

# Soil Carbon Sequestration, CO<sub>2</sub> Emission, and Soil Quality under Smallholder Farmers' Fields in Southern Ethiopia

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## Research

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# Abstract

## Background

Soil organic carbon (SOC) is key indicator of soil quality and health. It has quite a lot of benefits to the ecosystem. Information on the magnitude of carbon pool under field scale of subsistence farms is scanty. This study was aimed to assess SOC storage, CO<sub>2</sub> emissions and soil quality, under different fields in smallholder farms of southern Ethiopia. Five fields within a farm were investigated viz. coffee (*Coffea arabica* L.), enset (*Ensete ventricosum*), root and tuber crop field (RTC), cereal and pulse field (main field) and fallow land. For each field, eight representative farms that make a total of 40 farms were randomly selected. Surface soil samples were collected, and analyzed to determine soil physico-chemical properties. SOC stock (t ha<sup>-1</sup>), C-sequestration, and CO<sub>2</sub> emission were also computed.

## Results

The result showed that the field that sequestered more OC and emitted less CO<sub>2</sub> was Coffee > Enset > RTC > main 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), main 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% (main field) and 46.7% (Fallow). The result regarding soil quality further revealed significant differences in almost all of investigated parameters. The minimum and maximum values being recorded in all fields 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 parameter were observed in main and fallow fields. 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], main 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 quality. Thus, climate smart soil management practices that would enhance SOC and simultaneously increasing soil quality is suggested e.g., integrated nutrient management.

## 1. 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 cycle and influences the global climate, whereas sinking CO<sub>2</sub> and increasing carbon stock of the ecosystem has positive effects (Melenya et al., 2015). Soil is the

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

Soil organic carbon (SOC) is key indicator of soil quality and health (Bhunja et al., 2018; Vagen and Winowiecki, 2013). The benefits provided by SOC includes carbon 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 carbon 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 (Elias et al., 2019). On contrary, farming size at the face of growing population is decreasing time to time. There is also an expansion of agricultural areas in response to population growth and increasing demand for food (Teklu et al., 2020; Fanuel et al., 2016). It has been done at the expense of grazing and forest lands. These activities could have brought an increased interest in soil carbon sequestration and maintenance of soil ecosystem (Vagen and Winowiecki, 2013). 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.

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 (WZFEED, 2012). Like other parts in the country, farming is also entirely rain-fed and characterized by low input and low productivity. 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 carbon 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 carbon 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; Bhunja et al., 2018; Manna et al., 2015; Melenya et al., 201; Vagen and Winowiecki, 2013). For instance, in Eastern Ethiopia at 20 cm depth 88.23 t/ha organic carbon could have been lost if forest land is converted into crop land (Tessema and Kibebew, 2019). The same study further indicated higher carbon stock in coffee agroforestry ( $277.38 \pm 28.58 \text{ t ha}^{-1}$ ) than in cropland uses ( $138.95 \pm 25.0.1 \text{ t ha}^{-1}$ ).

While the effects of land use changes on SOC stocks and soil quality have been widely studied, SOC sequestration rate and subsequent effects under fields within a farm conditions are scanty. This would

result limited utility of soil management recommendations as it does not address farm complexities encompassing different fields having different land uses histories. Hence, assessing the effects of management practices on carbon stock and soil properties on field scale is necessary to set recommendation on the maintenance and enhancement of carbon stock. In Ethiopia very limited information under smallholder fields is available. These gaps call the need to explore the magnitude of soil carbon stock, carbon sequestration, CO<sub>2</sub> emission and soil properties under smallholder farmers' fields in Southern Ethiopia.

## 2. Materials And Methods

### 2.1 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 (Figure 1). The *woredas* have potential for diverse agricultural activities (Figure 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.

### 2.2 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 small holding to grow different crops (Table 1 and Figure 2). This includes coffee (*Coffea arabica* L.) based field; enset (*Ensete ventricosum*) based field; root and tuber field, and main field for 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, the main field after long years of cultivation is being fallowed. Though rarely practiced in the area due to land shortage, it was also considered for comparison.

