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Advances in quantifying soil organic carbon under different land uses in Ethiopia: a review and synthesis

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Abstract

Background: In the face of climate change and global warming, scientists globally are striving for effective techniques on how best to sequester carbon in order to reduce global warming and achieve environmental sustainability. This paper reviews the available literature on the influence of various land use changes on gains and/or losses of soil carbon (C) stocks in Ethiopia.

Results: Our review indicated that 33.3% of the studies reported soil organic carbon (SOC) concentration, 13.9% reported only SOC stock while 52.8% reported both SOC concentration and stock. Studies focusing on 0–30 cm only were 44%, other studies extending up to 40 to 100 cm were 50%, and studies extending to more than 100 cm accounted for 2.8% while studies without any depth specification accounted for 2.8%. Irrespective of soil type, C stocks in the top soil (0–30 cm) were found to be higher than at subsoil depths. Even though there is significant improvement in C sequestration in exclosures and community forests, the level of C sequestered is still below that of church forests.

Conclusion: Conversion of native forest to other land uses resulted in a significant decrease in the SOC stocks across Ethiopia. Absence of long-term field trials and non-existence of SOC database are among the major drawbacks of SOC studies in Ethiopia identified in this review. With better management practices, it is possible to restore depleted C concentrations and stocks even in degraded lands and to conserve C in more pristine lands across the rugged landscapes of Ethiopia.

Keywords: Agroecosystem, Climate change, Carbon sequestration, Land degradation, Luvisols, Resilience, Vertisols

Introduction

Rapid deforestation and degradation of forest resources remains a major problem in Ethiopia were effects of climate change (for example increase in average temperature, and variability in rainfall pattern) is highly being experienced and according to World Bank (2010), Ethiopia remains one of the countries most vulnerable to climate change. More so, the rugged landscapes of Ethiopia, especially northern Ethiopia have witnessed unprecedented degradation occasioned by agricultural intensification and land misuse for the past three millennia (Nyssen et al. 2015). Recently, the trend is gradually changing with concerted efforts by concerned stakeholders (local communities, non-governmental organizations (NGO's), concerned individuals, and organized environmental groups) to ensure total restoration of degraded landscapes in most regions of Ethiopia through sustainable approaches. Different land uses and soil management practices have variable contributions toward the nature, quality, and quantity of carbon (C) storage and/or CO_2 emission. The potential of soil to sequester carbon cannot be over-emphasized, and with approximately 2344 gigatone (Gt) (1 gigatone = 1 billion tones) of global organic carbon storage (Lal 2004a), making soil the largest terrestrial pool of organic carbon (Stockmann et al. 2013). To soil depths of 30 cm and 1 m, the global stock of soil organic carbon (SOC) has been estimated to be in the range of 684–724 Pg and 1462–1548 Pg respectively (Batjes 1996).

Thus, the soil is a potential natural sink for C because of being the largest terrestrial pool of SOC in addition

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to the relatively long residence time of organic C in the soil (Batjes 2001). In the 0–30 cm topsoil layer, the quantity of SOC is approximately twice the amount of C in atmospheric carbon dioxide (CO_2) and three times that in aboveground vegetation globally (Batjes 2001; Lal 2004a, 2004b). Across different regions in the world, the SOC concentration ranges from low to high in soils of arid and temperate regions respectively and extremely high in organic or peat soils (Lal 2004a, 2004b). Annual release of CO_2 from deforestation as estimated in the Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC) is approximately 25% of CO_2 released from fossil fuel burning (IPCC 2007; Powlson et al. 2011). Depletion of SOC pool has led to estimated loss of 78 ± 12 Pg C to the atmosphere (Lal 2004a). Ruddiman (2003) as reported in Lal et al. (2012) estimated that the total emission of CO_2 from the terrestrial biosphere is equivalent to 427 Pg considering emissions of CO_2-C over 800 years. In addition to emission from land use conversion with emphasis on the period of pre-industrial era to 2010, WMO (2010) reported that total anthropogenic emissions have increased atmospheric concentration of CO_2 from 280 to 390 ppm. Lal (2004a) estimated that soils under cultivation have lost approximately one-half to two-thirds of the native SOC pool in addition to cumulative loss of 30–40 Mg C/ha. It is well documented in the literature that soil C depletion is aggravated by soil degradation and worsened by soil mismanagement and land misuse (Lal 2002; Lal 2004a, 2004b; Powlson et al. 2011; Stockmann et al. 2013) predisposing the soil as a source of C emission. It is noteworthy that with the exception of Histosols having 13–27% soil organic matter (by weight) (SSSA 2001), tropical soils of Sub-Saharan Africa, and temperate soils of Europe/America has documented average soil organic matter content ranging between 0.5–3.0 and 10–13% soil organic matter respectively (Stockmann et al. 2013).

Recently in Ethiopia within the last few decades, concerted efforts by the local communities has been observed with regards to enthroning sustainable land management practices, for example establishment of exclosures geared toward restoration of degraded lands. Nyssen et al. (2015) systematically addressed the historical and future events of land resources management in Africa with emphasis on semi-arid area of northern Ethiopia. Their investigation revealed gradual decrease in gully erosion since around 2000, thus corresponding to enhanced and improved conservation practices in addition to enriched vegetative cover unlike the 1960s, when strong gully channel incision phase commenced.

Previous authors (Girmay et al. 2008; Shiferaw et al. 2013) have made appreciable efforts to review and synthesize studies of soil carbon stocks in Ethiopia with respect to land use, soil management practices, and climate mitigation, but with a focus at regional and selected areas of the country, which is a major gap this review intends to fill. Owing to disparity and dearth of available information in literature, our review reported both soil C concentrations and stocks reported in various studies in Ethiopia up to 2018 to represent the SOC pool.

This review intends to summarize and synthesize available literatures (past and present research findings) on soil carbon sequestration (viz-a-viz C concentration and stock) in the tropics with special focus on Ethiopia. Findings of this review will form the integral basis for improved policy formulation and concerted efforts toward ensuring sustainable land use and C storage across different landscapes in tropical agroecosystems. This review will thus form the foundation for the national soil database carbon pools estimate, which currently does not exist in Ethiopia. Most importantly, key findings of this review will be useful to land managers, agriculturists, environmentalists, and policy makers, in view of ensuring better soil management strategies geared towards increasing SOC quantity, quality, and stability in degraded soils of Ethiopia.

Methodology

For the purpose of this review, we reported both soil organic C concentration and stock to represent SOC pool. The methodological approach adopted was literature search, which was carried out using the following search engines and platforms: Web of Science (apps.webofknowledge.com), Research Gate (https://www.researchgate.net), Google Scholar (scholar.google.com), AGRIS (agris.fao.org), and Science Direct (http://www.sciencedirect.com). Related PhD and MSc theses and dissertations (unpublished) sourced from different university archives were also used for this review. Literatures published up to 2018 were used as the benchmark, while "soil carbon sequestration under different land uses and climate change mitigation" were uses as key words. More than 1000 papers were retrieved from the different search engines, but emphasis was laid on the papers with research findings focusing on Ethiopia. Individual articles from the collected literature were grouped with respect to research objectives and experimental types. Articles with replicated studies focusing on soil organic carbon concentration and stock in Ethiopia under different land uses, options for increasing soil carbon sequestration, and analytical methods for soil carbon determination formed the basis of sub-categorizing the research objectives. Soil organic carbon concentration and soil organic carbon stock are both reported in this review to represent soil organic carbon pool. In some places, SOC and soil organic matter (SOM) are used interchangeably. Our emphasis was only on SOC studies, thus articles on soil inorganic carbon (SIC) were not included in this review. Figure 1 indicates the different locations of the studies in Ethiopia cited in this review, Fig. 2 shows the land use cover map of Ethiopia while Appendix 1 presents the data of referred articles used in calculations.

The major land uses reported in the literature include natural forest, agroforestry, church forest, controlled grazing, open communal grazing, rainfed crop production, irrigation-based crop production, agroforestry, silvopasture, irrigation-based fruit production, exclosure, and grassland. Analytical methods used in all the reported studies varies, and included wet (Walkley and Black 1934) and dry (dichromate) combustion method, isotope ratio mass spectrometer, infra-red spectroscopy, and reflectance spectrometer for SOC determination (see Table 1). The core sampling technique was used in all articles for bulk density determination from undisturbed soil core samples for calculating SOC stock. Reported data were those showing (i) total SOC concentration and (ii) stocks (mass/area for a specific soil depth basis, for different land use types (see Table 2). Preparation of soil sample in all reported studies adopted removal of organic layers prior to sample collection, air-drying for at least 2–3 weeks, removal of coarse fragments/roots and debris, and sieving with < 2 mm sieve. Dominant soil type in reported studies according to World Reference Base for soil resources (WRB 2006) were mainly Lithosols, Nitosols, Cambisols, Regosols, Arenosols, and association of Arenosols with Regosols, Vertisols, and Leptosols. Due to differences in sampling depths in reported studies, data were grouped into two standard depth intervals (0–30 cm for top soil) and 30–100 cm for deep soil)

