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# Carbon stock, sequestration and soil properties among fields in smallholder farms in southern Ethiopia

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## Abstract

**Background:** Soil organic carbon (SOC) is key indicator of soil quality and health. It has substantial benefits to the ecosystem. Information on the magnitude of carbon pools under field scale of subsistence farms is scanty. This study aimed to assess carbon stock, sequestration and soil properties among different fields in smallholder farms of southern Ethiopia. Five field types within a farm were investigated viz. coffee (*Coffea arabica* L.), enset (*Ensete ventricosum*), root and tuber crop field (RTC), crop field used for growing cereals and pulses, and fallow land. For each field, eight representative fields as a replication were selected. Surface soil samples were collected, and analyzed to determine soil physico-chemical properties. In addition, C stock, C-sequestration, and CO<sub>2</sub> emission were also evaluated.

**Results:** The result regarding soil properties revealed significant differences in almost all of investigated parameters. The minimum and maximum values being recorded were: bulk density (BD) (1.05, 1.29 gm cm<sup>-3</sup>), pH (6.1, 7.0), SOC (1.1, 2.48%), TN (0.09–0.19%), available P (1.1, 70.9 mg/kg), total exchangeable bases (9.5, 20.5 Cmolc/kg), K/Mg (0.37, 1.02), B (0.4, 1.2 mg/kg) Cu (0.32, 0.91 mg/kg), Zn (5, 20.5 mg/kg), Fe (105.5, 133.8 mg/kg) and CEC (18.6, 27.5 mg/kg). Fields in the backyard (enset and coffee) showed lowest BD and maximum values of soil chemical properties. On contrary, highest BD and lowest values of chemical parameters were observed in crop and fallow fields. The result further indicated that the field that stocked and sequestered more carbon, and emitted less CO<sub>2</sub> was coffee > enset > RTC > crop field > fallow land. C-stock and sequestration (t/ha) magnitude was being: coffee (81.4, 298.5), enset (75.5, 277.0), RTC (68.8, 252.6), crop field (57.5, 211.0) and fallow (43.3, 159). Using coffee field as least CO<sub>2</sub> emitter and as the base value for comparison, the percentage increment in CO<sub>2</sub> emission out of the sequestered carbon was 7.2% (enset), 15.4% (RTC), 29.3% (crop field) and 46.7% (fallow). Soil deterioration index (%) relative to coffee field for OC, N, P, and K in their order was as follows: enset [− 2.8, 0, 254.5, 23.1], RTC [− 17.7, − 31.6, − 59.5, − 34.6], crop field [− 35, − 47.4, − 79, − 46] and fallow [− 55.7, − 52.6, − 94.5, and − 76.9].

**Conclusion:** Different fields within smallholder farms exhibited significant variation in amount of carbon sequestered, CO<sub>2</sub> emission, soil degradation and soil properties. Thus, climate smart soil management practices that would enhance carbon pool and simultaneously increasing soil quality are suggested e.g., integrated nutrient management.

**Keywords:** Carbon sequestration, Farm, Field, Soil nutrient, Soil degradation

## Background

Carbon dioxide (CO<sub>2</sub>) is a major cause of the atmospheric greenhouse gases. Increasing concentration of CO<sub>2</sub> into the atmosphere distorts the carbon(C) cycle and influences the global climate, whereas sinking CO<sub>2</sub> and increasing C stock of the ecosystem has positive effects (Melenya et al. 2015). Soil is the largest terrestrial

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sink of carbon (Melenya et al. 2015; Vagen and Winowiecki 2013). Sink of C from atmosphere to either plant into soil or from atmosphere into soil is called soil C sequestration.

Soil organic carbon (SOC) is key indicator of soil quality and health (Bhunia et al. 2018; Vagen and Winowiecki 2013). The benefits provided by SOC includes C storage, food and habitat for biodiversity, nutrient storage and supply, erosion control and increase buffering capacity, increasing soil infiltration rate and water holding capacity, and improving plant growth (Walcott et al. 2009). Thus, carbon sequestration in soil could be a 'win-win' situation, helping to reduce greenhouse gas levels in the atmosphere and improving soil quality for agricultural and forestry industries (Walcott et al. 2009). Meanwhile, agricultural practices can influence the C balance through emission as well as sequestration (Tessema and Kibebew 2019).

In Ethiopia, agriculture is the dominant sector supporting the livelihood of majority of population that is growing at faster rate. It is entirely rain-fed and characterized by low input and low productivity (Eyasu et al. 2019). On contrary, farming size at the face of growing population is decreasing. There is also an expansion of agricultural areas in response to growing population and increasing demand for food (Teklu et al. 2020). It has been done at the expense of grazing and forest lands. Disturbance of soil ecosystems results in rapid depletion of SOC. This in turn results land degradation through deterioration of soil physicochemical properties (Tessema and Kibebew 2019) and finally results declining of crop production, and food security problems. These activities could have brought an increased interest in soil C sequestration and maintenance of soil ecosystem (Vagen and Winowiecki 2013).

Farmers in densely populated areas of Ethiopia own less land size. Particularly, in Wolaita, southern Ethiopia, farming has been taking place in less than a quarter of hectare (WZFEDD 2012). Like other parts in the country, farming is also entirely rain-fed and characterized by low input and low productivity (Fanuel and Kibebew 2020). To cope up the adverse effects of climate and secure household food demands, smallholder farmers divided the small size land into different fields and grow annual and perennial crops. Management practices applied to each field within a farm are variable. Difference in soil management practices influences soil C stock and soil quality (Tessema and Kibebew 2019). This subsequently depresses the efficiency of each field to functioning best and produce more yields.