Field survey was conducted and representative fields in the farm were randomly selected. For each field indicated in Table 1 and Figure 2, four (4) representative replicates were identified. Then after, 20 fields per *woreda* and a total of 40 fields from the two *woreda* were surveyed. Socio-economic status of replicate field, elevation, slope, land scape position, soil management and land use history were considered during field selections. Each field was georeferenced using a GPS.

### 2.3 Soil Sampling and Laboratory Analysis

#### 2.3.1 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 diffused reflectance spectral analysis was also used to determine the amount of soil organic carbon (OC), total nitrogen (N) and cation exchange capacity (CEC). For the purpose of management, interpretation was given using proper ratings.

### **Organic Carbon and Total Nitrogen Stock**

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

$$\text{SOC (or TN) Stock (kg/ha)} = \text{Soil OC (\%)} \text{ or N (\%)} * \text{BD (kgm}^{-3}\text{)} * V \quad (\text{Eq. 1})$$

where

BD = bulk density ( $\text{Kgm}^{-3}$ ) and V= Volume of the soil in cubic meter = depth of soil (m) X Area of soil ( $\text{m}^2$ )

### **Conversion of soil organic carbon to $\text{CO}_2$ /Carbon sequestration (Stored)/-Eq. 2**

Carbon sequestration ( $\text{tha}^{-1}$ ) is the conversion of the total carbon stored (SOC) into carbon dioxide. It is obtained by multiplying SOC by 3.67 (i.e. the molecular mass of  $\text{CO}_2$ / atomic mass of C =  $44/12=3.67$ ).

### **Soil Degradation Index (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. The deterioration on SOC and macro nutrients (TN, available P and K) was computed. 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).

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

(Equation 3)

where SDI is deterioration index, PSF is value of individual soil property (P) under specific field (SF) and PRL 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.

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

CO<sub>2</sub> emission (tha<sup>-1</sup>) was computed as difference between reference field (RF) i.e., C sequestration (tha<sup>-1</sup>) on field having maximum value minus value of subsequent fields (tha<sup>-1</sup>). The field that sinks more carbon i.e. the field emitting the least CO<sub>2</sub> was taken as reference value for comparison. Then, CO<sub>2</sub> emission percentage was computed from the ratio of (CO<sub>2</sub> emission/ C sequestered)\*100.

## Data Analysis

One way Analysis of variance (ANOVA) was employed to test significance variation among fields. Data analysis was performed using Statistix 8 software.

# 3. Results

## 3.1. Effects on Selected Soil Physical Properties

Particle size distribution (PSD) among fields indicated non-significant differences but showed moderate variability (Table 2). However, lower sand content was measured in soils of fallow land. Silt content was showed decreasing trend from *enset*/ coffee fields towards main 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) was significant (p<0.05) differed among fields. Significantly lower BD value (1.05gcm<sup>-3</sup>) was recorded in soils under the *enset* field, whilst higher value (1.29gcm<sup>-3</sup>) was observed in soils under the fallow field (Table 2).

## 3.2. Effects on Soil Chemical Properties

Crop fields 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 were categorized under neutral pH (6.6–7.3) while main 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 main crop fields. Coffee field had 125% and 54% higher OC compared to fallow and main crop field, respectively. *Enset*, Coffee and Root and Tuber fields were qualified under optimum OC [1.71-4.1%] while main 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 main 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 main fields whereas it was very low (< 0.1) on fallow field (EthioSIS, 2014).

Crop fields showed significant ( $p < 0.05$ ) differences in terms of available P but not on S content. 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  $Ca^{2+} > Mg^{2+} > K^+$ . 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 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 used by Fanuel et al. (2018), the potential 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 also showed a decreasing trend from *enset* to fallow fields. *Enset* field had high CEC (25-40 cmol (+)/ kg) whereas, coffee, root crop and main field have CEC moderate (15 - 25) CEC; fallow lands qualified under low CEC (< 15 cmol (+) kg).