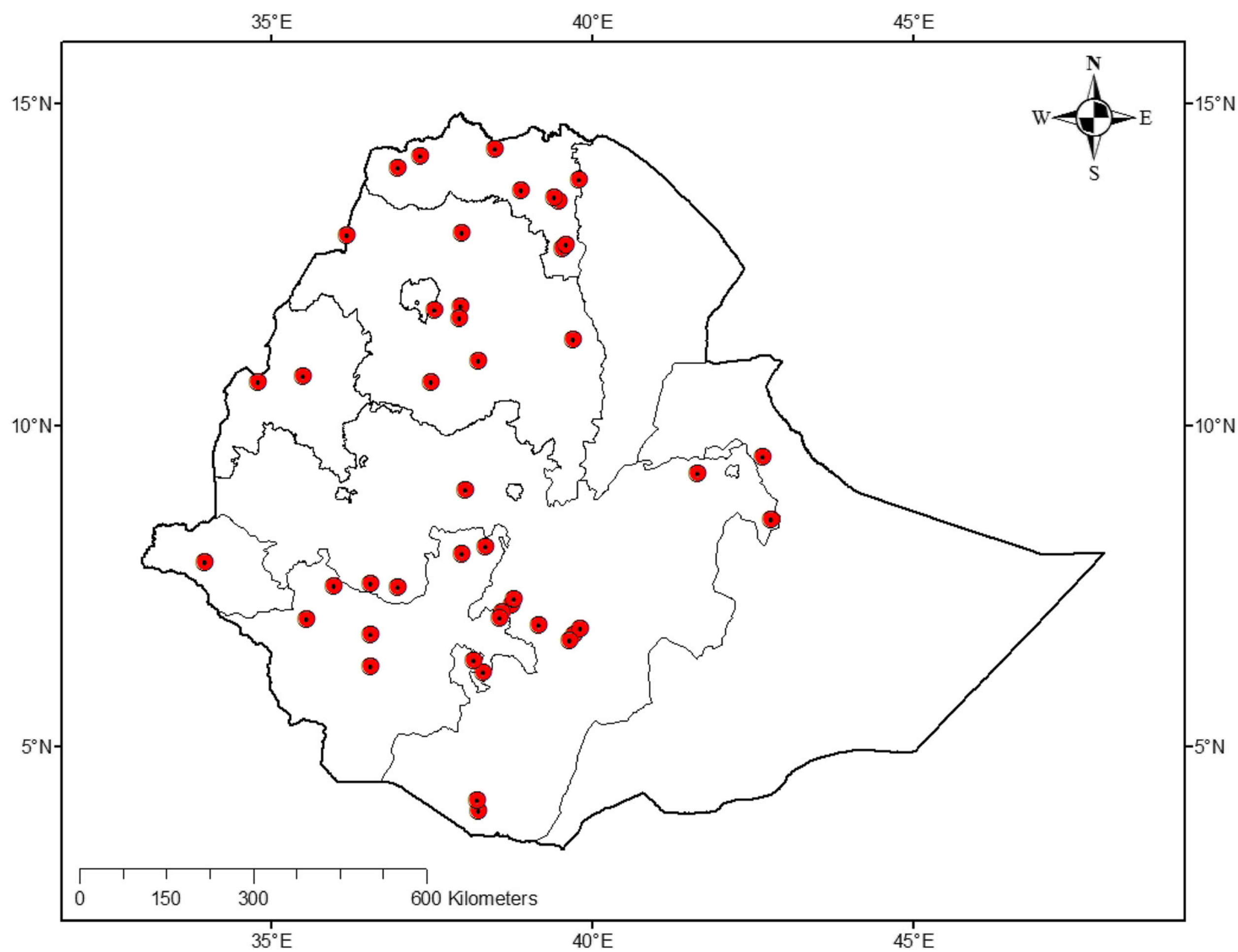

Fig. 1 Map of Ethiopia indicating the approximate location of the study sites referred to in this review as compiled from the literature

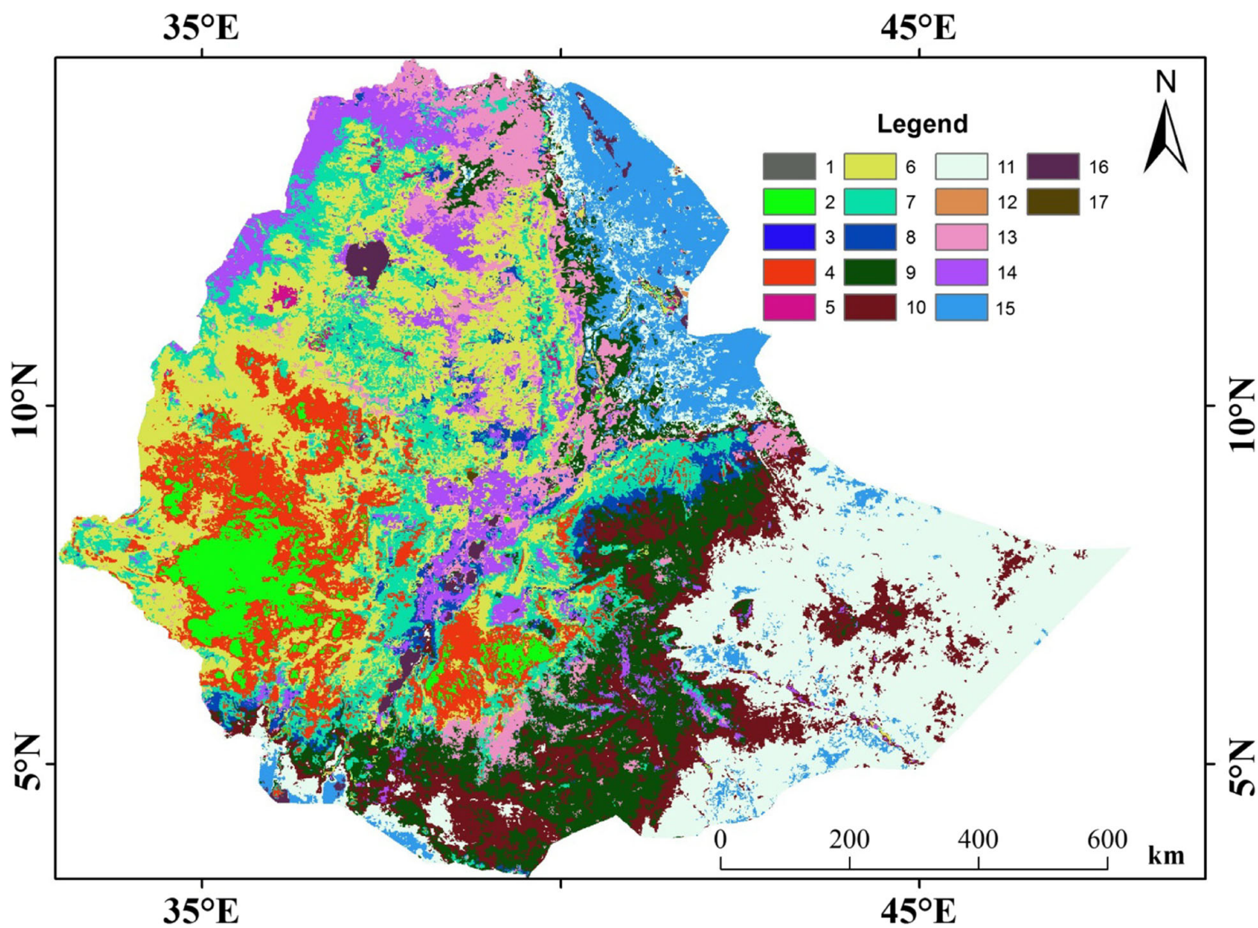

Fig. 2 Land cover map of Ethiopia (1: closed evergreen lowland forest, 2: montane evergreen forest (> 1000 m), 3 mangrove: 4: mosaic forest/croplands, 5: mosaic forest/savanna, 6: deciduous woodland, 7: deciduous shrubland with sparse trees, 8: closed grassland, 9: open grassland with sparse shrubs, 10: open grassland, 11: sparse grassland, 12: swamp bushland and grassland, 13: croplands (> 50%), 14: croplands with open woody vegetation, 15: bare soil, 16: waterbodies, 17: cities)

Table 1 Different methods of soil carbon determination used in referred authors

Methods*	Number of observations	Percentage proportion (%)
Ex-situ methods:		
1. Walkley and Black Method (Wet oxidation or combustion)	21	58.2%
2. Dry combustion method: CN analyser	9	25%
3. Dry combustion: weight-loss-on-ignition	2	5.6%
In-situ methods (in combination with Ex-situ methods):		
4. Isotope ratio mass spectrometer	1	2.8%
5. Dry combustion coupled Infra-red spectroscopy Isotope mass spectrometer	2	5.6%
6. Walkley and Black Method coupled Reflectance spectrometer	1	2.8%
Total	36	100

*See Appendix for details

Table 2 Soil organic carbon pools and different units reported by referred authors

Soil organic carbon pool*	Number of observations	Percentage proportion (%)
1. Soil carbon concentration (g/kg)	3	8.3%
2. Soil carbon concentration (%)	9	25%
Soil carbon concentration		**33.3%**
3. Soil carbon stock (Mg/ha)	3	8.3%
4. Soil carbon stock (kg m^{-2})	1	2.8%
5. Soil carbon stock (t/ha)	1	2.8%
Soil carbon stock		**13.9%**
6. Soil carbon concentration (g/kg) and Soil carbon stock (Mg/ha)	6	16.7%
7. Soil carbon concentration (%) and Soil carbon stock (Mg/ha)	8	22.2%
8. Soil carbon concentration (%) and Soil carbon stock (t/ha)	3	8.3%
9. Soil carbon concentration (g/kg) and Soil carbon stock (g m^{-2})	1	2.8%
10. Soil carbon concentration (%) and Soil carbon stock (g m^{-2})	1	2.8%
Soil carbon concentration and Carbon stock		**52.8%**
Total	36	100

*See Appendix 1 for details

to ensure comparability in reporting trend distribution. All articles reporting data for individual depths (e.g., 0–5, 5–15, 15–30 cm) were summed and included in standardized grouping of 0–30 cm depth while articles reporting data above 30 cm were included in 30–100 cm depth interval.

Uncertainties in soil organic carbon studies

Certain level of uncertainty still exist with respect to the relative amount of stored SOC under different land uses and agroecosystems across different landscapes of Ethiopia, SOC distribution and dynamics across soil profile, and its relative comparison (quantity, quality, and elemental composition) across vegetative covers under varying seasons and temperature regimes. Soil C change quantification in the soil is quite a challenging task and more specific emphasis should be paid to the extent of C stock below the topsoil (0–30 cm) zone. With focus on Sub-Saharan Africa in a systematic review, Vågen et al. (2005) advocated for further detailed investigative studies across different agroecosystems for clear understanding on C dynamics and behavior as an impact of land cover intensities. The general welfare coupled with the socioeconomic benefits of soil carbon sequestration (SCS) in African countries ought to be propagated in order to enlighten the local populace and equally stimulate them on the need to embrace best management practices to sequester carbon. The diversity in climate, geology, and topography of the country (Ethiopia) has given rise to a wide range of heterogeneity of soil types (Mesfin 1988; Haileslassie et al. 2005; Hurni et al. 2007). Thus, there is clear need for country-based and region-specific articulated studies to address the issues of accurate quantification and measurement of SOC especially below the subsoil zone under changing climate in Ethiopia.

Contrast to previous researchers, Powlson et al. (2011) and Stockmann et al. (2013) argued that increased levels of SOC with the adoption different approaches and management practices does not literally translate to capture or allocation of extra C from the atmosphere to land. However, this might just be due to ordinary movement of C within the biosphere from one pool to another, without any negative or positive consequences for climate change. This implies that not all findings reporting increased SOC in land uses under different management practices are actually C capture from the atmosphere. Powlson et al. (2008) further recommended the term "accumulation" to represent increases in SOC while "sequestration" should be specifically used for scenarios and circumstances of significant extra transfer or capture of C from the atmosphere, which represents a valid approach to mitigating climate change. Thus, this assertion needs to be critically examined by researchers in view of providing a clear mechanistic understanding of SOC sequestration and dynamics in the face of climate change.