Research findings in Ethiopia and elsewhere highlighted that the magnitude of soil C storage, carbon emission and soil quality responds strongly to aboveground

landscape dynamics, including land-use change, soil management practices and land degradation processes (Tessema and Kibebew 2019; Bhunia et al. 2018; Manna et al. 2015; Melenya et al. 2015; Vagen and Winowiecki 2013). For instance, in Eastern Ethiopia at 20 cm depth 88.23 t ha<sup>-1</sup> organic carbon could have been lost if forest land is converted into crop land (Tessema and Kibebew 2019). The same study further indicated higher C stock in coffee agroforestry (277.38 ± 28.58 t ha<sup>-1</sup>) than in crop-land uses (138.95 ± 25.01 t ha<sup>-1</sup>).

While the effects of land use changes on C stocks, C sequestration and soil properties have been widely studied, the mentioned information at field scale within a farm conditions are scanty. This would result limited utility of soil management recommendations as it does not address farm complexities. These gaps call the need to explore field scale variability of C pools and soil properties to set recommendation on the maintenance and enhancement of SOC. Hence, this study aimed to assess C stock, sequestration and subsequent effects on soil properties among fields in the smallholder farms of southern Ethiopia.

## Materials and methods

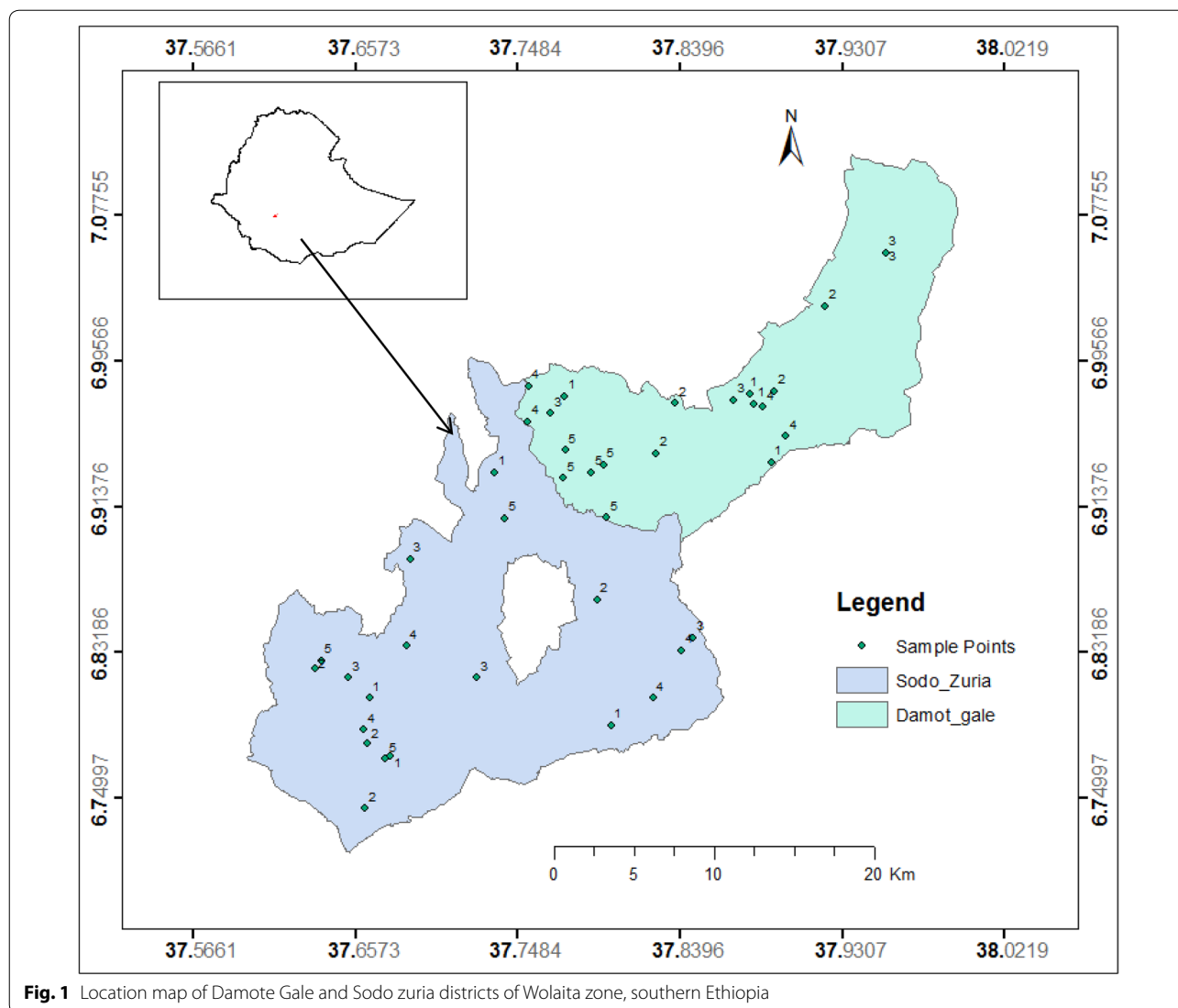
### Study area

The study was conducted in small holder farmers' fields of two adjacent *woredas* (i.e. districts), Wolaita Zone, Southern Nations, Nationalities' and Peoples' Regional State (SNNPRS) of Ethiopia namely Damot Gale, and Sodo Zuria (Fig. 1). The *woredas* have potential for diverse agricultural activities (Fig. 1 and Table 1). The sites are located under mid highland (1500–2300 m.a.s.l) agro-ecological zone. Nitisol is the most prevalent soil type in the area. Agricultural activities are characterized by small-scale mixed subsistence farming system.

### Selection and surveying of farms

Prior to sample collection different tasks were performed. Preliminary reconnaissance survey on the study site was conducted. It is noted that farmers in the area classify the farm into different fields (Table 1 and Fig. 2). This includes coffee (*Coffea arabica* L.) based field; enset (*Ensete ventricosum*) based field; root and tuber field (RTC), and crop field that used to grow cereals and pulses viz tef (*Eragrostis tef* (Zucc.) Trotter), haricot bean (*Phaseolus vulgaris* L.), wheat (*Triticum aestivum* L.) and maize (*Zea mays* L.). In addition, a crop field after long years of cultivation is being fallowed. Though rarely practiced in the area due to land shortage, it was also considered for evaluation.

