ORGANIC CARBON STOCKS, DYNAMICS AND RESTORATION IN RELATION TO SOILS OF AGROECOSYSTEMS IN ETHIOPIA: A REVIEW

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Abstract

Soils represent the largest carbon pool and play important roles for carbon storage for prolonged periods in agroecosystems. A number of studies were conducted to quantify soil organic carbon (SOC) worldwide. The objective of this review was to evaluate organic carbon stocks, dynamics and restoration in soils of agroecosystems in Ethiopia. Soil data from 32 different observations, representing four different agroecosystems, were analysed. The mean SOC stocks in the four agroecosystems varied and ranged from 25.66 (sub-humid agroecosystem) to 113.17 (humid mid-highland agroecosystems) Mg C ha^{-1} up to one meter depth. The trend of mean SOC followed (in descending order): humid mid-highland (113.17 Mg C ha^{-1}) > per-humid highland (57.14 Mg C ha^{-1}) > semi-arid (25.77 Mg C ha^{-1}) > sub-humid (25.66 Mg C ha^{-1}). Compared with soils of tropical countries, those in Ethiopian agroecosystems contained low SOC storage potential. This might be associated with differences in measurement and analysis methods as 53.1% of the studies employed the Walkley-Black Method, which is known to underestimate carbon stocks in addition to ecological and management effects. However, shifts of land management from rain-fed to irrigation farming systems exhibited progress in the improvement of mean SOC storage potential. The analyses showed that farming systems involving irrigation sequestered more carbon than rain-fed farm systems. The mean SOC in the various agricultural land uses followed the following trend (in descending order): agroforestry (153.57 Mg C ha^{-1}) > grazing land (34.61 Mg C ha^{-1}) > cereal cultivation (24.18 Mg C ha^{-1}). Therefore, the possible solutions for improvement of organic carbon stocks would be implementation of appropriate restoration strategies based on agroecosystems.

Keywords: Agricultural land uses, organic carbon stocks, organic carbon dynamics, soils of agroecosystems

Introduction

Carbon (C) exists in the atmosphere in the form of carbon dioxide (CO_2) whereas it can be found in the soil as organic and inorganic forms. It is predicted that the concentration of CO_2 has shown additional of 111 ppm in the atmosphere during 1850 to 2012 (WMO, 2012; Andres et al., 2012). The major sources of rising CO_2 concentration in the atmosphere are anthropogenic activities, such as fossil fuel consumption, clearing of forests for expansion of agricultural land and burning of forest biomass. Anthropogenic impacts contribute to approximately 32 billion metric tons of CO_2 emission into the atmosphere each year, of which deforestation accounts 20% worldwide. This is estimated to be one-third of total greenhouse gas (GHG) emissions (IPCC, 2007). A total of 0.7 to 2.1 G t C yr^{-1} have been lost because of land use change and associated land use processes (World Bank, 2012).

Soil organic carbon can be defined as the content of carbon in soils as a result of decaying remains of living organisms such as plants, animals and microorganism in various stages. It represents a dynamic balance between the inputs and loss from decomposition. This dynamic nature shows variations of SOC distribution in spatial and temporal scales (Hobley and Willgoose, 2010). SOC stocks can also vary spatially in agricultural land use and ecosystem types (World Bank, 2012). The ways of estimation of soil carbon stocks and dynamics range from field to global levels (Hillier et al., 2011). Global soil atlas provides reliable set of soil data that could not be limited by geographical and measurement scale (Global Soil Mapping, 2011).

Soils represent the largest carbon pools in agroecosystems and have a potential for storage of carbon for prolonged periods. Many research methods were built up to quantify SOC worldwide. The most recent reports have shown that soils contain 2 - 2.5 times (1500–2500 Gt) of carbon as does the atmosphere (560 Gt) and four times larger as the biotic pool (560 Gt) up to 1 m depth (Smith, 2004; Lal, 2004). At the global scale, soils of agroecosystems play vital roles on sequestration of about 2.1 billion tons of C yr^{-1} (Lal, 2010). However, historical land use and soil degradation have been attributed for the loss of 25 to 75% of the original SOC from agroecosystems (croplands and grazing lands). It could be equivalent to the loss of more than 78 billion tons of carbon globally (Lal, 2004).