Site-specific conditions, soil types, and dynamic nature of environmental-dependent variables (pH, temperature, precipitation, and various anthropogenic activities) were potential sources of variations in the reported SOC pool. More so, differences in analytical methods employed by the researchers equally accounts for variations in the trend of C pool reported in this review (see Table 1). Detailed overview of different techniques employed in modern times for SOC determination is well presented by Chatterjee et al. (2009).

Despite the wide usage of the "traditional" Walkley and Black (WB) method, due to its procedural simplicity (Wang et al. 2012), it has been heavily criticized due to its limitations, which include incomplete combustion, variations in oxidation of various forms of SOC by dichromate, high cost of chemicals used for the analysis, and considerable low efficiency in C determination (FAO 2001, 2007; Gelman et al. 2012; Amare et al. 2013; Gebeyehu et al. 2017). Nevertheless, more accurate, precise, and cost-effective measurement of SOC is required in C sequestration programs in terrestrial ecosystems in view of ensuring accurate quantification, verification, and monitoring of potential SOC stocks over time. Despite the acclaimed efficiency of dry combustion auto-analyzers, it is also associated with some levels of instrumental and measurement errors (Aynekulu et al. 2011; Batjes 2011). Estimated 1–2% measurement errors have been associated with SOC laboratory analysis determination using dry combustion auto-analyzers (FAO 2001). In-situ analytical methods, e.g., near-infrared spectroscopy (NIR) and mid-infrared spectroscopy (MIR), have been developed as a more reliable, efficient, and high precision method of SOC determination across landscapes using efficient sampling methodologies (Stockmann et al. 2013). A systematic combination of these analytical methods is relatively cheaper and cost-effective compared to the widely used "traditional" methods (Janik et al. 2007; Stockmann et al. 2013) with a higher degree of precision and accuracy.

Recently, Gessesse and Khamzina (2018) studied the reliability of WB method in analyzing C poor soils of semi-arid area of Ethiopia in comparison with elemental CN analyzer. Their findings showed that results obtained by WB method had a closer similarity with those obtained from CN elemental analyzer, using the Bland and Altman analysis. In conclusion, they proposed the use of 1.32 standard correction factor for SOC evaluation using the WB method in C-poor non-calcareous soils of semi-arid area of Ethiopia and tropical regions of sub-Saharan Africa.

Past and present scientific evidence of soil organic carbon distribution in Ethiopia

Ethiopia is strategically located in the horn of Africa (2° 54′ N–15° 18′ N latitude and 32° 42′ E–48° 18′ E longitude), though a land-locked country but with massive land area of 1.12 million km^2 (Shiferaw et al. 2013), coupled with diverse climate, parent material, land use, geology, and topography giving rise to a wide heterogeneity of soil types (Hurni et al. 2007; Mesfin 1988; Haileslassie et al. 2005). According to FAO (1986) as reported in Haileslassie et al. (2005), soils of Ethiopia are mainly of volcanic origin and Lithosols (14.7%), Nitosols (13.5%), Cambisols (11.1%), Regosols (12%), and Vertisols (10.5%) proportionally cover the country's vast area of landmass.

The potential of soil organic carbon (SOC) to act as a "managed" sink and reservoir for atmospheric CO_2 has received considerable attention in scientific literatures (Kirschbaum 2000; Post and kwon 2000; NMSA 2001; Guo and Gifford 2002; Lal 2004a, 2004b; Post et al. 2004; Lemenih and Itanna 2004; Lal 2008a, 2008b, 2008c; Smith 2008; Chabbi and Rumpel 2009; Post et al. 2009; Anikwe 2010; Luo et al. 2010; Niles et al. 2010; Nwite and Okolo 2017; Mbah et al. 2017; Okebalama et al. 2017). Significant increase in greenhouse gas (GHG) emissions in Ethiopia has been reported (NMSA 2001) while the sink capacity in agriculture, forestry, and land use sectors are rapidly decreasing, according to the first national GHG inventory carried out in 1994 (Shiferaw et al. 2013).

There exist several published scientific articles and case studies on soil carbon pools for different parts of Ethiopia (Yimer et al. 2006; Girmay et al. 2008; Hawando 1997; Solomon et al. 2002a; Lemenih et al. 2005; Haileslassie et al. 2005; Lemma et al. 2006; Edwards 2007; Chibsa and Ta 2009; Freier et al. 2009; Fisseha et al. 2011; Kim et al. 2015; Demessie et al. 2015; Berihu et al. 2017) but with a missing gap on the national soil database carbon pools estimate (Shiferaw et al. 2013; Okolo et al. 2016). However, most of the SOC researches were conducted in the southern part of Ethiopia, thus not giving a comprehensive clear overview of the trend in total soil carbon distribution data across different landscapes and regions of Ethiopia, which this review intends to address systematically. For example in the highlands of southern Ethiopia, changes in SOC stock was investigated by Lemenih et al. (2005) after reforestation of previously cultivated soil in comparison with continuously cultivated soils and adjacent natural forests soils. For *Cupressus lusitanica* and *Eucalyptus saligna*, they reported an average annual soil C accumulation estimate of 156 and 37 g C m^{-2} year^{-1} respectively. Their study, which focused on 0–10, 10–20, 20–40, 40–60, and 60–80 cm, further revealed that reforestation of previous croplands lead to restoration of lost C, even though the differences in deep soils (below 20 cm) were not significant. However, significant difference in soil C was observed in topsoil (0–10 and 10–20 cm) layers in the following order: Natural forest > *C. lusitanica* > *E. saligna* > Farmland. Similarly, Negasa et al. (2017) studied variations in soil properties under different land use types along a toposequence in smallholder-managed farms in southern Ethiopia. Their study focused on three land use types (agroforestry land, cultivated land, and grazing land), three slope categories (upper, middle, and lower slope), and four soil depths: 0–20 cm, 20–40 cm, 40–60 cm, and > 60 cm. However, SOC showed significant variation among land use types especially in top soil layers while Agroforestry land use type had higher SOC content and the least SOC content was recorded in cultivated land. Their results indicated that SOC content decreased down the slope and the low SOC in cultivated land was attributed to continuous tillage practices by the local smallholder farmers.

In exploring the magnitude of land degradation, estimated soil organic matter (SOM) loss of 1.17–78 Tg year^{-1} from 78 M ha of cultivated and grazing lands was reported by Demessie et al. (2015) in southern Ethiopia. They reported high soil quality index for natural forest and Juniperous procera, and advocated for protection of natural forests from additional accelerated degradation and conversion to other land uses. Increase in SOC storage and decrease in CO_2 emission can be achieved with afforestation and sustainable measures geared towards safe-guarding remnants of the forests. In Gambo district in southern Ethiopia, Demessie et al. (2011, 2012) compared the SOC trend among six plantation species with natural forest and reported higher SOC concentration in the 0 to 10 cm depth, which progressively decreased to the 100 cm depth across all land uses. The concentration of SOC varied from 3.4 to 10.2% in soils under plantations and natural forest. Juniperous procera in addition to the natural forest accrued more SOC across depths compared to other plantations (*Eucalyptus globulus*, *Eucalyptus saligna*, *Eucalyptus camaldulensis*, *Cupressus lusitanica*, and *Pinus patula*).

More so, Singh et al. (2010) in a study to assess the status of SOC and the rate of change in the chronosequences in southeastern Ethiopia reported that higher amount of SOC was concentrated in the topsoil (0 to 20 cm) and the concentration SOC in natural forest was significantly higher than that in agroforestry and agricultural lands. Singh et al. (2010) equally reported similar trend in a study to evaluate soil carbon sequestration under chronosequences of agroforestry and cultivated lands in southern Ethiopia. Specifically, SOC stocks in all chronosequences (12, 20, 30, 40, and 50 years) of traditional agroforestry were higher than the corresponding chronosequences under agricultural lands.

Lemma et al. (2006) in a study at Belete forest in southeastern Ethiopia used total carbon and ^{13}C analyses to assess the changes in SOC pools in relation to changes in land use. They reported apparent SOC accumulation rates of 1–3.2 Mg ha^{-1} year^{-1} within a space of 20 years following afforestation of an abandoned cultivated land. However, the accumulation rate is dependent on the type of species. Their study reported that continuous cropping following forest clearing gave rise to estimated loss of 43% (75.4 Mg ha^{-1}) total SOC and 73% (128.4 Mg ha^{-1}) forest-derived SOC within a timeframe of 75 years. Nevertheless, addition of 53.0 Mg ha^{-1} of SOC of C_4 crop origin (maize) to the farmland resulted in a lower net loss of SOC. Kim et al. (2015) in a study in Wondo Genet, Southern Ethiopia compared SOC and total nitrogen (TN) stocks in seven paired sites of home gardens and converted mono-crop fields following 1 to 20 years after conversion. They however reported 18–30% SOC loss as a result of the conversion of home garden agroforestry to crop fields. The research findings suggest that decline in soil fertility, water availability, and increases in GHG gases (CO_2 and N_2O) emissions is aggravated with the unsustainable management practice of conversion of home gardens to mono-crop. Also, in mono-crop fields, no significant relationship was observed between years after conversion and rates of decrease in SOC stock. In the Bale zone of southeastern Ethiopia, Abera and Belachew (2011) studied the effect of land use on SOC in soils from four land use types (forestland, grassland, fallow land, and cultivated land) and reported consistent decrease in SOC with increasing soil depth across all the land use systems. The highest SOC (12.95%) concentration was recorded in natural forest with the least concentration of 2.56% from cultivated land, considering the topsoil layer (0–10 cm) only. There was minimal variation in SOC concentration at lower depths among different land uses, whereas the topsoil showed significant difference in SOC distribution. This is an indication that the topsoil are mostly affected especially in croplands due to low C input, total (extractive) harvest, improper management practices, and tillage operations.