Field survey was conducted and representative fields in the farm were randomly selected. For each field indicated in Table 1 and Fig. 2, four (4) representative replicates per



**Fig. 1** Location map of Damote Gale and Sodo zuria districts of Wolaita zone, southern Ethiopia

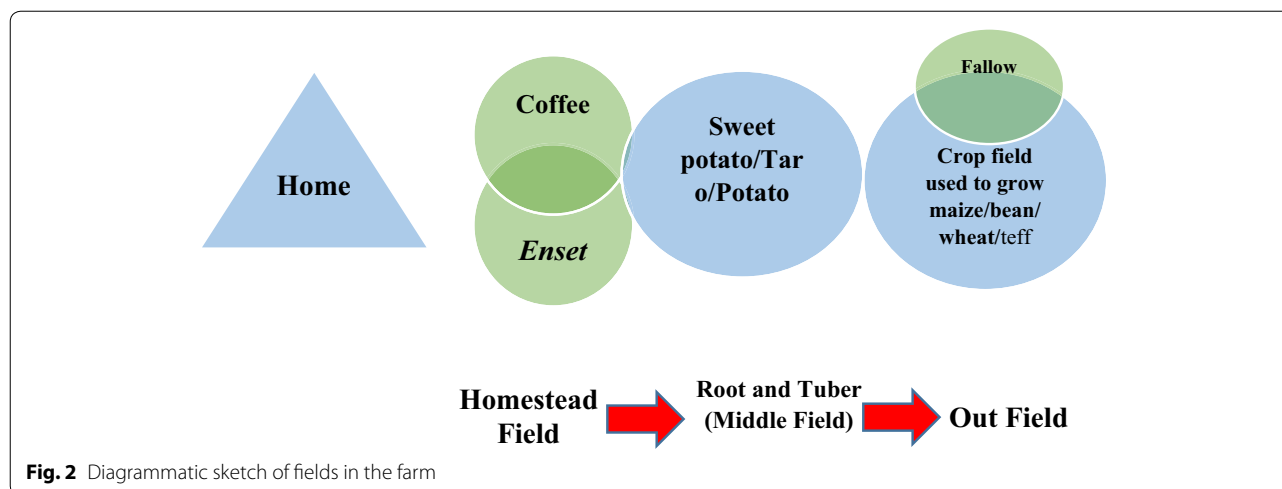
**Table 1** Characteristics of land use practices among fields in the farm

Field types	Location in the farm	Crop intensity (no. of crops/year)	Residue management	Topography	Fertilizer application		
					N <sup>a</sup> (kg/ha)	P <sub>2</sub> O <sub>5</sub> <sup>a</sup> (kg/ha)	FYM (t/ha)
Coffee	Homestead	1.5	Retained	Gentle slope	–	–	4.23
Enset	Homestead	1.25	Retained	Gentle slope	–	–	3.50
RTC field	Middle field	1.88	Removed	Gentle slope	–	–	3.51
Crop field	Out field	2.00	Removed	Gentle slope	13.2	20.5	–
Fallow land	Out field	–	Free grazing	hilly slope	–	–	–

<sup>a</sup> Source of fertilizer is urea (46-0-0) and Di-ammonium Phosphate (18-46-0), respectively

woreda were identified. Then after, 20 fields per woreda and a total of 40 fields from the two woreda were surveyed. Similarity in terms of socio-economic status, elevation, slope, land scape position, soil management and

land use history were considered during replicate field selections. Each field was georeferenced using a GPS.



### Soil sampling and laboratory analysis

#### Soil sampling procedure

From each field, 10–15 sub-samples from the surface were taken in zig zag pattern using soil auger to make a kilogram of composited sample. Each field was geo-referenced using the Geographical Positioning System (GPS). In addition, relevant information such as coordinates, elevation, slope, topography, and soil management practices were also collected. After soil processing (drying, grinding and sieving), selected soil physicochemical properties were analyzed using standard laboratory analysis procedures.

Particle size distribution (PSD) was analyzed by laser diffraction method using laser scattering particle size distribution analyzer (Horiba- Partica LA-950V2). Soil bulk density (BD) was determined using the core method as described by Anderson and Ingram (1993). Soil pH (1:2 soil: water suspension) was measured with a glass electrode (model CP-501) (Mylavarapu 2009). Available phosphorous (P), available sulfur (S), exchangeable basic cations [calcium (Ca), potassium (K), and magnesium (Mg), and extractable micronutrients (boron (B), copper (Cu), iron (Fe), manganese (Mn) and zinc (Zn)) were determined using Mehlich-III multi-nutrient extraction method (Mehlich 1984). The concentration of elements in the supernatant was measured using inductively coupled plasma (ICP) spectrometer.

Mid Infrared Diffuse Reflectance spectroscopy (MIR spectroscopy) was used to determine the amount of soil organic carbon (SOC), total nitrogen (N) and cation

exchange capacity (CEC). For MIR spectral analysis, soil samples weighing 0.035 g were loaded in a single well each in four consecutive wells of an aluminum microplate having 96 wells. The sample surface was gently pressed, leveled and smoothed using a micro-spatula (a rounded, smooth surface glass rod). The absorbance of diffused reflectance spectra was scanned using the HTS-XT accessory of a Bruker-TENSOR 27 spectrometer. The background (i.e. soil sample free well) was scanned using roughened surface well of the aluminum microplate. Absorbance spectra of the entire soil samples were measured using OPUS version 7.0 software (Bruker® Optic GmbH, 2011) with 32 scans and spectral range of 7400–600  $\text{cm}^{-1}$  (wave numbers) including part of near infrared (NIR) region. The spectrum acquisition took an hour per plate. The MIR region spectra, in the wave number range of 4000–600  $\text{cm}^{-1}$  (2500–16,667  $\text{nm}$ ) were used to predict soil properties. Quantitative analysis of the spectra was done using Quant 2 evaluation function of OPUS (software version 7) to predict concentration of SOC, TN and CEC. The average of four consecutive scans of each parameter was taken as a predicted data for the report. For the purpose of management, interpretation was given using proper ratings.