Estimations of African soils have shown that SOC stocks ranged from 133,420 − 184,116 Tg up to 1 m soil depth. The most recent quantification of SOC stocks in the continent has been estimated at 166,397 Tg C. This corresponds to 9% of global SOC stocks and 68% of the terrestrial C pool in Africa (Henry et al., 2009). Such amount of SOC varies in spatial scale between countries and regions. The highest SOC stocks are found in Middle Africa (33%) and East Africa (26.6%) regions while southern Africa contributes only 6% up to 1 m soil depth (Henry et al., 2009). At the country level, soils in Ethiopia contain 6,459 millions of tons of organic carbon up to 1 m depth (Henry et al., 2009), which corresponds to 13.9% of East African region and 3.9% of the African continent.

Soils, as structural element of agroecosystems, have potentials as carbon sources and sinks (Lal, 2007). Agroecosystems undertake carbon balancing in relatively short period (Han et al., 2008) because

agricultural practices strongly affect carbon cycling between agroecosystems and the atmosphere than other terrestrial ecosystems (Sainju et al., 2008). Therefore, many scientific communities aspire to search for efficient restoration techniques and management strategies of agroecosystem to sequester atmospheric CO_2. Management of agroecosystems is an important approach to restore SOC pools. SOC storage is a universal indicator to assess the status and improvement of land management and soil fertility (Lal, 2007; Patrick et al., 2013). It has been addressed through improvement of degraded agroecosystems, enhancement of organic carbon pool and assisting soil quality (Lal, 2011). Storage of SOC minimizes environmental problems, mitigates climate change and supports sequestration of more carbon in soils of agroecosystems (Lal, 2011).

Agroecosystems are very different from natural ecosystems because human activities manipulate soils, vegetation and other natural resources in the system for growing crops and other environmental benefits (Gliesman, 2007). These human activities can affect the nature of SOC stocks in spatial and temporal scale in agroecosystems than other ecosystems. Therefore, the purpose of focusing on agroecosystem was to analyze organic carbon storage, dynamics and restoration in relation to soils of agroecosystems in Ethiopia.

Materials and Methods

Study areas

Agroecosystems can be classified by agroecological factors, which determine classification of agroecological zones (Wood et al., 2000). Similarly, the present SOC data in agroecosystems were compiled refereeing to agroecological zones. Current agroecological zones in Ethiopia are classified as major categories of arid, semi-arid, sub-moist: moist, sub-humid, humid and peri-humid using temperature and moisture regimes (EIAR, 2011). Out of these categories, soil carbon stocks in semi-arid, sub-humid, humid and peri-humid areas were the main data sources for this study (Table 1). The altitude of these areas ranged from 800 to 3200 m. The data were obtained and compiled only for these areas due to limited studies related to carbon stocks in other areas.

Table 1: The agro-ecosystems studied and their characteristics

Agroecosystem	Salient Characteristics*	Altitudinal range (m)*	Soil Type(s)**
Semi-arid	High temperatures (26-34 ^{0}C), low precipitation (400-700 mm) (Aridity index range = 0.20 - 0.50), poorly developed soils and low biomass production, and pastoral/crop cultivation common	500 - 1500	Xerosols, volcanic origin (Adosols)
Sub–humid	Temperature (15– 30 ^{0}C), precipitation (700 - 1000 mm), (Aridity index range = 0.50 - 0.65)	1500 - 2100	Xerosols, volcanic

			origin (Adosols)
Humid mid-highland	Temperature (18 - 20 ^{0}C), precipitation (900 - 1,500 mm, (Aridity index range = 0.65 - 0.75), and cultivation of annual and/or perennial crops common	2,100 - 2500	Nitosols, Cambisols, Lithosols,
Per-humid highland	Temperature (14 – 18 ^{0}C), precipitation (1500 - 2,000 mm, (Aridity index range > 0.75), and suited for perennial crop cultivation and forests	2,500 - 3500	Nitosols, Cambisols, Lithosols

* = MOA (2000); and ** = FAO (1984).