### 3.3. Stocks of C and N, C sequestration and CO<sub>2</sub> Emission

Nitrogen and carbon stored in the fields and amount of CO<sub>2</sub> sequestered is presented in Table 3. Coffee field stored the 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 in the order of coffee > *enset* > RTC > crop field > fallow land implying that it decreases towards the main fields. N stock was significantly ( $p < 0.05$ ) varying among fields and showed moderate variability. N stock 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 stead accumulated 30-50% more N than middle and main fields.

Significant variation in the amount of CO<sub>2</sub> stored (carbon sequestered) ( $p < 0.05$ ) was observed. It followed the trend of C stock. This signifies that coffee and *enset* fields have better soil quality than fallow and crop fields as a result they reduce CO<sub>2</sub> gas emission into the atmosphere. The study showed that the magnitude of sequestration is even more under coffee. 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 can be noted that coffee followed by *enset* field sequesters substantial amounts of soil carbon. This suggested that fields away from home should be targeted to benefit from carbon sequestration.

### 3.4. Soil Deterioration Index (Degradation Index) among Crop Fields

Soil degradation 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], main field [-35, -47.4, -79, -46] and fallow [-55.7, -52.6, -94.5, and -76.9] (figure 4 and 5). The DI for mean values of TN and SOC was: 1.7% (*enset*), 26.03% (Root and Tuber

field), 40.9 (main field), 55.4% (Fallow field) (figure 4). In all cases, the magnitude of soil degradation is increasing towards the fallow field.

## 4. Discussion

### Field Management

Though the average land holding size is very small, the small holder farm in southern Ethiopia is subdivided into fields and used to manage *enset*, coffee, root and tuber and cereal and pulse crops. The fields are intensively cultivated and the spaces available under each field are utilized *via* intercropping (Table 1). Soil management practices by using fertilizer are field specific. For instance, *enset*, coffee, and root and tuber fields are exclusively managed with farm yard manure (FYM) and house wastes. The amount of organic inputs are in the order of coffee > *enset* > root and tuber fields. Organic inputs can build soil 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, the main fields that belong to cereal and pulses, on the other hand, 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 et al., 2016).

### Soil Properties

The difference in particle size distribution and soil texture among fields was probably attributed to the presence of higher water erosion on the main and fallow field (Fanuel et al., 2016). On fields covered with perennial crops (*enset* and coffee), soil particles are less likely detached with erosion and impacts rain droplets. This is probably due to higher SOC and canopy cover. Relatively, lower SOC on main and fallow fields would make the soils susceptible to erosion made distant fields to have 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 main field 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 bulk density ( $r = -0.5$ ). 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). The acidic soil reaction in main 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).

Likewise, other soil chemical properties have also shown significant differences among crop fields. This is illustrating the widely contrasting SOC and nutrient dynamics among fields. Noticeable gradient from *enset* towards main field is 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, main 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 carbon stock, C Sequestration and CO<sub>2</sub> Emission**

*Enset* and coffee fields relatively are found the most sustainable and less degradable fields in terms of the SOC and carbon sequestered followed by root and tuber fields > main field > fallow land. The higher SOC and carbon sequestered in the *enset*/coffee fields could be attributed to the relatively higher organic inputs to the soil than others (Table 1). The low SOC stocks in main and fallow fields are possibly due to continuous cultivation and complete residue removal. The prevalence of erosion in main and fallow fields may result in low SOC stock (Vagen and Winowiecki, 2013).

Comparatively, the higher SOC and carbon sequestration on soils of 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 relatively result higher soil OC and carbon sequestration. The better SOC also reduced the amount of CO<sub>2</sub> gas emitted into the atmosphere. The implication is that, soil management 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. 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 main field and fallow land recorded lower carbon pool and higher emissions 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) at 0-20cm 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) fields at 0-20cm depth were less compared to similar 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 Crop 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) and *enset* (3.5 t/ha) fields are below the required amount. As an example, amount applied on *enset* field are very far from 10-20 t/ha 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.