#### Carbon and N Stocks, and C sequestration

Stocks of soil organic carbon (SOC), stocks of nitrogen (N) and carbon sequestration ( $\text{t ha}^{-1}$ ) were computed following the equation of Donovan (2013).

$$\text{Soil C (or N) Stock (t ha}^{-1}\text{)} = \text{Soil OC (or N) (\%)} * \text{BD (kg m}^{-3}\text{)} * V * 10^{-3} \quad (1)$$

where BD: bulk density ( $\text{kg m}^{-3}$ ) and V: volume of the soil in cubic meter = depth of soil (m)  $\times$  area of soil ( $\text{m}^2$ ).

Carbon sequestration ( $\text{t ha}^{-1}$ ) refers to the amount of carbon stored in the form of  $\text{CO}_2$ . It is obtained by multiplying SOC by 3.67 (i.e. the molecular mass of  $\text{CO}_2$ /atomic mass of C =  $44/12 = 3.67$ ).

$$\text{Carbon sequestration (t ha}^{-1}\text{)} = \text{SOC (t C/ha)} \times \text{CO}_2/\text{C} \quad (2)$$

### CO<sub>2</sub> emission

To understand the  $\text{CO}_2$  balance of each field, net  $\text{CO}_2$  emissions ( $\text{t ha}^{-1}$ ) were calculated from difference between reference field (RF) i.e., C sequestration ( $\text{t ha}^{-1}$ ) on field having maximum value minus sequestration in subsequent fields ( $\text{t ha}^{-1}$ ) (Eq. 3). The field that sinks more C was taken as reference value for comparison.

$$\text{CO}_2\text{emission (t ha}^{-1}\text{)} = \text{C sequestration (t ha}^{-1}\text{)} \text{ on RF} - \text{C sequestration (t ha}^{-1}\text{)} \text{ in other fields} \quad (3)$$

where RF is a reference field that store (sequester) maximum carbon. With this assumption, %  $\text{CO}_2$  emission was also computed from the ratio of ( $\text{CO}_2$  emission/C sequestered)\*100.

### Soil deterioration index among crop fields

Soil deterioration index (DI) (%) was calculated by adopting the approach indicated in Tessema and Kibebew (2019). It is assumed that the farm before conversion into coffee, *enset*, root and tuber, main field and fallow fields was similar in terms of SOC and other properties. Thus, the DI of SOC and macro nutrients (TN, available P and K) under different fields was computed by comparing to reference field (Eq. 4). In addition, the change in SOC and TN were averaged to evaluate the magnitude of change on the two influential and interrelated properties (Tessema and Kibebew 2019).

$$\text{SDI(\%)} = \frac{\text{PSF} - \text{PRF}}{\text{PRF}} \times 100 \quad (4)$$

where SDI is deterioration index, PSF is value of individual soil property (P) under specific field (SF) and PRF is mean value of individual soil property (P) under reference field (RF). Note: Reference field refers to the mean of individual soil property (P) (e.g. SOC) on the field showing highest value.

### Data analysis

One way analysis of variance (ANOVA) was employed to test significance variation among fields. In addition, Pearson correlation analysis on selected parameters was

performed. Data analysis was performed using Statistix 8 software.

## Results

### Effects on selected soil physical properties

Particle size distribution (PSD) among fields indicated non-significant difference and it showed moderate variability (Table 2). However, lower sand content was measured in soils of fallow land. Silt content showed decreasing trend from *enset*/coffee fields towards crop field (crop and fallow field). Furthermore, higher clay content was found on fallow land followed by crop field. As a result, *enset* and coffee fields have silty clay texture while other fields have clay texture (Table 2). Soil bulk density (BD) significantly ( $P < 0.05$ ) differed among fields. Significantly smaller BD ( $1.05 \text{ g cm}^{-3}$ ) was recorded from *enset* field, whilst higher BD value ( $1.29 \text{ g cm}^{-3}$ ) was

observed in the fallow field (Table 2).

### Effects on soil chemical properties

Different fields in a farm have shown significant ( $P < 0.05$ ) differences in soil chemical properties except S and Fe (Table 2). In terms of soil reaction, *enset*, coffee and root and tuber fields (RTC) were categorized under neutral pH (6.6–7.3) while crop and fallow fields were found under moderately acidic (5.6–6.5) reaction as per the ratings of EthioSIS (2014). SOC and TN content showed declining trend from homestead to out fields. Coffee field had 125% and 54% higher OC compared to fallow and crop field, respectively. *Enset*, coffee and RTC fields were qualified under optimum OC [1.71–4.1%] while crop field and fallow lands were categorized under low (1.2–1.7%) and very low (<1.2%), respectively (EthioSIS (2014)). Significantly ( $P < 0.05$ ) high TN content was found in soils under *enset* and coffee fields while the least was recorded on crop fields. TN was under optimum range (0.15–0.3%) on *enset* and coffee fields. TN was low (0.1–0.15%) on RTC and crop fields whereas it was very low (<0.1) on fallow field (EthioSIS (2014)).