In the study area, 32 soil data focusing on SOC stocks in cereal cultivation, grazing land and agroforestry were evaluated. In grazing lands, which were dominated by livestock production, studies on soil carbon stocks in free (open) communal grazing lands were considered.

Methods of determination of SOC

SOC can be determined using direct and indirect methods. Carbon content in soil samples can be directly determined by measuring soil variables. The most direct SOC determination involves collecting soil samples in the field, and samples can be analyzed in the laboratory by combustion techniques (Pearson, 2007; Hairiah et al., 2010). This method includes wet and dry combustion and various types of infrared spectroscopy. However, wet combustion is the most dominant direct method of SOC determination (Walkley-Black Method) followed by dry combustion techniques, and a few studies used infrared spectroscopy techniques for *in situ* measurement.

Indirect determination of SOC changes over large areas worldwide includes stratified accounting with database, remote sensing and simulation models. These are increasingly important to fill gaps in the direct SOC determination method. Replication of soil samples can be used to describe changes in SOC under varying climatic condition, soil and management types. It reduces extra wastage of money and time to estimate CO_2 emissions in large area under a wide range of biological, physical and agricultural management conditions.

Data analyses

Data were quantified as mean, range and median to describe spatial distribution of SOC stocks in different agroecosystems, agricultural land uses and farmland management. In some research findings, SOC data were found in the form of raw data, such as soil depth, organic carbon concentration and bulk density. So, in this case, SOC stocks were calculated as SOC stocks = D * % C * BD, where SOC is soil organic carbon (Mg C ha^{-1}), D is depth of soil layer (cm), %C is percent of carbon concentration (g 100 g^{-1}) and BD is bulk density of soils (g cm^{-2}).

Results and Discussion

SOC measurement and determination

The results revealed that a large range of soils (96.9%) were measured using ground-based measurements and laboratory analyses, and only a few (3.1%) were model-based monitoring of sites (Table 2; Appendix 1).

Table 2: Methods of soil carbon determination employed by the observations

Methods*	Number of observations	Proportion (%)
Walkley-Black Method	17	53.1
Dry combustion	12	37.5
Dry combustion and Infra-red spectroscopy	2	6.3
Modeling and Walkley-Black Method	1	3.1
Total	**32**	**100**

* = See Appendix 1 for details.

A number of ground-based surveys are conducted to quantify SOC stocks (Pearson et al., 2007; Hairiah et al., 2010). The purposes of these studies were to determine the ways of CO_2 emission as well as identify and measure changing soil carbon stocks (Lal, 2004). Different methods and direct or indirect measurements and use of models were employed to quantify SOC stocks (Mäkipää et al., 2012). The use of these different methods and measurements are to increase precision and accuracy during quantification of SOC (Smith et al., 2010).

Direct methods of determination

The results showed that the majority of SOC contents were determined by using laboratory analyses methods ranging from the older Walkley-Black method (53.1%) to the modern method of dry-combustion elemental analyzer (43.8%). The largest application of ground-based soil survey was conducted and analyzed in Walkley-Black Method since it is easy to handle many samples and useful for assessing change of SOC. The accuracy of methods used to quantify the change in carbon stocks could contribute to variations among different research results. Amare et al. (2013) explained that determination of SOC using the Walkley-Black Method showed variations between and within sampling sites.

