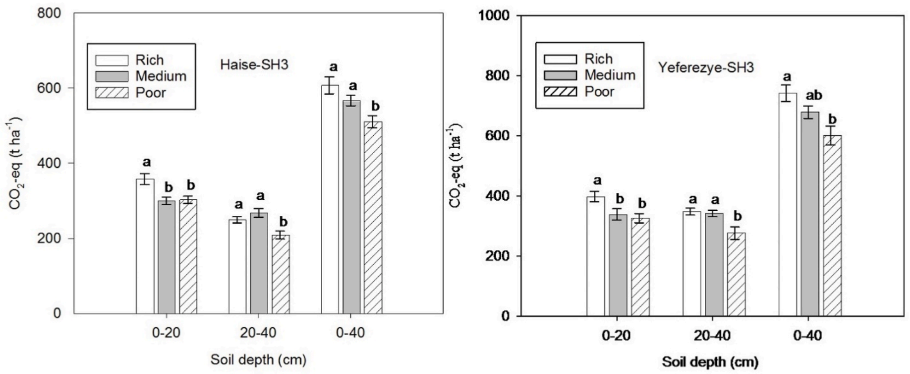

**Fig. 6.** Average (n = 9, ±) SOC sequestered ($CO_2$-eq) in relation to wealth categories. Error bars represent standard error. Values represented by different letters indicate significant differences. SH3 represent Tepid sub-humid mid highlands and M3 represent Tepid moist mid highlands agro ecological zones.

sequestered ($CO_2$-eq) (0–40 cm) was rich farmers > medium-wealth > poor farmers at both sites (Figs. 5 and 6). Total nitrogen stocks followed a similar trend, but there was no significant differences in the total N stocks among soils managed by the different wealth categories (Fig. 5).

### *3.4. Impact on net carbon dioxide emissions*

At Haise 40.1 t $ha^{-1}$ $CO_2$-eq (6.6 %) was emitted by the management practices of medium-wealth farmers compared to rich farmers, and 96.6 t $ha^{-1}$ (15.9 %) by the management practices of poor farmers. At Yeferezye, this was 63.88 t $ha^{-1}$ $CO_2$-eq (8.6 %) by medium-wealth farmers and 141.13 t $ha^{-1}$ (19.0 %) by poor farmers (Table 6).

## 4. Discussion

### *4.1. Effects on soil properties*

Previous authors have found significantly lower soil bulk densities associated with enset compared to croplands, but at Haise, the bulk densities were observed to be significantly higher in enset farms managed by resource poor farmers than those managed by medium-wealth or rich farmers. This is likely to be associated with the change in SOC content due to incorporation of organic manures in the enset farms; higher SOC was observed in enset based home-gardens by Ref. [38] and enset farms by Ref. [34] compared to arable outfields. It is well-established that there is usually a negative correlation between soil organic matter and bulk density (e.g. Chaudhari et al. [64]. Application of organic fertilizers increases the organic matter content and aggregate stability [65] and soils become more friable, porous, well-aggregated and chemically active, which tends to result in lower bulk density [66,67]. Therefore, the significantly higher bulk densities observed in farms managed by resource poor farmers could be attributed to the limited addition of organic inputs.

**Table 6**
Carbon dioxide ($CO_2$) emission as influenced by management of wealth status of the farmers compared to the reference enset farm (resource rich farmers' farm) in southern Ethiopia.

| Management categories | Soil depth (cm) | C sequestered ($CO_2$-eq) (t/ha) | $CO_2$ emission (t/ha) | $CO_2$ emission (%) |
|---|---|---|---|---|
| Haise | | | | |
| Farms managed by rich farmer | 0–40 | 607.7 ± 22.4 | | |
| Farms managed by medium-wealth farmer | 0–40 | 567.6 ± 14.4 | 40.1 | 6.6 |
| Farms managed by poor farmer | 0–40 | 511.1 ± 16.2 | 96.6 | 15.9 |
| Yeferezye | | | | |
| Farms managed by rich farmer | 0–40 | 742.4 ± 27.4 | | |
| Farms managed by medium-wealth farmer | 0–40 | 678.6 ± 20.7 | 63.88 | 8.6 |
| Farms managed by poor farmer | 0–40 | 601.3 ± 31.5 | 141.13 | 19.0 |

Bulk density is also affected by factors such as water, aeration status, root penetration, clay content, texture, land use and management [68]. Therefore, different soil management practices due to the difference in resources owned by farmers could also affect bulk density of the soil. However, reduced inputs of organic matter in resource poor farms is suggested by the indicators used to categorize farmers (Tables 2 and 3) where resource poor farmers owned a smaller number of livestock compared to resource rich and medium-wealth farmers, which limits their access to organic manures. In addition, resource poor farmers own less outfields (Tables 2 and 3) than resource rich and medium-wealth farmers and this might affect the availability of crop residues that could be used for soil amendments.