In a meta-analysis to assess the long-term effect of land management on SOC in Ethiopia, Shiferaw et al. (2015) reported that the trend in SOC distribution across different land uses were crop land (CL), grass land (GL), and forest land (FL) corresponding to 1.7, 2.6, and 2.8 g kg^{-1} respectively. However, the variability pattern for SOC was FL > GL > CL, thus the FL recorded the highest SOC content while the CL recorded the lowest SOC content. This result agrees with the previous findings of higher SOC storage in natural ecosystems compared with managed ecosystems of continuously cultivated lands (Assefa et al. 2017; Berihu et al. 2017). In reviewing the impact of different soil management practices and land use changes on soil C stock in Ethiopia, Girmay et al. (2008) showed that land use conversion from forest to crop land, to open grazing, and to plantation lead to decline in C stock in approximately 0–63%, 0–23%, and 17–83% respectively at the topsoil layer. The authors proposed adoption of land restorative measures as a panacea to increasing SOC pool. With the adoption of restoration measures, the potential of soil C sequestration ranges from 0.066–2.2 Tg C year^{-1} and 4.2–10.5 Tg C year^{-1} on rainfed cultivated land and rangeland respectively. The proposed land restorative measures in the form of establishments of exclosures is widely practiced in Ethiopia at the moment but still faces challenges of recurrent trespassing and population pressure on the very scarce land.

In the Gacheb catchment of the White Nile Basin, southwest Ethiopia, Kassa et al. (2017) investigated the influence of deforestation on selected soil fertility indices, SOC, and nitrogen (N) stocks. The study focused on four depths (0–20 cm, 20–40 cm, 40–60 cm, and 60–80 cm), three land uses (natural forest, agroforestry, and croplands), and three elevations (high, middle, and low). Their results showed that the forest top soil layer (0–10 cm) recorded higher SOC concentration compared to other land uses while the loss of SOC as a result of conversion of forest to cropland ranges from 3.3 Mg ha^{-1} year^{-1} to 8.0 Mg ha^{-1} year^{-1}. Forestland recorded the highest SOC stock followed by agroforestry with the lowest SOC stock in cultivated land. Undisturbed nature of the natural ecosystems may have contributed to the high SOC content unlike the continuous tillage practices in cropland, which depletes SOC content. In the south-eastern highlands of Ethiopia, Yimer et al. (2006) estimated SOC and TN stocks in 0–30 cm and 30–100 cm soil layers for three vegetation communities; Schefflera-Hagenia, Hypericum-Erica-Schefflera, and *Erica arborea* (shrub size), at different topographic aspects. The results obtained indicated significant variation in SOC among the vegetation communities in the top 30 cm depth. At the 100 cm depth, the overall mean SOC ranged from 32.67 to 46.03 kg C m^{-2} among the studied vegetation types across different aspects. The study further showed that the topsoil (30 cm depth) stores approximately 45% of the SOC stock thus indicating the ease of losing potentially huge quantity of CO_2 to the atmosphere through deforestation of these vegetation and/or conversion of forest lands into grazing and cultivation.

Furthermore, still on the highlands of southeastern Ethiopia, Yimer et al. (2007) studied the impact of changes in land use on SOC concentration in three adjoining land uses: native forest, cultivated land, and grazing land. Their result indicated significant reduction in the original native quantity of SOC in the upper 100 cm soil layer by 30.9% as a result of converting native forests into cultivated lands over a period of 15 years. Their findings equally noted that converting native forests to cultivated lands has given rise to significant reduction in the total quantity of SOC stored in the topsoil as a result of low organic matter supply and reduced C turnover in the soil.

In the plateaus of southern Ethiopia, Solomon et al. (2002a) investigated the composition of organic matter in native forest, tea plantations, Podocarpus-dominated natural forest, Cupressus plantations, 25-year cultivated lands (Paleudalf), and 30-year cultivated lands (Palehumults). According to their findings, significant depletion of total SOC (55% and 63%) in the surface soils was due to forest clearing and continuous cultivation respectively. Silt-size separates recorded reduced SOM, thus signifying the high susceptibility of silt-associated SOM to changes in land uses in the study area.

Also in southern Ethiopia, Freier et al. (2009) investigated the SOC dynamics as impact of its chemical configuration on Nitisols under Podocarpus falcatus dominated natural forest and *Eucalyptus saligna* plantation. At 20–30 cm soil depth, there was a massive change to less negative $\delta^{13}C$ values, thus signifying a modification from C_4 savanna to C_3 forest during the late Holocene. Using compound-specific stable isotope analysis, their measurements indicated significant differences in C storage among sites. However, explanation for these differences can be fully elucidated with an initial loss of 15–26% of SOC approximately half a century years ago, as a result of deforestation. More so, in a study of five major soil types (Andosols, Fluvisols, Nitisols, Solonetz, and Vertisols) in the Rift Valley of Ethiopia for comparison of SOC status over a time period, Itanna et al. (2011) reported that in four of the five soils studied, SOC losses amounted to 60–75% in less than three decades. Comparing the five soil types, their study revealed that SOC content ranked from highest to lowest in the order of Solonetz, Vertisols, Andosols, Nitisols, and Fluvisols. This assertion is however debatable considering the fact that no information was provided for the land use and management practices of the different soil types under consideration. Land use and management practices exert profound influence on C dynamics irrespective of the soil type. It is therefore illogical to conclude on SOC distribution trend of different soil types without providing information on the particular land use or management practice.

Over the last millennia, land degradation due to changes in land-uses, unsustainable soil management practices, and increase in population has exerted high pressure on the fragile soils of Ethiopia, thus a serious environmental problem that yearns for sustainable solution. Warra et al. (2015) in Kacho catchment, southeastern Ethiopia, assessed some soil quality indicators as a function of topographic aspects and changes in land cover. From the study, soil degradation index results showed that SOC content declined due to change in land cover from natural vegetation to cropland. Due to the negative impact of agricultural management practices in their study, Warra and co advocated for an integrated land resource management for restoration of the degraded land in view of sustaining agricultural growth and productivity.

In a study to evaluate the capability of dry Afromontane forest of Danaba, Oromia Regional State of Ethiopia for CO_2 mitigation potential, Bazezew et al. (2015) estimated that the SOC density at 30 cm depth was 186.40 t ha^{-1} which is equivalent to 684.09 CO_2. From sustainability point of view, integration of carbon sequestration with Reduced Emission from Deforestation and Degradation (REDD+) and Clean Development Mechanism (CDM) carbon trading system of the Kyoto Protocol was advocated by the authors in order to obtain financial value of CO_2 mitigation.

In a meta-analysis to review the effect of long-term land management practices on SOC in Ethiopia, Shiferaw et al. (2013) reported SOC values of 1.7, 2.6, and 2.8 g/kg for cropland (CL), grassland (GL), and forestland (FL) respectively, with ranking order of variability as FL > GL > CL. With emphasis on biomass and soils, the review reported that accelerated carbon depletion within two cropping seasons occurs on an estimated 0.2 million ha and 8 million ha for forestlands and cropping lands respectively. The use of SOC as a major indicator for showing the sustainability of long-term management practices across various landscapes was the major finding of Shiferaw and co. However, focusing mainly on studies from southern parts of Ethiopia was a major limitation of this review, thus not a clear representative of the whole country.

Significant scientific evidence abounds to justify that climate change is a rapidly growing global dilemma and Ethiopia is actually feeling the impact. Low SOC content is a major characteristic of most soils in northern Ethiopia (Girmay et al. 2008) thereby leading to structural degradation and decline in soil quality, thus the urgent need for sustainable best management practices for enhanced SCS. Soil carbon depletion across Ethiopia (mainly in the highlands) has been very severe due to high increase in population, deforestation, agricultural intensification, and high livestock pressure (Assefa et al. 2017), thus militating against sustainable agricultural productivity.

With focus on semi-arid area of northern Ethiopia at a watershed level, SOC showed a declining trend with depth within and among most land uses in both magnitude and differential concentrations as reported by Gelaw et al. (2014). Dominant soils in the study area are Arenosols, and association of Arenosols with Regosols (WRB 2006). The land uses under consideration were rainfed crop production (RF), agroforestry-based crop production (AF), open communal pasture (OP), silvopasture (SP), and irrigation-based fruit production (IR). Their study focused on 0–30 cm depth and showed high potential of SOC sequestration when croplands are converted to grasslands or with the systematic integration of suitable agroforestry trees in croplands. The trend of SOC stock (0–30 cm) were 25.8, 16.1, 52.6, 24.4, and 39.1 Mg ha^{-1} in AF, RF, OP, IR, and SP land uses, respectively. Dissimilarities in soil types and management practices across different land uses may have contributed to the variations in C concentrations within the watershed. Furthermore, at watershed level in a semi-arid area of northern Ethiopia, Gelaw et al. (2015a) assessed the influence of land use on SOC and total nitrogen (TN) storage and reported highest SOC concentration (12.6 g kg^{-1}) in open pasture land use at 0–15 cm soil depth. Other land uses considered in the study includes rainfed crop production, agroforestry-based crop production, silvopasture, and irrigation-based fruit production. Their study suggested that conversion of rainfed cultivation into grass and tree-based land use systems holds huge restoration potential for sequestration of SOC.

Hailu (2010) asserted that the degraded highlands of northern Ethiopia, which are mainly Vertisols, Luvisols, and Cambisols, are at a low level of organic carbon based on Landon (1991) nutrient rating. This assertion collaborates previous submissions of Girmay et al. (2008), Assefa et al. (2017) and Berihu et al. (2017) whom reported significant loss of SOC in highlands of northern Ethiopia. Some human activities such as unsustainable agricultural practices in Ethiopia (continuous cropping without fallowing, total harvest, bush burning) have resulted in significant emission of carbon dioxide (CO_2) to the atmosphere thus giving rise to massive depletion of carbon stock in both soils and biomass (Shiferaw et al. 2013). According to Stockmann et al. (2013), quantifiable global warming currently being experienced is a result of the increase in atmospheric CO_2—from about 280 to more than 380 ppm over the past 250 years.