Although traditional Walkley-Black method has become popular procedure for determination of SOC, it lacks repeated measurement and good levels of replication. It can also lead to underestimation of carbon stocks because of the incomplete oxidation in the laboratory analysis (Hobley and Willgoose, 2010; Venkanna et al., 2014). In addition, it contributes to negative environmental impact because of the discharging of toxic chemicals. As the cost for chemicals involved in the Walkley-Black method is

very high, it leads to low efficiency in carbon stock determination. Therefore, this traditional method of laboratory analysis becomes challenging for its continuous application to estimate SOC. On the other hand, instrumental error of modern dry combustion auto-analyzers could be less than 0.1%. Hence, laboratory analysis using appropriate procedures showed 1-2% measurement error in dry combustion techniques (FAO, 2001). However, elemental combustion techniques have also some limitations in practical work for many samples and sequential assessment of SOC (Aynekulu et al., 2011; Batjes, 2011). Therefore, the use of infrared spectroscopy method can minimize those limitations associated with Walkley-Black method and dry combustion methods for estimation of SOC stocks (Vågen et al., 2013; Amare et al., 2013). It is, thus, worth noting that quantification of SOC using Walkley-Black method contributes to inaccuracy and low precision of SOC determination.

Model-based measurement

Model-based measurement in this study accounts for 3.1%, indicating the need for more estimation of SOC stocks to fill gaps on direct determination. A model-based soil carbon monitoring system consists of a model of soil carbon and input data to the model, and results in the determination of soil carbon. The method has been accepted as the most promising method for the estimation of the stocks and changes of SOC (Aynekulu et al., 2011; Mäkipää et al., 2012). Model-based evaluation of soil carbon can involve many inputs, such as litter production of vegetation, temperature and moisture affecting the decomposition rate of organic matter in the soil, and soil texture as affecting stabilization of organic matter in the soil and controlling soil moisture conditions. In addition, whenever land-use change is an important factor affecting soil carbon, it is essential to account for the effects of land-use change on a model-based soil carbon monitoring system. Therefore, model-based method can involve many soil variables associated with their significant roles on soil carbon stocks.

Soil organic carbon dynamics at the level of agroecosystems

The descriptive analyses revealed that mean soil carbon stocks between agroecosystems varied (Table 3). Compared with carbon storage in soils of agroecosystems of other tropical regions (Batjes, 1999; FAO, 2001), Ethiopian agroecosystems exhibited low carbon storage capacities (Table 3).The majority of measurements and analysis of soil carbon stock were achieved through Walkley-Black Method, which could result in the underestimation of findings in addition to ecological elements, e.g. climate, physiography, soils types, vegetation and farming systems) and management practices. These ecological elements can determine turnover of carbon in agroecosystems. Therefore, ecological elements coupled with farm management (e.g. irrigation or rain-fed) and land use practices (e.g. agroforestry) contributed variations on the distribution of soil carbon content along the agroecosystems. Many investigators explained that biotic factors and management activities, such as irrigation production in watershed areas at the local condition (Haile et al, 2014; Shiferaw et al., 2015) and ecological elements, such as climate at the large scale, like tropical regions (FAO, 2001), play fundamental roles and affect carbon inputs into the soil and decomposition processes (Girmay and Singh, 2012).

Table 3: SOC storage (Mg C ha^{-1}) in different agroecosystems of Ethiopia in comparison with tropical regions (1 m depth)

Agroecosystems	Number of Observations (%)*	Range of SOC Stock (Ethiopia)	Mean SOC (Ethiopia)	Range of SOC stock (Tropical Regions)**	Mean SOC (Tropical Regions)**
Semi-arid	6 (19)	20.3 - 40.4	25.77	37.1 - 40.8	38.95
Sub–humid	9 (28)	13 - 36.6	25.66	64.4 - 68.2	66.3
Humid mid-highland	14 (44)	23.6 - 256.3	113.17	176.8 - 182.5	179.65
Per-humid highland	3 (9)	18.7 - 124.74	57.14	56 - 59	57.5

* = See Appendix 1 for details; and ** = FAO (2001).