By contrast to the Haise site, the values of soil bulk density at Yeferzye were not significantly different between the farms of different wealth status. The different results observed at the two sites could again be due to the difference in resources owned by farmers. Resource poor farmers in Yeferezye had more livestock (1 cow, 1 goat and 2 chickens) and owned more farmland (0.5 ha) than resource poor farmers of Haise (only 1 cow and 0.1–0.375 ha of total farmland) (Tables 2 and 3).

The soil pH values did not significantly differ between soils managed by the three wealth categories at either location. However, compared to the cropland soils in the outfields, soil pH was higher in the soils of enset fields at both sites. In the upper layer (0–20 cm) of the outfields, soil pH ranged from pH 5.1 to 5.4 (strongly acidic) at Yeferezye and from 5.8 to 6.1 (moderately to slightly acidic) at Haise, while the soil pH in the enset fields was neutral to slightly alkaline, ranging from 6.78 to 7.13 at Yeferezye and 6.92 to 7.03 at Haise. The pronounced increase in soil pH in the enset fields could be attributed to the long-term application of organic manure and household waste, which is usually mixed with wood ash. In red soils [69], also observed a steady increase in soil pH due to long term application of manures from an initial value of 5.7 to pH 6 to 7, and [70] indicated that the pH of an acid soil can be increased by use of manures of high organic matter and carbonate content.

The soil moisture in the upper soil depths (0–20 cm) was also significantly different in the enset plots managed by the different wealth categories (Fig. 3). This again can be explained by the differences in manure applications. Organic matter is well-known to improve the water-holding capacity, infiltration and plant-available water in the soil [61,62]; this is because organic matter increases the number of micropores and macropores in the soil, either by gluing soil particles together or by creating favorable living conditions for soil organisms [63].

Therefore, farmers can improve the water-holding capacity of the soil by raising the organic matter content [71]. The amount of water held by the soil was observed by Nyamangara et al. [72] to significantly increase with manure applications, suggesting that the difference in soil moisture observed in this study could again be attributed to the difference in the amount and quality of manure applied to the soil by the farmers of different wealth status.

### *4.2. Soil organic carbon and total nitrogen*

Many soils in Ethiopia are degrading due to high levels of erosion and decreasing organic matter, resulting in declining productivity and farm income [73]. Soil organic matter impacts soil structure [74], which controls water holding capacity [75], root aeration [76] and structural stability [77]. Soil organic matter also affects crop production through the release of nutrients as the organic matter decomposes [78]. Therefore, in a SOC depleted soil, such as is found in this area of Ethiopia, increasing SOC is likely to have a strong impact on resilience to extreme weather events, crop production and household livelihoods.

The results showed significant impacts of management on the SOC content. The significantly higher SOC content in soils managed by resource rich and medium-wealth farmers than those managed by poor farmers could again be attributed to the different amounts and continuous addition of organic inputs. Repeated applications of solid cattle manure increases soil organic matter [70], and the differences in results of the present study are likely to be related to the higher number of livestock owned by the rich and medium-wealth farmers as compared to the poor (Tables 2 and 3).

The observed differences in SOC of the soils at the two study sites, can be explained by the differences in resources owned by the farmers of different wealth categories at the sites (Tables 2 and 3). Due to competing uses of crop residues for various purposes (e.g. fuel wood, livestock feed, soil amendment), the resource poor farmers in the study areas might not get enough resources to use for soil amendment. Socioeconomic factors and farmers' perception of soil fertility influence the use of agricultural inputs [79], whereby household wealth, in particular, can influence the quantity of organic inputs [80]. Amede and Diro [31] reported that resource rich enset farmers in Ethiopia produced about two times the amount of farmyard manure and crop residues as poor farmers.

Although studies comparing SOC in enset fields between soils managed by farmers of different wealth status are limited, different authors have indicated higher SOC in enset fields compared to the outfields (the main field which is far from the home garden/enset farm), for example 2.5 % SOC [30] and 2.24–2.64 % SOC [38]. However, these values are lower than the values recorded from the soils even managed by the resource poor famers in the current study (Fig. 4).