Corral-Nuñez et al. (2014) evaluated the status of soil organic matter (SOM) in croplands and exclosures (protected areas) in northern Ethiopia. The SOM was converted to SOC for ease of reporting in conformity with other reported studies. Appreciable depletion of SOC content in farmlands (1.2% to 1.7%) with significant increase in SOC content (1.5% to 3.2%) was observed in exclosures following 20-year protection and recovery period. In assessing the role of forests and soil carbon sequestration on climate change mitigation, Alemu (2014) asserted that more than 80% of the total terrestrial aboveground C and 70% of the total belowground SOC is sequestered by the forest ecosystems. The study emphasized the need for adequate protection of the existing remnant forests, which serves as major terrestrial carbon sink. The above scenario (protection of the forest remnants) is pivotal to restoration of SOC in degraded landscapes of northern Ethiopia. In investigating the SOC and N stocks of different land use systems along a climatic gradient in northwest Ethiopia, Assefa et al. (2017) reported that 60% of the total SOC stocks were found in the topsoil (0–10 cm). More so, clear vertical gradient in SOC stock were observed down the soil profile in forests, considering the following soil depths: 0–10 cm, 10–20 cm, 20–30 cm, and 30–50 cm. With emphasis on Desa'a dry Afromontane forest in northern Ethiopia, Berihu et al. (2017) investigated the impact of changes in land use-land cover on concentrations of SOC and TN sequestration. The study revealed significant difference in SOC distribution among dense forest (2.3%), open forest (1.7%), open grazing land (1.6%), and cropland (1.2%). More so, higher SOC (44.9 t ha^{-1}) was sequestered in the top soil (0–20 cm) compared to the subsoil layer (20–40 cm). Their findings indicated that the current management practice at the Desa'a forest area is not sustainable and advocates for more sustainable practices to avoid further degradation of the remnant of the forest. They further indicated that conversion of forestland to other land use might result in huge loss of SOC and other essential soil nutrients.

In northern highlands of Ethiopia, Miheretu and Abegaz (2017) studied the apparent changes in some soil properties as an impact of different land uses and slope position. The study reported a decline in soil fertility as a result of changes in land uses from forest to grazing and cropland. Significantly ($p < 0.05$) lower concentration of soil organic carbon was found in cultivated land relative to the forested land. Significant variations in SOC content and selected physico-chemical soil properties were observed as a result of differences in slope positions. Haileslassie et al. (2005) assessed the drivers of soil nutrient depletion in Ethiopia with focus on smallholders' mixed farming systems with the application of partial versus full nutrient balances. Crop production, fertilizer use, and land use histories/land management practices were the data collected courtesy of agricultural sample survey. On the other hand, soil properties, rainfall distribution, and different land use types were processed using geographic information systems (GIS). Excluding areas under permanent and vegetable crops, the soil nutrient stocks across all regions of Ethiopia were found to be decreasing. The assessment indicated that removal of residues, total harvest, and leaching losses accounted for the major causes of nutrient losses under permanent and vegetable cropping while erosion accounted for the major causes of nutrient losses in under cereals and other annuals.

Welemariam et al. (2018) assessed the impact of exclosures and soil and water conservation (SWC) practices on SOC concentration, SOC stock, and microbial biomass carbon in the highlands of northern Ethiopia. They reported that exclosures with terraces gave the highest SOC stock (29 Mg/ha) followed by exclosures only (24 Mg/ha), terraces (21 Mg/ha), and non-conserved grazing lands (16 Mg/ha). The topsoil layer (0–15 cm) recorded significantly higher (24 Mg C ha^{-1}) SOC stock than the lower (15–30 cm) soil depth (20 Mg C ha^{-1}). Welemariam and co advocated for the integration of SWC measures in exclosures in order to derive the synergistic benefits of the sustainable practices in view restoration of degraded lands of the region and increasing SOC stock.

In view of the foregoing and from the available works on SOC in Ethiopia, virtually all the researchers reported change in carbon pool with soil depth. Change in land uses from forest to cultivated and grazing land leads to appreciable depletion of SOC content. The topsoil was found to sequester more carbon than the subsoil across various landscapes in Ethiopia. Generally, this particular trend was observed across different agroecological zones of Ethiopia irrespective of the soil type. This assertion underscores the importance of adopting sustainable management practices to reduce accelerated release of C from the fragile topsoil. Conversion of grasslands and croplands to forest and exclosures has been found to significantly increase SOC content. However, there are continued threats to the remaining primary forests in Ethiopia, which serves as a major sink for aboveground and belowground C alike (Berihu et al. 2017). Removal of CO_2 from the atmosphere by plants has been recognized by the Climate Change Treaty (Kyoto Protocol) as a very effective approach for climate change mitigation while long-term studies on C stocks to monitor the dynamics and distribution under various land uses has been advocated for (Marland et al. 2007). Potential adverse impacts of global warming in Ethiopian context include increased incidences of floods, tropical storms, and recurring droughts; runoff; changes in the pattern and amount of rainfall distribution; and fluctuations in the amount and intensity of sunshine and coastal marine disruption. Thoughtful mitigation measures will be an ideal approach for controlling atmospheric CO_2 with the adoption of strategies that promotes increasing C storage and reducing CO_2 emissions (USGS 2008). Land degradation and climate change are the two major drivers of exacerbated environmental problems in Ethiopia (NMSA 2001; Niles et al. 2010).

Our review indicated that 33.3% of the studies reported SOC concentration, 13.9% reported only SOC stock while 52.8% reported both SOC concentration and stock (Table 2). However, studies focusing on 0–30 cm only were 44%, other studies extending up to 40 to 100 cm were 50%, and studies extending more than 100 cm accounted for 2.8% while studies without any depth specification accounted for 2.8% (Table 3).

It should also be noted that owing to the heterogeneity of Ethiopian soils, coupled with the different climatic settings and varying soil properties, current scientific knowledge and available data on soil carbon stock remains insufficient and also distorted. Absence of long-term field trials/experiments on SOC in Ethiopia is another research gap identified in this review which yearns to be addressed, and if implemented will form a vital input for modeling SOC changes over time.

Table 3 Various depths reported in referred articles

Depth*	Number of observations	Percentage proportion (%)
0-30 cm only	16	44%
40 up to 100 cm	18	50%
>100 cm	1	2.8%
No depth specification	1	2.8%
Total	36	100

*See Appendix 1 for details

For more precision and accuracy in SOC studies, incorporation of GIS and remote sending (RS) approach in SOC studies has received considerable global attention but is rather proceeding slowly in Ethiopia. Few studies in Ethiopia focused mainly on SOC distribution using GIS and RS (Vågen et al. 2012, 2013). However, majority of the studies involving RS and GIS focused basically on land use cover/change (Asmamaw et al. 2011; Kindu et al. 2013; Hailemariam et al. 2016; Demissie et al. 2017; Birhane et al. 2019), land suitability/capability for crop production (Kahsay et al. 2018; Yohannes and Soromessa 2019), and erosion or soil loss modeling (Mellerowicz et al. 1994; Israel 2011; Gebreyesus et al. 2014; Woldemariam et al. 2018). Integration of GIS and RS in SOC studies can increase our power of precise prediction in terms of SOC storage and dynamics under different land use types in modulable scenarios of changing climate. With focus on Ethiopian soils, Vågen et al. 2013 reported that predictions based on Landsat reflectance were quite robust (SOC $R^2 = 0.79$), thus a reliable basis of creating predicted surface maps for SOC and related soil properties. Therefore, the implication of this result is that incorporating GIS and RS in SOC studies will increase our level of precision in predicting SOC storage and changes over time.

In view of increased land use intensification due to the increasing food, energy, and water demand for the teeming world population Foresight (2011), proper soil management practices (details discussed in the section below) for enhanced carbon storage is very pertinent to conserve this valuable natural resource for future generations, especially in Ethiopia where land degradation is on the increase.

Options for increasing soil organic carbon stock in Ethiopia and in the tropics

It is very imperative to identify and select wide range of feasible approaches that are environmentally friendly and which aim to reduce CO_2 emissions and promote C sequestration. Robert (2006) asserted that effective soil C sequestration can be achieved through the following means: (i) conversion of cropland to forest or pasture/paddock—accounting for 0.5 t C/ha/year average increase; (b) adoption of conservation agriculture and change in agricultural management practices that deplete soil C and overall soil quality—e.g., raised-bed cultivation in arid region, no-tillage, avoiding total harvest by leaving 30% residue or cover crops on the surface of the soil. This assertion is in line with similar studies across different regions of

Ethiopia where improvement in C stock has been recorded with conversion of arable and grazing land to forest and/or exclosure (Mekuria 2013; Mekuria and Yami 2013; Assefa et al. 2017). Revegetation and afforestation has been recommended as effective approaches for atmospheric CO_2 reduction to ensure C sequestration in both soils and vegetation (IPCC 2012). The conversion of native forests to plantations, croplands, and other unsustainable land uses negatively influenced the SOC pool in soils across Ethiopia (Demessie et al. 2015; Berihu et al. 2017).

In Ethiopia, significant increase in SOC and improvement of ecosystem services has been achieved through the conversion of open grazing lands to exclosures (protected areas with zero grazing and prohibition of human activities) across different agro-ecological zones (Descheemaeker et al. 2006a, 2006b; Corral-Nuñez et al. 2014; Assefa et al. 2017; Welemariam et al. 2018). For example, Corral-Nuñez et al. 2014 studied the current and predicted SOM in northern Ethiopia and reported significant recovery of SOM ranging from 2.6 to 5.6% in exclosure after 20 years compared to 2.1% to 2.9% in cropland. They opined that the low SOM content in croplands was due to mono-cropping, planting on steep slopes, non-retention of residues, and use of residue and animal manure as energy source for cooking. More so, Assefa et al. 2017 reported that the conversion of a degraded open grazing land to exclosure significantly increased SOC stock in the topsoil layer (0–10 cm) by 42%. Similarly, Welemariam et al. 2018 studied the impact of different land use and management practices on SOC and reported that exclosures backed up with community-based soil and water conservation practices increased SOC stock. Their result indicated that exclosure with terraces, exclosures alone, terraces, and non-conserved open grazing lands gave 29, 24, 21, and 16 Mg C/ha respectively. Welemariam and co therefore advocated for the establishment of exclosures and construction of terraces in open grazing lands as possible ways of increasing SOC stock and restoration of degraded lands.

Apart from being protected from grazing and any form of human activity, these exclosures are home to so many soil and water conservation (SWC) practices and technologies which are very instrumental in the land restoration and regeneration processes. For example, rural communities in Ethiopia has made concerted efforts over the past few decades in erecting stone terraces, soil bunds and other physical barriers on the farmland, establishment of exclosures, and taking active part in voluntary tree planting projects through coordinated free-labor (Mitiku and Kindeya 1998; Fitsum et al. 1999; Reda 2015). Currently, over 75% of the smallholder farmers in Ethiopia practices terrace construction on their farmlands (Nyssen et al. 2007). These restoration approaches by the local communities have been instrumental in restoration of the degraded lands of Ethiopia especially in the northern semi-arid area while improving the native SOC content for sustainable agricultural productivity. Afforestation of degraded croplands and grazing lands with eucalyptus increased SOC stock to nearly 70% of the natural forest levels within 30 years in northwest Ethiopia (Assefa et al. 2017). In most regions of Ethiopia, establishment of exclosures has successfully removed grazing pressure, thus allowing gradual regeneration of native vegetation, with significant increase in SOC especially within the top soil layer. Significant improvements with the establishment of exclosures on open grazing lands in rural communities of Ethiopia especially relating to increasing SOC and regulating ecosystem services is well documented (Wolde and Veldkamp 2005; Yayneshet et al. 2009; Mekuria 2010, 2013; Mekuria and Yami 2013; Ubuy et al. 2014; Assefa et al. 2017).