Semi-arid agroecosystems

The analyses revealed that the soils of semi-arid agroecosystem have low carbon fixation capacity, with a mean SOC storage of 25.77 Mg C ha^{-1} than other agroecosystems (Table 3). Other studies have also shown that soils of semi-arid agroecosystems maintained low SOC stocks (Shrestha and Stahl, 2008), and the rate of carbon sequestration is retained slowly in the semi-arid tropics (0.1 - 0.2 t of C ha^{-1} yr^{-1}) as a factor of climate (FAO, 2001; Lal, 2004).

Compared with carbon saturation levels of the soils in semi-arid tropics (73.21 Mg ha^{-1}) up to 60 cm soil depth (Venkanna et al., 2014), there is a need for greater efforts to improve SOC levels in semi-arid agroecosystems of Ethiopia. Application of irrigation farming would improve carbon sequestration. On the other hand, application of low-input value for improvement of organic carbon in agroecosystem (Emiru and Gebrekidan, 2013) and naturally consisting of sandy and infertile soils might contribute to low carbon content in the soil (Gui et al., 2010). In addition, wind erosion of soils and deterioration of vegetation cover attribute to the decline of SOC and susceptibility for land degradation (Wani et al., 2009) in semi-arid agroecosystems. Low carbon storage potentials in semi-arid agroecosystems reflect more CO_2 emission into the air than sequestration in the soil. Such factors can play significant role for depletion of SOC pool, reduction of biomass productivity and exacerbate global warming (Lal, 2004).

Semi-arid regions are generally characterized by high temperatures, low precipitation, poorly developed soils and low biomass production (Raiesi, 2012). For improvement of carbon sequestration in these conditions, adequate management practices should be implemented to improve potential of the SOC stocks (Sousa et al., 2012). Effective implementation may reduce climate effects while it increases carbon storage potentials in soils.

As a result of these effects, multiple management efforts are required for restoring degraded soils, including agroecological-based technologies. Enhancing nutrient recycling mechanisms and adopting

water harvesting measures (World Bank, 2010) as well as maintenance and restoration of woody vegetation, mainly trees, as wind erosion break ameliorate the effects of and improve ecosystem services in the area. Practice of agroforestry systems on semi-arid agroecosystems are limited and have not played significant role in carbon storage. Similar studies have shown that agroforestry systems have not shown significant role for carbon sequestration potential in semi-arid than those on fertile humid sites (Srinivasaraoet al., 2013). Stressing on irrigation and intensive soil cropping may improve soil quality in semi-arid regions (Mulualem et al., 2015), because these practices can result in greater SOC contents.

Sub-humid agroecosystems

The SOC in the sub-humid agroecosystem varies from 13 to 36.6 Mg C ha^{-1} (Table 3). Andosol soil type and its subsequent conversion into low-input agricultural systems are responsible for the lowest amount of SOC stock (Solomon et al., 2002; Emiru and Gebrekidan, 2013). For example, within similar elevation and amount of rainfall, significance differences of SOC stocks were observed in the Andosols of Alaba (14.4 Mg C ha^{-1}) and Vertisol of Debrezit area (33.9 Mg C ha^{-1}). These complex interactions between low-input agricultural systems and soil types affected the SOC storage capacities of agroecosystems. In general, the major factor contributing to low carbon stocks in sub-humid tropics is poor productivity (Venkanna et al., 2014).