## **5. Conclusion**

The result illustrates significant differences on SOC and nutrient dynamics among fields. SOC, nutrient and soil deterioration showed noticeable gradients. The magnitude of gradient in decreasing order is formed towards *enset*/coffee → root and tuber fields' → main field → fallow field. Field level variation of soil management practices attributed to differences the magnitudes of SOC stocks and soil quality. Hence, land management practices that maintain and enhance carbon sequestration in fields within the

farm will be important. In addition, strategies that able to manage soil erosion and nutrient depletion have to be integrated.

In conclusion, on main and middle fields of the farm, zero/minimum tillage with residue mulch and cover cropping, maintaining/incorporation of crop residues, integrated use of organic and mineral fertilizers are recommended. In order to reduce the prevalence of erosion, and maintain/increase SOC integrated soil and water conservation practices is also suggested. Although coffee/*enset* fields were comparatively better, soil management is not enough. Thus, integrated nutrient management is suggested. Finally, the observed gradient calls for quantification of field specific management recommendation e.g. amount of SOC, integrated nutrient management and intercropping system.

## **Declarations**

### **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.

### **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.

### **Conflict of Interest**

The author declares that there is no competing interest.

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### **Author contributions**

Fanuel Laekemariam collected, analyzed, interpreted and prepared the manuscript.

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## **Abbreviations**

BD (Soil bulk density)

DI (Soil degradation index)

SOC (Soil organic carbon)

PSD (soil particle size distribution)

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## Tables

Table 1. Characteristics of land use practices

Field types	Location in the farm	Crop intensity (No. of crops/year)	Residue Management	Topography	Fertilizer application		
					N* (kg/ha)	P <sub>2</sub> O <sub>5</sub> ** (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
Main field	Out field	2.00	Removed	Gentle Slope	13.2	20.5	-
Fallow land	Out field	-	Free grazing	Hilly Slope	-	-	-

- and \*\* Source of fertilizer is urea (46-0-0) and Di-ammonium Phosphate (18-46-0), respectively.

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

Land Use	Unit	Enset	Coffee	RTC	C&P	Fallow	CV (%)	LSD <sub>0.05</sub>
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	gmcm <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, C and P= main field with cereal and pulse

Table 3. N Stock, SOC and CO<sub>2</sub> sequestered under different field

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

Table 4: CO<sub>2</sub> emission compared to coffee field

	<b>C sequestered (t/ha)</b>	<b>CO<sub>2</sub> Emission (t/ha)</b>	<b>CO<sub>2</sub> Emission (%)</b>
Coffee	298.5	-	-
Enset	277.0	21.5	7.2
RTC	252.6	45.9	15.4
Cereal and Pulse	211.0	87.5	29.3
Fallow	159.0	139.5	46.7