Investigated fields showed significant ( $P < 0.05$ ) differences in terms of available p. Available P ranged (mg/kg) from 1.1 (fallow) to 70.9 (*enset*) fields. Exchangeable cations among fields were also significantly ( $P < 0.05$ ) different. The amount in all fields were in order of  $\text{Ca}^{2+} > \text{Mg}^{2+} > \text{K}^+$ . The minimum and maximum (cmol (+)/kg) in their order was: Ca (6.4–13.3), Mg (1.8–3.1) and K (0.6–3.2). The exchangeable bases among fields were in the order of: *enset* > coffee > RTC > crop

**Table 2 Soil physical and chemical properties among fields in the farm**

Parameters	Unit	Field type					CV (%)	LSD <sub>0.05</sub>
		Enset	Coffee	RTC	Crop field	Fallow		
Sand	%	14	14	18	14	10	44.6	ns
Silt	%	40	41	39	37	34	56.0	ns
Clay	%	46	45	43	49	56	54.0	ns
Texture		Silty Clay	Silty Clay	Clay	Clay	Clay		
BD	g cm <sup>-3</sup>	1.05c	1.09c	1.12bc	1.19b	1.29a	8.3	0.09
pH	–	7.0 a	6.9a	6.7ab	6.3bc	6.1c	8.4	0.56
SOC	%	2.41ab	2.48a	2.04bc	1.61c	1.10d	22.1	0.43
TN	%	0.19a	0.19a	0.13b	0.10b	0.09b	0.04	34.5
AvP	mg/kg	70.9a	20.3 b	8.1 b	4.2b	1.1b	167.4	35.5
Av S	mg/kg	11.1	11.2	10.0	9.2	9.3	29.9	ns
Ca	Cmolc/kg	13.3a	10.4 b	9.4 b	8.1bc	6.4 c	26.3	2.6
Mg	Cmolc/kg	3.1a	2.7a	2.1 b	2.1b	1.8b	20.1	0.48
K	Cmolc/kg	3.2a	2.6a	1.7b	1.4b	0.6c	29.0	0.56
K:Mg	–	1.02a	0.96ab	0.84bc	0.70c	0.37d	22	0.17
C:N	–	13.1b	13.1b	29.4a	16.5ab	12.4b	76.8	13.2
B	mg/kg	1.2a	0.95b	0.56c	0.56c	0.4c	35.0	0.26
Cu	mg/kg	0.91a	0.66b	0.66b	0.45bc	0.32c	39.9	0.24
Fe	mg/kg	105.5	107.1	105.4	107.5	133.8	20.0	ns
Mn	mg/kg	213.25a	191.13ab	180.37abc	156.13bc	131.63c	31.4	55.7
Zn	mg/kg	20.5a	13.4b	9.9bc	8.0cd	5.0d	40.0	4.6
TEB	Cmolc/kg	20.2a	16.5b	14.0bc	12.4cd	9.5d	21.4	3.2
CEC	Cmolc/kg	27.5a	24.5b	21.8bc	21.0cd	18.6d	12.0	2.8

ns not significant, RTC root and tuber field

field > fallow land. The proportion of K and Mg varied from 0.37 (fallow) to 1.02 (enset). Following the K and Mg threshold value of 0.7 adopted by Fanuel et al. (2018), the potential of Mg-induced K deficiency on crop field and fallow land was suspected. The result regarding micronutrients (mg/kg) such as B, Cu, Mn and Zn among fields were significant and their content ranged from: 0.4–1.2, 0.32 to 0.91, 131.6–213.3, 5.0 to 20.5, respectively. In all cases, the minimum and maximum value was recorded from fallow and *enset* fields, respectively. CEC showed decreasing trend from *enset* to fallow fields. *Enset* field

showed high CEC (25–40 cmol (+)/kg) whereas, coffee, RTC and crop field recorded moderate CEC (15–25) CEC; and fallow lands qualified under low CEC (<15 cmol (+) kg).

#### C and N stocks, C sequestration and CO<sub>2</sub> emission

Stocks of C and N in the fields and amount of C sequestered are presented in Table 3. Coffee field stored significantly highest ( $P < 0.01$ ) organic carbon and the lowest were recorded in the fallow land. However, coffee and *enset* fields were found statistically at par. C stock was

**Table 3 N and C Stock, and C sequestered under fields in the farm**

	Field type					CV (%)	LSD <sub>0.05</sub>
	Enset	Coffee	RTC	Crop field	Fallow		
N stock (t/ha)	6.0a	6.3a	4.2b	3.6b	3.3b	36.3	1.73
N stock (kg/m <sup>2</sup> )	0.6a	0.63a	0.42b	0.36b	0.33b	36.3	0.17
C stock (t/ha)	75.5a	81.4a	68.8ab	57.5bc	43.3c	24.3	16.1
C stock (kg/m <sup>2</sup> )	7.55a	8.13a	6.88ab	5.75bc	4.33c	24.3	1.61
C sequestered (t/ha)	277.0a	298.5a	252.6ab	211.0bc	159.0c	24.3	59.0
C sequestered (kg/m <sup>2</sup> )	27.7a	29.85a	25.26ab	21.1bc	15.9c	24.3	5.9

in the order of coffee > *enset* > RTC > crop field > fallow land implying that it decreases towards the out fields. N stock was significantly ( $P < 0.05$ ) varying among fields and showed moderate variability. It was in the order of coffee > *enset* > RTC > crop field > fallow land. Yet, N stock at coffee field was statistically at par with *enset* field. Generally, fields close to home accumulated 30–50% more N than middle and out fields.

Significant variation ( $P < 0.05$ ) among fields in C sequestration was observed. It followed the trend of C stock. This signifies that coffee and *enset* fields have stored better amount of C than fallow and crop fields as a result they reduced CO<sub>2</sub> emission into the atmosphere. The CO<sub>2</sub> emission (amount and percentage) relative to coffee field ranged from 21.5 t/ha (7.2%) (*enset* field) to 159.0 t/ha (46.7%) on fallow land (Table 4). It was also noted the magnitude of C sequestration in coffee field was relatively superior to *enset* field.