It is worthy of mention that land degradation is synonymous to loss of soil nutrient and depletion of SOC, thus any concerted effort to restore the degraded lands through appropriate soil management practices will eventually lead to increased SOC status and decrease in CO_2 emission. Organic amendments (for example animal manure, crop residue, vermicompost, and green manure), if incorporated into the soil, has the capacity of maintaining and enhancing soil quality, in addition to improving the native nutrient pool (Agegnehu and Amede 2017). Organic amendments in addition to acting as precursors to soil organic matter (Agegnehu et al. 2012) also acts as a major factor in enhancing availability of nutrient, improving soil water content and recycling of nutrient in the ecosystem, as well as addition of nutrients to the stock (Amede et al. 2003), thus a good soil conditioner for sustainable agriculture.

Thus, approaches that enhance SOC increment in agricultural ecosystems systematically improve atmospheric CO_2 sequestration as well as organic-matter pools restoration, which is very critical to soil quality and health (Hooker et al. 2005). Nevertheless, important drivers for effective sequestration of SOC includes increased plant growth and productivity, increased net primary production, reduced rate of decomposition (Tieszen 2000), stabilization of carbon in the subsoil, organic amendment application to the soil (Powlson et al. 2011), and biochar application (Sohi et al. 2010; Verheijen et al. 2009). Substantial increase in the total soil C pool with the application of biochar from various sources is well documented (Steiner 2010; Matovic

2011; Mekuria and Noble 2013; Jiang et al. 2013; Woo 2013; Mbah et al. 2017). For instance, Nigussie et al. (2012) reported 0.71% C increment on a Nitosol in southeastern Ethiopia following the incorporation of maize stalk biochar (5 t ha^{-1}) compared to a control (unamended plot). However, Lal (2016) submitted that biochar impact on soil C dynamics is dependent on biochars' properties in relation to the feedstock, pyrolysis, antecedent soil characteristics, and management systems. More so, Sohi et al. (2009) as reported in Mekuria and Noble (2013) argued that the extent of the impact of biochar application on soil carbon sequestration (SCS) and agricultural production remains variable and not fully understood mainly due to the different soil processes (chemical, physical, and biological) and biophysical interactions occurring due to biochar application, which yearns for more critical study for clear understanding. Conservation tillage, cover crops, integrated soil fertility management (ISFM), irrigation, restoration of degraded soils, management of pasture lands, forest soils, stabilization of carbon in subsoil, and afforestation (see Lal 1998; Lal 2008b; Lal et al. 2012) are among the recommended soil and crop management practices acting individually and collectively to improve the SOC pool in the terrestrial ecosystem.

Jobbagy and Jackson (2000) argued that crop production in addition to various forms of biomass distribution strongly affect C distribution within the soil profile, thus SOC will probably be stored longer with long residence time in deeper soil profiles (Stockmann et al. 2013). With the implementation of recommended management practices (RMPs) and best management practices: conservation tillage, mulch farming, compost, elimination of bare fallow, integrated nutrient management, reclamation of eroded soils, restoration of salt affected soils, water conservation and management, afforestation, grassland and pastures, conservation tillage, use of cover crops, integrated soil fertility management, and improved grazing (Lal 1998; Lal 2008b), SOC can accumulate in soils owing to minimized/reduced erosion losses and attendant increase in the quantity and quality of biomass being returned to the soil. Increased soil water conservation, improved soil health and overall soil quality, and SOC pool enhancement are among the benefits of adopting these practices (Lal 2004). According to Lal (2004a, 2004b), common RMPs in line with the principles of keys to successful SCS include (i) conservation-effective measures that minimizes attendant risks of runoff and soil loss (erosion) for example, conservation agriculture (CA) comprising no-till (NT) farming, mulching, cover cropping, green manuring, and integrated nutrient management (INM) that provide adequate amount of plant nutrients for improved crop productivity that enhance biocomplexity and provide a continuous ground cover such as cover cropping and integration of crops with livestock (Lal 2015a, 2015b); (ii) growing deep-rooted plants to transfer C into the subsoil such as agroforestry; and (iii) adding recalcitrant material into the soil that is quite resistant to decomposition by microorganisms and has long mean residence time (MRT) (e.g., use of biochar).

In the face of intense land degradation in Ethiopia, adopting the integrated nutrient management (INM) or ISFM strategy together with RMPs is very important for effective SOC sequestration. For example, with the application of manure and other organic amendments, Corral-Nuñez et al. (2014) reported that the amount of SOM increased from 2.1 to 2.9% in cultivated soils of semi-arid area of northern Ethiopia. Mekonnen (2006) stated that the incorporation of organic manure together with mineral fertilizer in a Nitosol in Southern Ethiopia increased organic carbon by 8.68% over the initial status. A 2-year field experiment conducted on a strongly acid clay loam (Haplic Alisols) soils in southern Ethiopia using farmyard manure (FYM) and mineral fertilizer (NPK) recorded significant increase in total organic carbon in amended plots over unamended control plots (Boke 2014).

Lal (2004b) posited that the implementation of a land use restoration approach and RMPs on cultivated soils can lead to decrease in atmospheric CO_2 emission thus leading to improved food security, enhanced water quality, and environmental sustainability. Restoration of significant portion of the depleted SOC pool is achievable with the implementation of restoration of degraded lands, adoption of ISFM, conservation agriculture, in addition to other sustainable management practices that improve SOC in the ecosystem (Lal 2004a, 2004b; Powlson et al. 2011). With the adoption of RMPs, Lal (2004a) submitted that SOC rates of 50 to 1000 kg/ha/year and 0.9 ± 0.3 Pg C/year for measurable rates and global potential rates of SOC sequestration, respectively, can be achieved.

Powlson et al. (2011) posited that the following examples of land management practices increase SOC: conversion of cultivated land to forest or grassland, restoration of degraded lands with the introduction of resilient trees/shrubs, use of organic amendments, adoption of reduced-tillage in cropping systems, stabilization of carbon in subsoil, and biochar application.

Maximizing the quantity of SOC that might be stored in landscapes at regional and global level can be a veritable tool for climate change mitigation and improving soil quality (Stockmann et al. 2013). Loveland and Webb (2003) proposed a critical value of 2% SOC with a resultant significant depletion in soil quality below the critical value in cultivated soils of temperate regions. However, the critical value of 2% SOC content advocated in temperate regions is yet to be verified for tropical soils (Patrick et al. 2013) where soil degradation and decrease in soil fertility has continued unabated and currently at its peak. In a review of data from dryland sites, Janzen et al. (1998), as reported in Krull et al. (2003), showed that dry matter yields decrease after soil organic matter levels fall below 2%. Hassink (1997) as reported by Stockmann et al. (2013) posited that critical concentration of SOC (~ 1.5% and ~ 0.8% for sandy and clay soils respectively) may be recommended as guide for farmers. Recarbonization of biosphere C as opined by Lal et al. (2012) is another viable option and sustainable approach for C sequestration and special emphasis should be on restoration of soil C pools, which comprises the soil inorganic carbon (SIC) and SOC pools. In addition to ensuring mitigation and adaptation to climate change, the recarbonized soils further ensures significant restoration of SOC pool which improves soil quality, ecosystems services, sustainable agricultural productivity, and food security (Lal 1998; Lal 2008b).

The objective of these land management practices and best management practices as outlined by Lal 2008c is to ensure a positive C budget with improved quality and efficient natural ecosystem. Wide range of degraded soils abounds with SOC pool highly depleted particularly in the tropics. Degradation by erosion and depletion of essential nutrients are quite significant among degraded soils (Girmay et al. 2008). Numerous benefits exist due to restoration of degraded soils, which includes improved water quality and reduction in CO_2 emissions as a result of increased biomass production (Stockman et al. 2013). Close to 750 million ha of degraded land has been estimated by Grainger (1995) to exist in the tropics with prospects of soil quality improvement and, reclamation and afforestation. The SOC sequestration capability is close to 0.5 Megagram (Mg) ha^{-1} $year^{-1}$ while 1.1 Pg C $year^{-1}$ is estimated to be the SOC sequestration of 750 million ha. In soils of arid and semi-arid areas, Lal (2001) estimated 0.4–0.7 Pg C $year^{-1}$ SOC sequestration potential with the adoption of desertification control strategies. Elsewhere, Squire et al. (1995) has reported comparable estimates.

In addition to the management practices aforementioned, there are well formulated national polices (for instance, conservation and ecosystem strategies, environmental protection policy, and Ethiopian government policy on fertilizer), ratified governmental laws and proclamations, action plan, and strategic work plans geared toward enhanced SCS in Ethiopia (Shiferaw et al. 2013) but requires proper monitoring and evaluation to achieve the desired goals. According to the report of BoPED (1995), the National Forests Priority Areas (NFPAs) in Ethiopia that are 59 in number is an offshoot of the national policies coupled with the exclosures being established by local communities in addition to church forests being established by the Ethiopian Orthodox churches. Establishment of exclosures and church forests is seen as a sustainable approach to restoration of degraded lands across Ethiopia following intense exploitation of the NFPA's. It is noteworthy that these exclosures were established on areas formerly used as community open grazing lands (Aerts et al. 2009; Mekuria and Aynekulu 2013) with the main purpose of revegetation, restoration of forest lands, conservation of marginal lands, and restoration of degraded lands (Nyssen et al. 2015). This approach helps to maintain biodiversity in the drylands by protecting the degraded lands from the intrusion of humans or livestock (Mekuria and Aynekulu 2013). However, protection of the forest remnants is very important to avoid continuous deforestation and further land use conversion (as is the case in most parts of Ethiopia) in order to ensure huge improvement of SOC stocks and strong ecosystem services and functions (Demessie et al. 2015). Restoration of degraded Ethiopian landscapes with the establishment of exclosures and protection of the forest areas for enhanced carbon sequestration potential of soils would enable Ethiopia to partake in the Clean Development Mechanism (CDM). If adopted, this will ensure improvement of the livelihood of the poor smallholder farmers in addition to accruing economic benefits arising from payments for C credits (carbon emission reduction [CER] credits) in conjunction with developed countries.