In addition to adding organic inputs, the canopy of the enset crop can also contribute to high accumulation of SOC by protecting the soil from erosion due to its year round vegetation cover [81–83]. Borrell et al. [84] reported that due to large leaf surfaces of enset, rainfall is intercepted limiting erosion. By contrast, studies indicate that monocrop fields with less vegetation cover can expose fields to soil erosion [85,86] and be an important source of $CO_2$ losses [87]. Therefore, the relatively low vegetation cover in the enset field of resource poor farmers, associated with more frequent and earlier harvesting of enset, is likely to expose the soil to more erosion, runoff and higher decomposition of SOC compared to those of the resource rich and medium-wealth farmers. Elias [35] observed richer farmers conducting less frequent harvesting of enset compared to resource poor farmers.

Other factors such as soil texture, rainfall and soil types could also affect the SOC contents and stocks. Higher SOC contents and stocks measured in soils from Yeferezye compared to Haise could be attributed to the higher clay content recorded in the soils at this location (Table 5). Soils with higher clay content had higher SOC content and stocks compared to soils with lower clay content [88]. The higher annual rainfall at the Yeferezye site compared to Haise (Table 1) may also contribute to the higher SOC stocks. Okolo et al. [88] reported that SOC stocks increased with increasing mean annual precipitation. The difference might also be attributed to the inherent difference of the soils of the study areas; Luvisols at Yeferezye and Lixisols at Haise. Most Luvisols are fertile soils, whereas Lixisols are strongly weathered soils with low levels of available nutrients and nutrient reserves [89].

Total nitrogen at both sites followed the same trends as observed in SOC. Total nitrogen content showed a decreasing trend from resource rich to the resource poor farmers. Fields of resource rich farmers were categorized as having "very high total nitrogen" ($>$0.25 %) while those of resource poor farmers were categorized as "high total nitrogen" (0.12–0.25 %) in both locations [42].

### *4.3. Impact on net carbon dioxide emissions*

Well managed (resource rich) enset farms remove a significant amount of $CO_2$-eq from the atmosphere (Fig. 6) and reduce $CO_2$ emissions compared to the farms that are managed by the resource poor (Table 6). This implies that well managed enset prevents the soil from degrading and reduces $CO_2$ emissions. While previous studies [30,38,90] focused on the differences in SOC between different land uses, the current study focused on wealth categories, indicating that even under an enset farming system, the SOC stored in soils and $CO_2$ emitted from the soils are significantly influenced by wealth status of farmers.

The average removal of $CO_2$-eq by the enset farm from 0 to 40 cm depth was 562 t $ha^{-1}$ at Haise and 674 t $ha^{-1}$ at Yeferezye, indicating the potential of enset farming systems to mitigate climate change. However, the $CO_2$ emitted to the atmosphere from the soils managed by resource poor and medium-wealth farmers compared to the optimum management by rich farmers increased by 6.6–15.9 % at the Haise site and 8.6–19.0 % at the Yeferezye site (Table 6). As resource poor farmers account for 41.9 % of farmers in Haise and 39.3 % in Yeferzye, about half of enset farmlands were not optimally managed and did not receive adequate organic inputs. Therefore, this calls for different options for soil amendment to be designed to minimize the dependency of enset farms on livestock manures.

## 5. Conclusions

Regardless of socioeconomic status, enset farms in Haise (Lemo) and Yeferezye (Chaha) stored more SOC and total nitrogen in 0–40 cm soil depth than non-enset farms. However, 15.9 %–19 % less C was stored in soils of resource poor farmers compared to those of wealthier farmers. This implies that there is a gap between the potential and practice of enset farming in terms of SOC stocks and reduction of $CO_2$ emission to the atmosphere. The results suggest that the wealth status of farmers influences soil properties by controlling the amount of organic inputs that can be added to soils. This, implies that in addition to establishing an enset farm and maintaining it for several years, proper management and application of sufficient organic inputs are required to store soil C and improve other soil properties (soil bulk density, moisture content and soil pH) as well as to reduce emissions of $CO_2$ to the atmosphere. Resource poor farmers account for 41.9 % and 39.3 % of farming communities in Haise and Yeferzye, respectively, indicating nearly half of the enset farmlands in these areas were not managed to their optimum potential for C sequestration. The results also indicate the dependence of enset-based farming on livestock production, as manure is the main sources of organic input used in enset farms. Therefore, we suggest that to sustainably maintain this farming system and achieve potential social and environmental benefits, as well as ensuring year-round household food security, resource poor farmers should use locally sourced or homemade compost or vermi-compost to fertilize enset farms to compensate for reduced availability of animal manures.

## Ethics approval

Not applicable to this manuscript.

## CRediT authorship contribution statement

**Mulugeta Habte:** Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation. **Sheleme Beyene:** Writing – review & editing, Supervision. **J.U. Smith:** Writing – review & editing, Supervision, Funding acquisition.

## 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.

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