#### Soil deterioration index among crop fields

Soil deterioration index (DI) (%) relative to coffee field for OC, N, P, and K in their order was: *enset* [−2.8, 0, 254.5, 23.1], RTC [−17.7, −31.6, −59.5, −34.6], crop field [−35, −47.4, −79, −46] and fallow [−55.7, −52.6, −94.5, and −76.9] (Figs. 3, 4). The average DI value of TN and SOC was: 1.7% (*enset*), 26.03% (RTC), 40.9 (crop field), 55.4% (fallow field) (Fig. 4). In all cases, the magnitude of soil degradation is increasing towards the fallow field.

## Discussion

### Field management

Though the average land holding size is very small, small holder farmers in the study area is sub-divided the farm into different fields and used to manage *enset*, coffee, RTC and crop field. The fields are intensively cultivated and the spaces available under each field are utilized via intercropping (Table 1). Soil management practices were found field specific. For instance, *enset*, coffee, and RTC fields are exclusively managed with farm yard manure

(FYM) and house wastes. The amount of organic inputs applied was in the order of coffee > *enset* > RTC fields. Organic inputs can build soil organic matter (OM), restores the plant nutrient into the soil system, and attaches soil particles and protect from erosion (Walcott et al. 2009). On the other hand, fields that belong to cereal and pulses are managed with inorganic fertilizer. However, the amount used by each field was inadequate to replenish the soil quality (Table 1). This may cause the depletion of soil organic matter and essential nutrients to extent limiting crop yield (Eyasu et al. 2019; Fanuel and Kibebew 2020).

### Soil properties

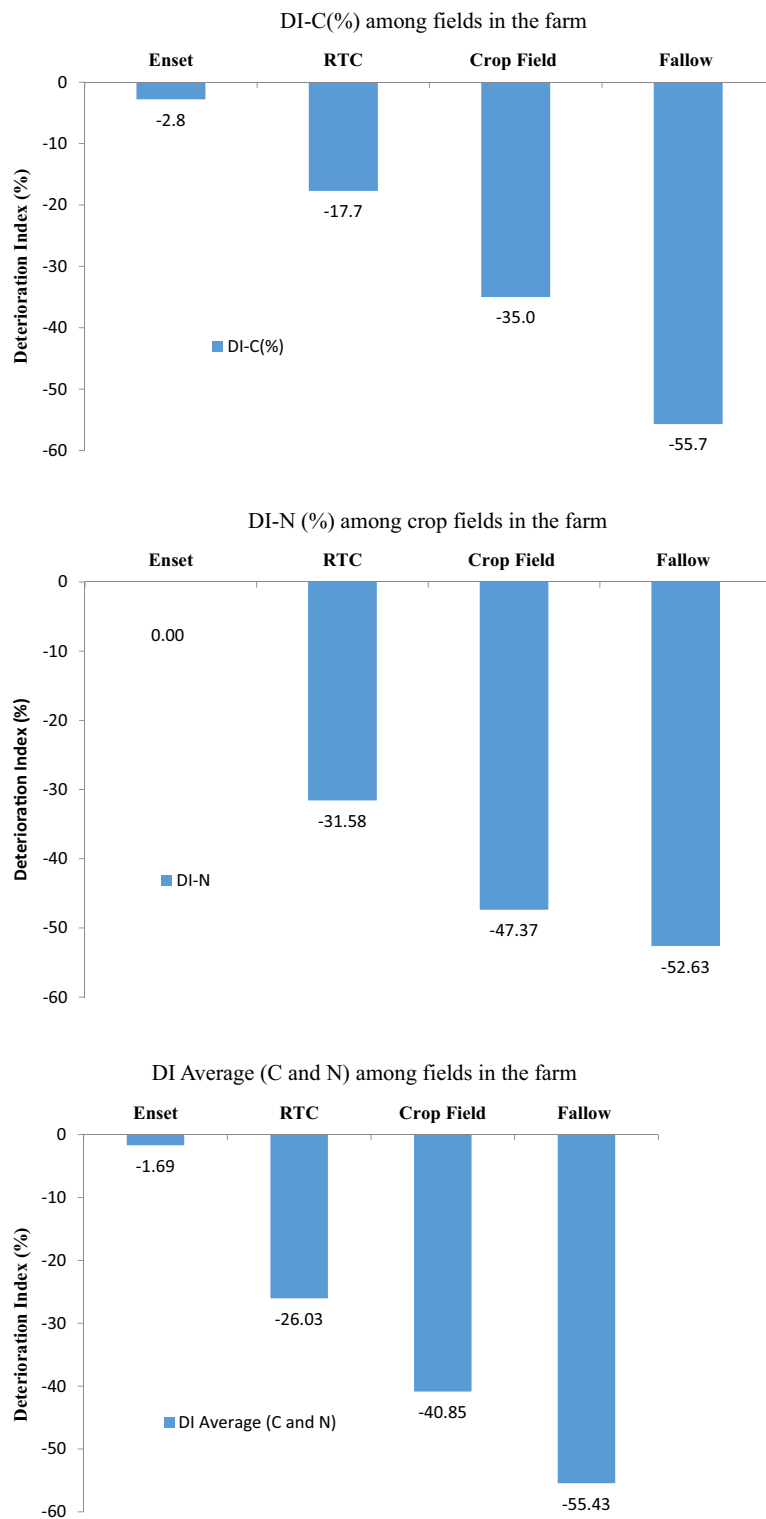
Differences in particle size distribution and soil texture among fields was probably attributed to the prevalence of water erosion on the crop and fallow field than other fields (Fanuel et al. 2016). On fields covered with perennial crops (*enset* and coffee), soil particles are less likely detached with erosion and impacts of rain droplets. This is probably due to higher SOC and better canopy cover. Comparatively, lower SOC on crop and fallow fields would make the soils susceptible to erosion and made them to have high clay content and clay texture. Tessema and Kibebew (2019) also reported the higher clay content at the surface of cultivated lands. They pointed out that the selective removal of the finer particles, such as silt and clay, by water erosion from the natural forest and their subsequent accumulation on cultivated lands caused the higher clay content.