# Figures

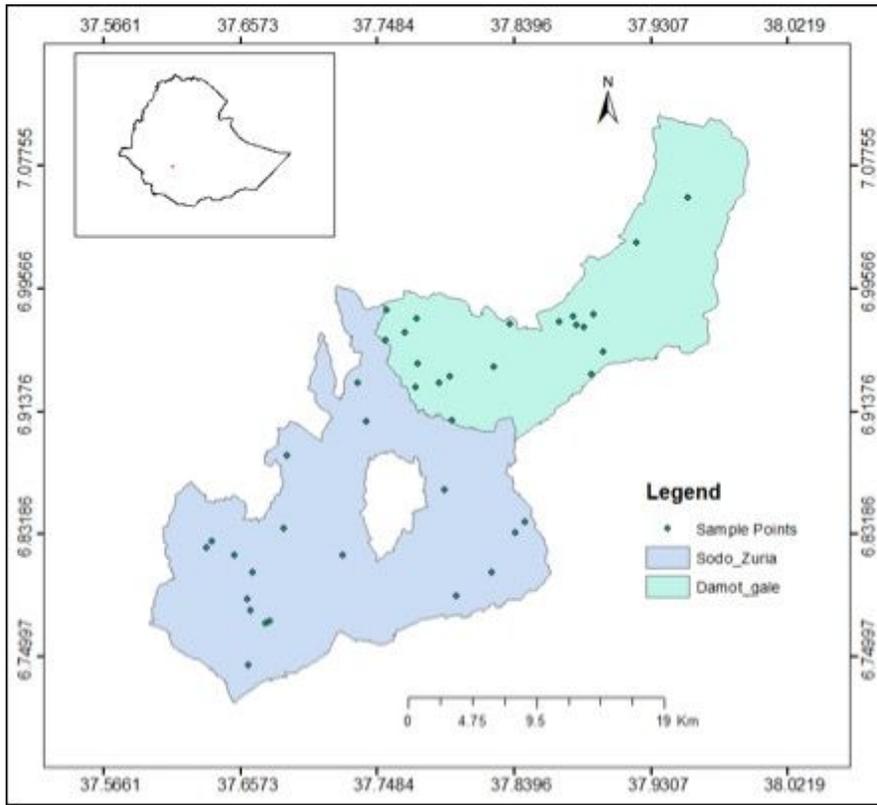


Figure 1

Location map of Damote Gale and Sodo zuria districts of Wolaita zone, southern Ethiopia