Furthermore, documented evidences exist regarding the role of Ethiopian Church forests in restoration of degraded lands, atmospheric CO_2 reduction, and ecosystem service regulation (Wassie and Teketay 2006; Eshete 2007; Tura and Eshetu 2013; Cardelús et al. 2013a, 2013b; Abiyu et al. 2018). Widely adored and revered because of its religious and sanctifying status under the protection of the Ethiopian Orthodox Tewahido Church [EOTC] (Wassie 2002), the Ethiopian Church forests serves as sanctuary and sacred abode to diverse species of flora and fauna. It also plays a huge significant role in conservation of biodiversity (Bongers et al. 2006; Wassie and Teketay 2006; Cardelús et al. 2013a). Population pressure coupled with recurrent extreme weather conditions (drought, flooding, etc.) has over time been posing a great threat to the remnants of the church forests.

Abiyu et al. (2018) however submitted that approximately 35% of church forest disturbances in Ethiopia are attributed to climate extreme events, which is a strong indication that the disturbance is anthropogenically and climatically induced.

With more concerted efforts toward effective safeguarding approaches, church forests, in addition to being more protected than other forests (Tura and Eshetu 2013), also sequesters more C both above and below-ground (Descheemaeker et al. 2006a, 2006b; Cardelús et al. 2013b; Aerts et al. 2016). Tura and Eshetu (2013) reported that the average trend in C storage in church forests is 0.6 + 0.69 t, 0.6 + 0.69 t, 17.83 + 19.13, and 135.94 + 21.25 t ha^{-1} for aboveground (AG) biomass carbon per tree, mean above ground biomass carbon per tree, dead litter, and soil C respectively. Comparing young exclosures, middle-aged exclosures, old exclosures, grazing lands, and church forests, Descheemaeker et al. (2006b) reported that church forest sequestered more SOC compared to other agroecosystems. More so, Mekuria et al. (2009) reported that the average SOC at the topsoil layer and AG carbon stock of church forest were 52.7 Mg C ha^{-1} and 21.3 Mg C ha^{-1} respectively. This implies 36–50% and 39–68% increment in soil and aboveground carbon stocks due to conversion of degraded grazing lands to exclosures. Recently, Gebremedhin et al. (2017) investigated the impact of converting grazing land into cultivated lands in northern Ethiopia and reported significant loss of SOC and other studied fertility indices. Distribution of SOC in the study was 11.5, 5.3, 6.9, 4.7, 4.8, and 4.6% for Church forest, seasonal grazing land, open grazing land, 6-year exclosure, 16-year exclosure, and 20-year exclosure respectively. Thus in view of the foregoing, it can be clearly observed that C storage in church forest is relatively higher compared to exclosures and other land uses. Detailed study by Wassie and Teketay (2006) with emphasis on soil seed banks in church forests of northern Ethiopia indicated that huge amount of persistent seeds of herbaceous species accumulates in church forest soils in great magnitude thus leading to increased soil C storage and stabilization.

However, with persistent encroachment on the existing and remnants of church forests, it has been proposed that erection of fences, controlling grazing pressure, and promotion of planting seedlings will go a long way in maintaining and restoring of church forests in the rugged landscape of northern Ethiopia (Wassie et al. 2009; Aerts et al. 2016).

Evidence of payments for carbon credits in Ethiopia

As the second largest country in Africa after Nigeria (Worldometers 2018), Ethiopia is targeting significant economic transition toward attaining middle-income status in addition to achieving its net carbon neutral goal by the year 2025. However, with over 85% of its population dependent on agriculture, natural disasters such as droughts and floods exerts tremendous social and economic impact. According to Arens and Burian (2012), only Ethiopia among the least developed countries (LDCs) to develop CDM projects has the highest technical potential, projected at about 32 million certified emission reductions (CERs) annually.

The Oromia Forested Landscape Program (OFLP) in the southern part of Ethiopia harbors Ethiopia's largest concentration of biodiversity. Domiciled in Ethiopia's massive Oromia region, which constitutes 34.3% of the country's landmass, OFLP appears to be the country's most prominent program to mobilize resources toward its net carbon neutral by 2025 goal. Established with two World Bank funds, the $68 million OFLP project, aims at the restoration of forests on degraded lands ($18 million) and for programs targeting carbon sequestration assessment and performance enhancement ($50 million) respectively (CDM Overview). The OFLP will receive payments of up to $50 million for verified carbon credits against an agreed forest reference emission level from the World Bank for a decade. The forest reference emission level is part of a critical policy framework that gives countries a point to measure the results they have gained from REDD+ (reducing emissions from deforestation and forest degradation in developing countries) implementation.

At the continental level, the Humbo natural regeneration (reforestation) project managed by World Vision and registered under the CDM in December 2006 with a 30-year lifespan is the only significant carbon finance project currently active in Ethiopia (Mulugetta 2011). Established on 2728 ha of land, the project has won global recognition as Africa's first carbon credits for reforestation. Reported evidence by the Federal Democratic Republic of Ethiopia (2015) indicates that the area has 880,000 t of carbon dioxide stock which is equivalent to USD 13.2 million over 30 years. In general, with more than 18 million ha of forests covering about 16% of its land area, Ethiopia has a vast potential and is among the countries partnered with Forest Carbon Partnership Facility (FCPF) to implement REDD+ (Gonzalo et al. 2017). The total forest carbon stock is estimated at 2.7 billion according to the Federal Democratic Republic of Ethiopia (2015) report. Currently, the country has more than 13 protected areas for biodiversity and wildlife conservation covering a total land area of 3.7 million ha of land. Out of the total, six preserved areas with a combined total of 1.2 million ha of land have a forest carbon approximately 60 million metric tonnes. More so, various afforestation and reforestation programs are still ongoing nationwide and at different levels of development and transition.

In view of the foregoing, the recent United Nations Gold Future Policy Award 2017 won by Ethiopia, beating 26 other nominated policies to the prize through the sustainable practices of Tigray region on land restoration portend "potentially marketable" areas for carbon trading in Ethiopia. It is worthy to mention that the recent United Nations Gold Future Policy Award 2017 won by Ethiopia actually represents unique collective, well-coordinated action, voluntary labor and the involvement of youths in Tigray region of northern Ethiopia in massive land restoration on a very significant large scale. Major decrease in erosion incidences, recharging of the ground water, and the adoption of sustainable agricultural practices growth were made possible as a result of the massive land restoration of the dry lands of Tigray region leading to significant food self-sufficiency and economic growth. Many area exclosures established on the reclaimed degraded lands across the landscapes of northern Ethiopia poses a potential source of carbon trading (Kassahun et al. 2009) if they remain undisturbed over a long period of time with verifiable amount of carbon stock. Nevertheless, the carbon stock potential of area exclosures may not compare to that of church forests considering age of establishment and diversity in tree species and biodiversity. However, detailed studies and investigations are still required in this regard for more experimental verifiable conclusion. However, for effective participation in the global carbon trading, technical training on methods and assessment approaches for both intervention specific and economy-wide emissions accounting remains apparent and very important. At the moment, technical knowhow is limited and spread among very few professionals and non-state experts, which still remain a major setback in the Ethiopian carbon trading program.

Conclusion and recommendations

Unsustainable land management practices (deforestation, total/extractive harvesting, uncontrolled grazing, continuous cultivation without fallowing, and bush burning) being practiced in many locations in Ethiopia have been found to be a key factor in the increased CO_2 emissions in the country. Our findings highlighted massive losses in soil carbon due to forest conversion to other land uses and severe C losses due to agricultural intensification in degraded lands. Huge differences exist in the amount of soil carbon stored within and among soil types, in relation to vegetative cover, climate, landscape configuration, and textural classes of soil across different landscapes of Ethiopia. These observed differences in the amount of stored SOC may be due to the nature of soils, type of analytical tools, and apparatus used for the respective studies. However, the topsoil layers across different landscapes in Ethiopia recorded higher SOC pool than subsoil, thus underscoring the importance of sustainable land management practices to reduce CO_2 emission from the fragile topsoil layers. The establishment of exclosures by local communities in Ethiopia and continued protection of church forests proves to be a sustainable way of revegetation and land restoration in line with the United Nations Sustainable Development Goals. Thus, the introduction of carbon payments will stimulate concerted efforts among the local farmers and community dwellers to sustain the conservation of exclosures as a profit-orienting project. However, there is a need for further studies to address both biophysical and socioeconomic issues of carbon sequestration in the tropics. There should be more emphasis on the areas of future research, especially use of climate scenarios to simulate the nature and distribution of SOC over time especially below the subsoil, carbon dating, and assessment by various proxies of microbial activities to study SOC dynamics with regards to land use changes. More so, further studies should focus on subsoil carbon dynamics across different agroecological zones, which are currently less reported in Ethiopia. Soil carbon modeling has received very little attention in Ethiopia. Thus, modeling changes in SOC across the soil profile will increase our prediction of C dynamics. In addition to establishing SOC long-term field trials which is currently lacking in Ethiopia, current research interest should seek to focus more on the quality rather than only the quantity of SOC stored in different landscapes which is very essential to our holistic understanding of the status, composition, and behavioral dynamics of SOC in the face of changing climate. This will provide systematic understanding of SOC dynamics under heterogeneous landscape such as Ethiopia, thus highlighting the need for further studies on impact of management practices on distribution of SOC across depths. In addition to boosting agricultural productivity and ensuring sustainable agricultural development, this will equally go a very long way in stimulating the best management practices for SOC stock among the inhabitants of the region. Furthermore, it would also ensure active participation of the zone (Ethiopia) in the Clean Development Mechanism (CDM), suggested in the United Nations Framework Convention on Climate Change (UNFCCC 2002) Article 12 of the Kyoto Protocols.