The lower soil bulk density (BD) on *enset* field and higher BD value on out-fields could be linked with the presence of higher and lower soil OM accumulation, respectively (Oguike and Mbagwu 2009). This is also justified with significantly ( $P < 0.001$ ) inverse relationship between organic matter and BD ( $r = -0.5$ ). The soil BD values in all fields were within the favorable range (Hazelton and Murphy 2007). Thus, restriction of plant growth as consequence of excessive compaction is less likely to occur.

Farmers apply home left wastes particularly wood ash into *enset* and coffee fields. This is why these fields had neutral soil pH than main/fallow field that was not getting same treatment (Lalisa et al. 2010). Pearson correlation matrix also indicated that pH was significantly ( $P \leq 0.001$ ) correlated with amount of clay ( $r = -0.36$ ), available P ( $r = 0.55$ ), total exchangeable bases ( $r = 71$ ), and CEC ( $r = 0.64$ ). Overall, the acidic soil reaction in out-fields could be due to leaching, depletion of basic cations through crop harvest and continuous use of acid-forming fertilizers, such as urea and di-ammonium phosphate ( $(\text{NH}_4)_2\text{HPO}_4$ ) (Table 1) (Yihenew et al. 2015; Alexandra et al. 2013).

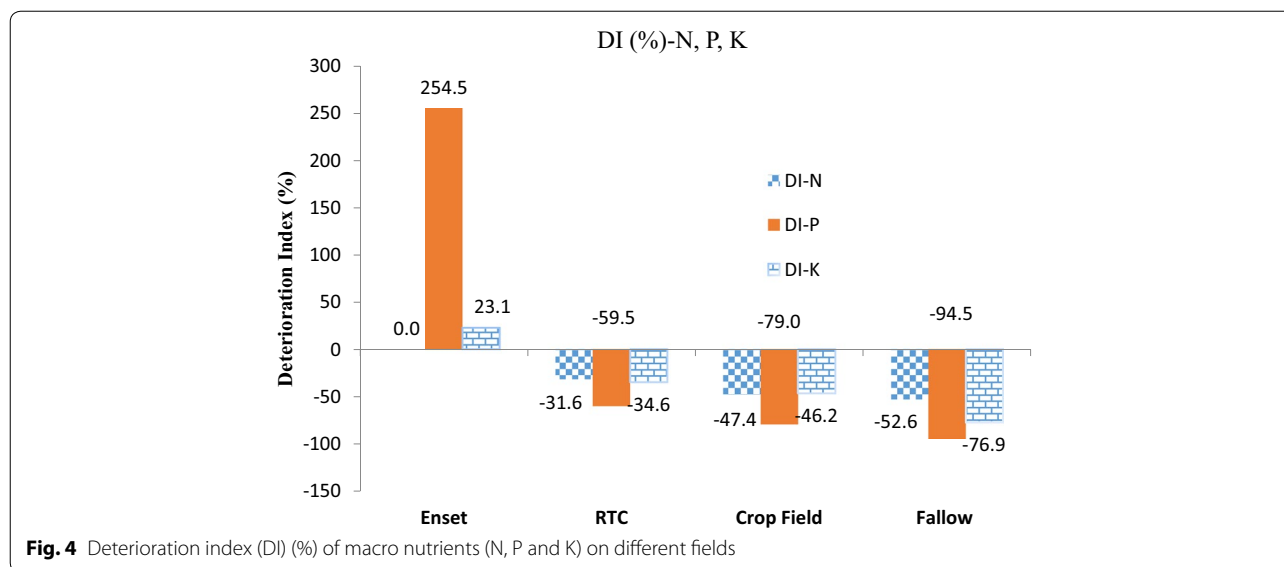
**Table 4** CO<sub>2</sub> emission among fields in the farm as compared to coffee field

Field type	C sequestered (t/ha)	CO <sub>2</sub> emission (t/ha)	CO <sub>2</sub> emission (%)
Coffee	298.5	–	–
<i>Enset</i>	277.0	21.5	7.2
RTC	252.6	45.9	15.4
Crop field	211.0	87.5	29.3
Fallow	159.0	139.5	46.7



**Fig. 3** Deterioration index (DI) (%) of C, N and their average on among fields in the farm





Likewise, other soil chemical properties have also shown significant differences. This is illustrating the widely contrasting SOC and nutrient dynamics among investigated fields. Noticeable gradient from *enset* towards out-fields was observed. The higher total N under *enset*/coffee field could be attributed to higher SOC content, which is the major source of total N (essentially organic nitrogen). This is best described by highly significant ( $P \leq 0.001$ ) and positive correlation between TN and OC ( $r = 0.98$ ). Farmers relatively retain more residues under *enset* and coffee fields. The continuous decomposition of organic materials supplied over a period of time and the lesser occurrence of soil erosion due to particle aggregation on *enset*/coffee fields might be attributed to higher level of p, total exchangeable bases, soil micronutrients and CEC (Walcott et al. 2009). Furthermore, the application of home left wastes particularly wood ash into coffee and *enset* fields might result the high exchangeable bases. Pitman (2006) reported that wood ash provides considerable amount of Ca, Mg, K and other trace elements. The higher exchangeable bases on backyard fields is due to the effect of external inputs (wood ash, and household and animal wastes) because of its proximity to living quarters was also reported by Lalisa et al. (2010).