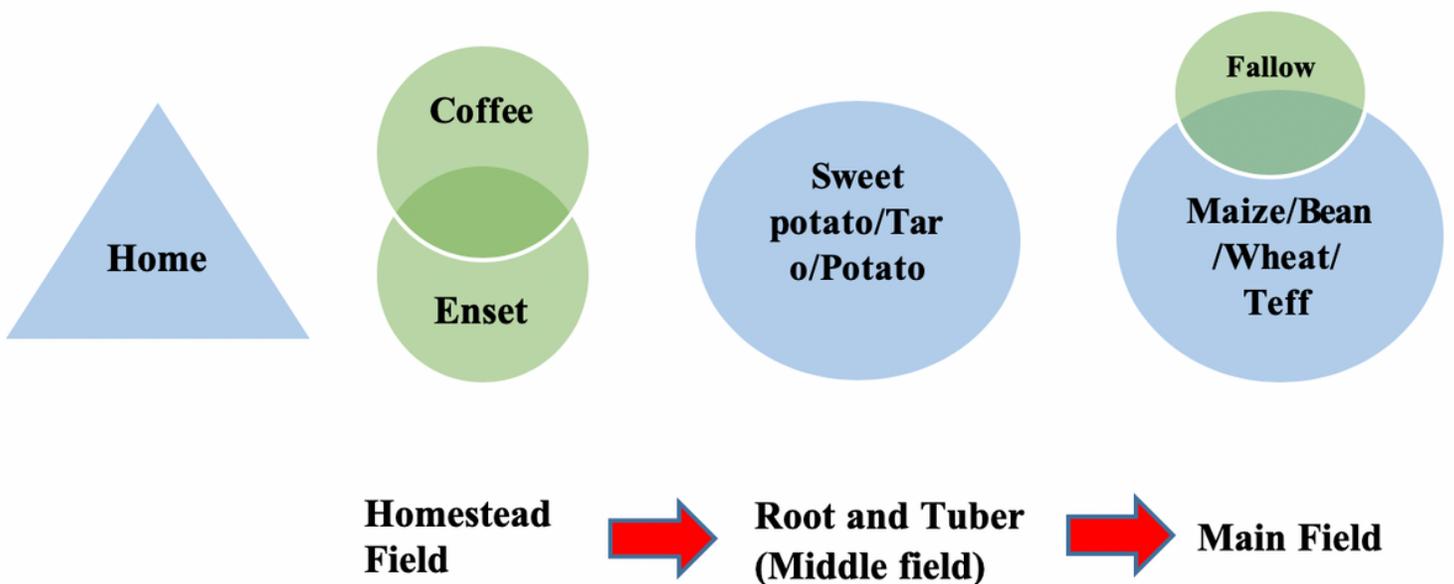


Figure 2

Diagrammatic sketch of fields in the farm

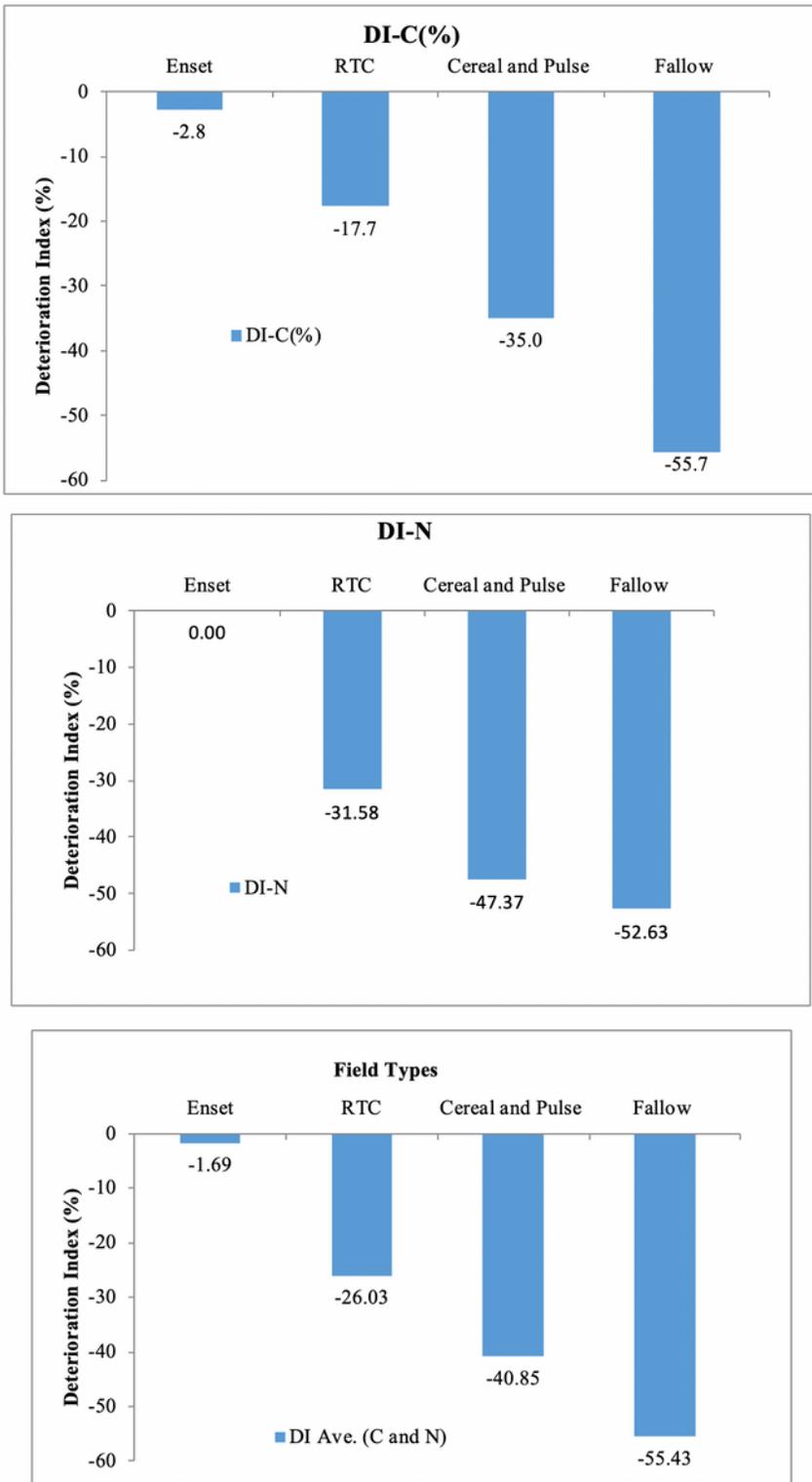
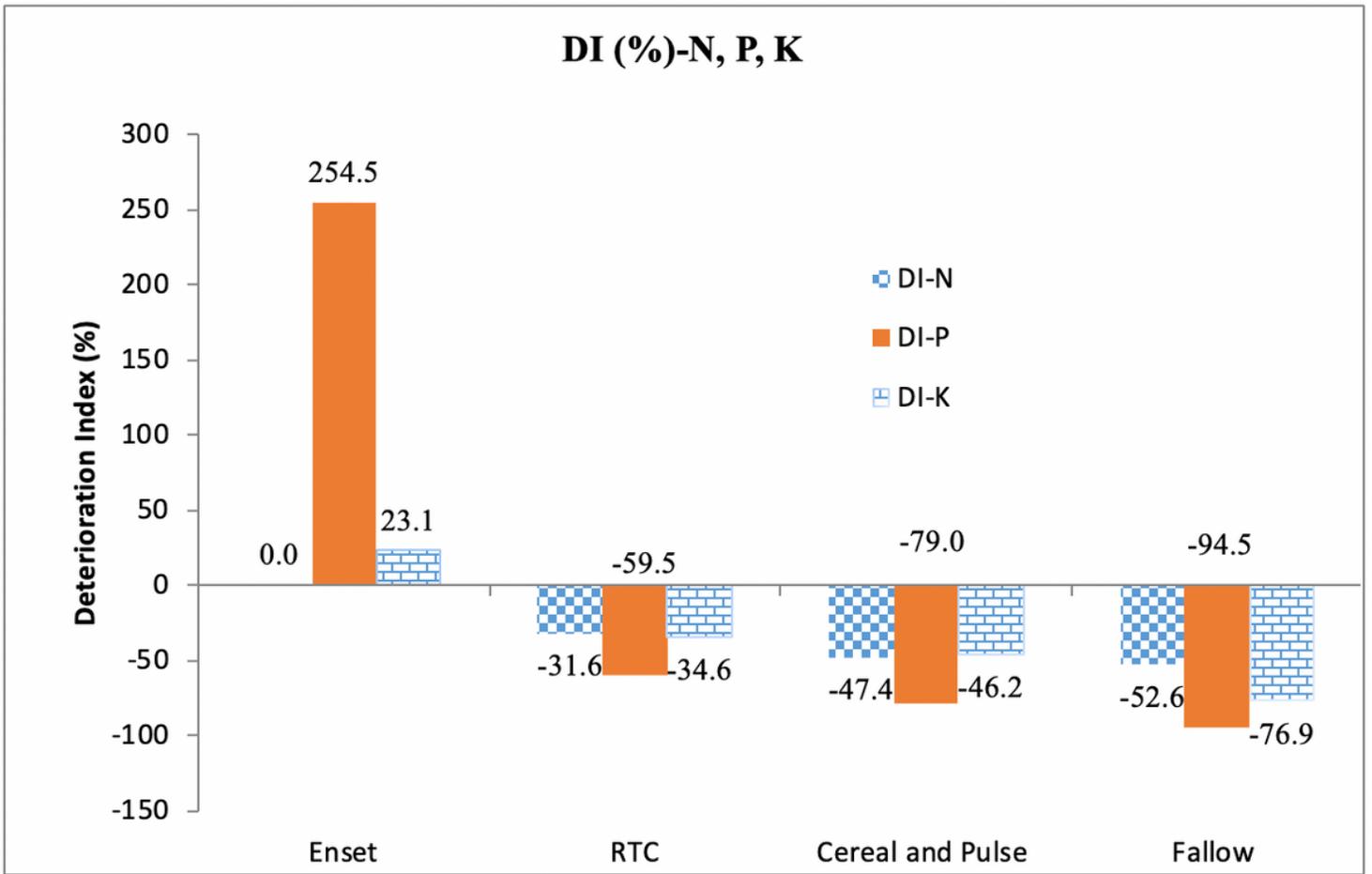


Figure 3

Deterioration index (DI) (%) of C, N and their mean on different fields



**Figure 4**

Deterioration index (DI) (%) of macro nutrients (N, P and K) on different fields