Appendix

Table A1 Soil organic carbon distribution and methods of SOC determination in different land uses in Ethiopia

Referred journal	Research focus	Methods of SOC determination	Soil depth	Land use type	Reported SOC pool
Yimer et al. 2006	SOC and TN stocks as affected by topographic aspect and vegetation.	Walkely and Black wet oxidation method	0-30 and 30-60cm	Cropland, grazing land and forestland	SOC stock (kg m^{-2})
Yimer et al. 2007	Changes in SOC and TN Contents in 3 adjacent land use types	Walkely and Black wet oxidation method	0-20, 20-40, 40-100cm	Cropland, grazing land and forestland	SOC concentration (%)
Gelaw et al. 2013	Organic C and N associated with Aggregates and particle sizes under different land uses	CN analyser by dry combustion method	0-10 and 10-20 cm	Rainfed crop production agroforest, open communal pasture, silvopasture, and irrigation based fruit production	SOC concentration (g/kg)
Gelaw et al. 2014	SOC and TN stocks in different Different land uses	CN analyser by dry combustion method	0-15, 15-30 and 30-50 cm	Rainfed crop production agroforest, open communal pasture, silvopasture, and irrigation based fruit production	SOC concentration (g/kg) and stock (Mg/ha)
Gelaw et al. 2015a	Land use impact on SOC TN storage	CN analyser by dry combustion method	0-15, 15-30 and 30-50 cm	Rainfed crop production agroforest, open communal pasture, silvopasture, and irrigation based fruit production	SOC concentration (g/kg) and stock (Mg/ha)
Gelaw et al. 2015b	Soil quality indices	CN analyser by dry combustion method	0-15 cm	Rainfed crop production agroforest, open communal pasture, silvopasture, and irrigation based fruit production	SOC concentration (%)
Berihu et al. 2017	SOC and TN losses following deforestation	Walkely and Black wet oxidation method	0-20 and 20-40 cm	Dense forest, open forest, grazing and farm land	SOC concentration (%) and Soil C sequestered (t/ha)
Corral-Nunez et al. 2014	Current and predicted trend of SOM	Walkely and Black wet oxidation method	0-30 cm	Farm land and exclosures	SOC concentration (%)
Kassa et al. 2017	Impact of deforestation on soil ferility, soil C and nitrogen stock	Walkely and Black wet oxidation method	0-20, 20-40, 40-60 and 60-80 cm	Forest, cropland and Agroforestry	SOC concentration (%) and stock (Mg/ha)
Lemma et al. 2006	Soil carbon sequetration under Different exotic tree species	Isotope ratio mass spectrophotometer	0-5. 5-10, 10-20, 20-30 and 30-50 cm	Native forest, farm land and plantation	SOC concentration (g/kg) and stock (Mg/ha)
Lemenih et al. 2005	Changes in SOC and TN following reforestation of previously cultivated land	LECO-1000 CHN Analyzer	0-10, 10-20, 20-40, 40-60 and 60-80 cm	Continuos cultivation, natural forest and plantation	SOC concentration (g/kg) and stock (g m^{-2})
Yosef 2012	Carbon stock potentials of woodlands	Walkely and Black wet oxidation method	0-30 cm	Boswellia papyrifera woodland and farmland	SOC stock (Mg/ha)
Bazezew et al. 2015	Above-and below-ground C in a Community forest	Walkely and Black wet oxidation method	0-10, 10-20 and 20-30 cm	Afromontane forest	SOC concentration (%) and stock (t/ha)
Itanna et al. 2011	Effect of land use change and soil type on SOC status	CN analyser by dry combustion method	Profile pits with varying depths ranging from 0- 140, 150, 160, 177 cm	Agroforestry and farmland	SOC concentration (g/kg) and stock (Mg/ha)
Cardelús et al. 2013a	Assessment of Ethiopian sacred grove	Elemental analyser coupled to Isotope ratio mass spectrophotometer	0-10 cm	Church forest	SOC concentration (%)
Abera and Belachew 2011	Effect of land use on SOC and TN	Walkely and Black wet oxidation method	0-5, 5-15, 15-30 and 30-60 cm	Fallow, cultivated, natural forest and grassland	SOC concentration (%)

Table A1 Soil organic carbon distribution and methods of SOC determination in different land uses in Ethiopia *(Continued)*

Referred journal	Research focus	Methods of SOC determination	Soil depth	Land use type	Reported SOC pool
Kim et al. 2015	Impact of land use change on SOC and TN stocks	Walkely and Black wet oxidation method	0-10, 10-20, 20-40, 40-70, 70-100 cm	Home garden and converted mono-crop field	SOC concentration (%) and stock (Mg/ha)
Demessie et al. 2012	Effects of eucalyptus and coniferous plantations on soil properties	Walkely and Black wet oxidation method	0-10, 10-20, 20-40, and 40-60 cm	Eucalyptus and coniferous plantations	SOC concentration (%)
Singh et al. 2010	SOC concentration and stock under different land uses	Walkely and Black wet oxidation method	0-10, 10-20, 20-40, 40-60, and 60-100 cm	Agroforestry and cropland	SOC concentration (%) and stock (Mg/ha)
Shiferaw et al. 2015	SOC to mitigate land degradation and climate change	Walkely and Black wet oxidation method	0-30 cm	Cropland, grassland and forestland	SOC concentration (g/kg)
Michelsen et al. 2004	SOC stocks in different ecosystems	Shimadzu TOC analyser	0-30, 30-55 and 55-100 cm	Dry deciduous forest, dry woodland and different types of wooded grassland	SOC concentration (%) and stock (Mg/ha)
Gebremariam and Kebede 2010	Effect of land use chnage on SOC, above-grounf biomass and aggregarte stability	Walkely and Black wet oxidation method	0-15, and 15-30 cm	Farmland, forest land and uncontrolled grazing land	SOC concentration (%) and stock (t/ha)
Tura and Eshetu 2013	C stock in Church forests	Walkely and Black wet oxidation method	0-30 cm	church forest	SOC concentration (%) and stock (Mg/ha)
Assefa et al. 2017	Effect of land use and deforestation on SOC and TN	CN Elemental analyser	0-10, 10-20, 20-30 and 30-50 cm	Forest, Eucalyptus, grazing and cropland	SOC concentration (%) and stock (kg m^{-2})
Haile et al. 2014	Impact of land use change on SOC and TN	Walkely and Black wet oxidation method	0-15, 15-30, and 30-45 cm	Cropland, grazing land and Eucalyptus camaldulensis woodlot	SOC concentration (%) and stock (Mg/ha)
Girmay and Singh 2012	Effect of land use change on SOC and soil quality	Walkely and Black wet oxidation method	0-20, 20-40, 40-60 and 60-80 cm	Cultivated land, grazing land and area exclosure	SOC concentration (%) and stock (Mg/ha)
Haileslassie et al. 2006	Assessment of soil nutrient depletion on smallholder mixed farming system	Walkely and Black wet oxidation method	0-30 cm	Enset-based farming and teff-based farming	SOC concentration (%)
Vagen et al. 2013	Mapping land degradation and soil properties using Landsat approaches	DC-IRS	0-20, and 20-50 cm	Cropland and shrub land	SOC concentration (g/kg)
Mohammed and Beleke, 2014	Changes in C stock and sequestration potential under native forest and	Walkely and Black wet oxidation method adjacent land uses	0-30 cm	Native forest, annual crop field and coffee based agroforestry	SOC stock (Mg/ha)
Solomon et al. 2002b	SOM composition as influenced by deforestation and agricultural management	CN analyser by DC method	0-10 cm	Forest and cropland	SOC concentration (g/kg) and stock (Mg/ha)
Negash and Starr 2015	Soil carbon stocks of indigenous agroforestry systems	LOI; ignition at 550°C for 2h	0-30, and 30-60 cm	Agroforestry systems (Enset, Enste-Coffee and Fruit-Coffee)	Soil C stock (Mg/ha)
Amare et al. 2013	Predicting SOC using soil spectroscopy for Ethiopian highlands	Walkely and Black wet oxidation method and Reflectance spectrometer	Not specified	Cropland, grassland, forest land	SOC concentration (%)
Belay et al. 2018	C dynamics of dry tropical Afromontane forest ecosystems	LOI; ignition at 550°C for 2h	0-10, 10-20, 20-30, and 30-50 cm	Church forest, Community forest and agricultural land	Soil C stock (t/ha)
Negasa et al. 2017	Variations in soil properties under different Smallholder farmers along a toposequence	Walkely and Black wet oxidation method	0-20, 20-40, 40-60 and 60-100 cm	Agroforestry, cultivated land, and grazing land	SOC concentration (%)

Table A1 Soil organic carbon distribution and methods of SOC determination in different land uses in Ethiopia *(Continued)*

Referred journal	Research focus	Methods of SOC determination	Soil depth	Land use type	Reported SOC pool
Welemariam et al. 2018	SOC and MBC distribution under various land uses and management practices	Walkely and Black wet oxidation method	0-15, and 15-30 cm	Terraced grazing land, exclosure with terrace, , exclosure alone, and non-conserved open and communal grazing land	SOC concentration (%) and Soil C stock (Mg/ha)

C Carbon, *SOC* Soil organic carbon, *SOM* Soil organic matter, *TN* Total nitrogen, *TOC* Total organic carbon, *DC-IRS* Dry combustion and Infra-Red spectroscopy, *LOI* Loss of Ignition, *MBC* Microbial biomass carbon

Abbreviations

AF: Agroforestry-based crop production; AG: Aboveground; AR4: Fourth Assessment Report; BoPED: Bureau of Planning and Economic Development; C: Carbon; CA: Conservation agriculture; CDM: Clean Development Mechanism; CERs: Certified emission reductions; CL: Cropland; CO_2: Carbon (IV) oxide; EOTC: Ethiopian Orthodox Tewahido Church; FAO: Food and Agriculture Organization; FL: Forest land; FYM: Farmyard manure; GIS: Geographical information system; GL: Grass land; Gt: Gigatone; INM: Integrated nutrient management; IPCC: Intergovernmental Panel on Climate Change; IR: Irrigation-based fruit production; ISFM: Integrated soil fertility management; LDCs: Least developed countries; MRT: Mean residence time; N_2O: Nitrous oxide; NFPAs: National Forests Priority Areas; NGOs: Non-governmental organizations; NPK: Nitrogen-phosphorus-potassium; NT: No-till; OFLP: Oromia Forested Landscape Program; OP: Open communal pasture; Pg: Petagram; REDD+: Reduced Emission from Deforestation and Degradation; RF: Rainfed crop production; RMPs: Recommended management practices; RS: Remote sensing; SCS: Soil carbon sequestration; SIC: Soil inorganic carbon; SOC: Soil organic carbon; SOM: Soil organic matter; SP: Silvopasture; SWC: Soil and water conservation; Tg: Teragram; TN: Total nitrogen; UNFCCC: United Nations Framework Convention on Climate Change; USD: US Dollar; WB: Walkley and Black; WRB: World Reference Base for soil resources

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Availability of data and materials

The authors declare that the review work data and material are available. In addition, all data generated or analyzed during this study are included in this manuscript.

Authors' contributions

All authors contributed equally in all article steps. All authors read and approved the final manuscript, after editing and formatting by CCO and ANR.

Ethics approval and consent to participate

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Consent for publication

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