The lower nutrient values in RTC, crop and fallow fields might be due to non-use of mineral fertilizers containing S, K and micro nutrients, and continuous crop uptake without compensation. In addition, the practice of complete residue removal degrades the SOC and soil quality of the crop fields. According to Fanuel et al. (2016) farmers in the area do not deliberately practice fallowing; rather they practiced when the cultivable land has

reached to the point of no return. Thus, SOC and nutrient content under fallow field becomes very poor. The recovery process demands more time soil.

#### Soil C stock, C sequestration and CO<sub>2</sub> emission

*Enset* and coffee fields relatively were found the most sustainable and less degradable fields in terms of SOC and C sequestered followed by RTC fields > crop field > fallow land. The higher C stock and sequestration in the *enset*/coffee fields could be attributed to the relatively higher application rates of organic inputs than other fields (Table 1). The low SOC stocks in crop and fallow fields are possibly due to continuous cultivation and complete residue removal. The prevalence of erosion in crop and fallow fields may result in low SOC stock (Vagen and Winowiecki 2013).

Comparatively, the highest carbon stock and sequestration on coffee than *enset* fields is also ascribed to the long years of accumulation. Coffee plants stay for longer years in the field than *enset* plant. For this reason, continuous decomposition of the accumulated organic inputs and the litter under coffee fields could result highest carbon stock and sequestration. Nevertheless, soil management practices at coffee and *enset* fields such as maintaining crop residue application, applying FYM and home left residues could play an important role in the maintenance of SOC levels, soil quality and productivity. The implication is that the more stocks of C, the lesser CO<sub>2</sub> emitted into the atmosphere. According to Melenya et al. (2015) applying of organic inputs like mulching increases recycling of nutrients and minerals, fertilizer use efficiency, improves soil chemical and physical properties and, decreases soil erosion.

Soil under the crop field and fallow land recorded lower carbon pool and higher CO<sub>2</sub> emission than *enset*/coffee based complexities. According to Melenya et al. (2015), soil degradation processes as well as rapid decomposition of organic matter in cultivated soils were the major cause for the release of CO<sub>2</sub> from the system as the land use systems that added more residues recorded less emission of CO<sub>2</sub>. The present result also corroborated with previous studies by Bhunia et al. (2018) who reported significantly lower storage capacity of carbon in the fallow land.

Soil carbon stock (t ha<sup>-1</sup>) at 0–20 cm under different land uses in eastern Ethiopia by Tessema and Kibebew (2019) indicated the following amount: natural forest (141.34 ± 12.32), coffee agroforestry (93.78 ± 6.92 t/ha), grazing land (57.38 ± 10.29) and crop land (53.11 ± 8.42). In the present study, the amount in coffee (54.23 t/ha) and crop (38.33 t ha<sup>-1</sup>) fields at 0–20 cm depth were less compared to the study in Ethiopian coffee-agroforestry and crop land uses, respectively (Tessema and Kibebew 2019). This signifies that farming practices are very exploitive. Furthermore, the loss of organic carbon is likely to increase CO<sub>2</sub> emission from the soil system. Therefore, implementing climate smart field management practices that fit to subsistence farming condition but having a capacity to enhance SOC pool, restore soil quality and minimize emission has to be put in place. Amongst them conservation tillage, integrated nutrient management, agro-forestry, intercropping and green manuring are suggested (Manna et al. 2015; Melenya et al. 2015; Jarecki and Lal 2003).

#### Soil deterioration index among fields

Comparing different fields, the higher DI in the crop and fallow fields could be associated with inadequate soil management practices. Fanuel et al. (2016) indicated that smallholder farmers in the study area apply few/no organic inputs, completely remove of crop residues and practice more intensive cultivation. The inputs applied could not compensate the mineralization of OM and N losses and accelerate the oxidation rate of soil OM (Girma and Endalkachew 2013). The finding of Tessema and Kibebew (2019) in Ethiopia also indicated a high and low deterioration index under cultivated lands and coffee agroforestry, respectively. The authors explained that highly exploitive farming practices on crop land attributed to the net degradation of OC and TN. Nonetheless, organic inputs applied to coffee (4.23 t ha<sup>-1</sup>) and *enset* (3.5 t ha<sup>-1</sup>) fields are below the required amount (Table 1). As an example, amount applied on *enset* field are very far from 10 to 20 t ha<sup>-1</sup> which is the amount suggested for better growth and yield of *enset* (Mulugeta and Admasu 2012). Thus, soil management practices that maintain and enhance the carbon pool are suggested.

#### Conclusion

The result among fields in the farm illustrates significant differences in soil physio-chemical properties, C stocks and sequestration. Noticeable gradients on measured parameters were formed. The gradient from better to worse direction was towards *enset*/coffee→root and tuber field→crop field→fallow field. Overall, variation in soil management practices at field level was the driving factor resulting differences in carbon stock and soil quality. Finally, the detected gradient calls for field specific management recommendation.

In conclusion, on out fields implementing climate smart field management practices that would enhance SOC pool, restore soil quality and minimize emission has to be put in place. This may include conservation tillage, integrated nutrient management, agro-forestry, maintaining/incorporation of crop residues, and green manuring. In order to reduce the prevalence of erosion and also obtain feed for livestock's, integrated soil and water conservation practices have to be promoted. Although backyard and middle fields in the farm were comparatively better, soil management was not adequate. Thus, integrated use of organic and mineral fertilizers is suggested.

#### Abbreviations

BD: soil bulk density; DI: soil degradation index; SOC: soil organic carbon; PSD: soil particle size distribution.

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#### Authors' contributions

FL collected, analyzed, interpreted and prepared the manuscript. The author read and approved the final manuscript.

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#### Availability of data and materials

I declare that the data and materials presented in this manuscript can be made available as per the editorial policy of the journal.

#### Ethics approval and consent to participate

Not applicable to this manuscript.

#### Consent for publication

All data and information are generated and organized by the authors.

#### Competing interests

The author declares that there is no competing interest.

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