Humid mid-highland agroecosystems

The humid mid-highland agroecosystem stored more SOC, ranging from 23.6 to 256 Mg C ha^{-1}(Table 3). The presence of Nitosols and agroforestry practices in Gedeo area has led to, relatively, the highest amount of SOC stocks (256 Mg C ha^{-1}) (Table 3). In addition, large amount of CO_2 can be sequestered in this agroecosystems as a consequence of availability of moderate temperature and rainfall, the good management practices and soil types. Studies have also shown that SOC stocks can increase with elevation due to relatively higher moisture levels and lower temperatures at the higher elevations (Hoffmann et al., 2014). Lower temperatures can limit organic matter decomposition rates. These conditions lead to low CO_2 emission from the soil and, thus, contribute to higher SOC accumulation/stocks. The balance between primary productivity and soil respiration can result in soil organic accumulation. Therefore, enhancement of primary productivity through agroforestry systems can improve carbon storage potentials in the soil. However, continuous cultivation based on rain-fed agriculture and improper addition of fertilizers for increasing crop yield contributed to low storage of carbon and cause wide range of variation in SOC within the same agroecosystem.

Per-humid agroecosystems

The SOC storage in per-humid area ranged from 18.7 to 124.74 Mg C ha^{-1}(Table 3). The high storage of SOC in this system was due to commencement of intercropping of trees in agricultural areas while continuous cultivation with rain-fed practices resulted in low SOC storage. Many studies demonstrated that the soils in the Ethiopian highlands have been degraded (Hurni et al., 2007), causing major

environmental problems (Haile et al., 2014) due to the change in land use systems with the aim of expansion of agricultural land. Hence, conservation and restoration measures, including soil and water conservation, are being implemented in cultivated areas and exclosures (Aerts et al., 2009; Teketay et al., 2010) in grazing lands to restore degraded lands (Shiferaw et al., 2015). As a consequence of such condition, SOC can be improved on the degraded areas of agroecosystems.

Dynamics of soil carbon storage in farm land management

The total extent of rain-fed and irrigated farming in agroecosystems account about 2.6 and 0.12 billion ha, respectively (FAO, 2001), of which 0.65 billion ha of cultivated lands are found in the tropical zone. The cultivated area in Ethiopia is estimated at about 12 million ha of land. Out of the cultivated land, the potential areas for irrigation land are estimated at one-fourth (three million hectares) of the country. However, most of the fertility of soils in the agroecosystems are highly deteriorated, which could also contribute to loss of organic carbon (ATA, 2013). The spatial distribution of SOC stocks in irrigated and rain-fed farmland systems are discussed in the following sections.

Irrigated farming system

An irrigation system is one of the farmland management practices that can be used to increase soil organic matter content by increasing productivity and biomass (FAO, 2001). Irrigated farmland soils stored relatively more SOC than rain-fed farmland soils (Table 4). This reflects that better management of irrigated farm land results in positive impacts on SOC stocks than rain-fed farmland. Previous studies also suggested that efficient use of inputs on irrigated farmlands sequestered more CO_2 than rain-fed farmlands (Girmay et al., 2008; Mulualem et al., 2015). Irrigated systems, particularly in the semi-arid regions, can contribute to a rapid increase in SOC, focusing on relevance of crop residues to the soils and growing nitrogen fixing plants. In some of the dominant rain-fed cropping systems, cereal cultivation exhibited reduced organic carbon stock compared with grazing lands and agroforestry systems. This indicates that shifting from rain-fed cropland to irrigation cropland management improves productivity and environmental condition of agroecosystems (Mulualem et al., 2015) since these practices can contribute towards greater contents of soil organic matter. Therefore, diversification of cropland management, particularly, on cultivated soils could provide an opportunity for climate adaptation.

Rain-fed farming system

The mean SOC stock in rainfed-farming systems showed lower value than irrigated farm systems (Table 4). This reflected that high degree of soil degradation resulted in low carbon stocks in rain-fed farmlands due to continuous cultivation, poor management and low external input. The role of rain-fed framing systems differ regionally where it supports to produce most crops for poor communities in developing countries like Ethiopia. However, climate change can affect rain-fed farming, particularly in semi-arid regions (World Bank, 2010), and contributed to low potential of CO_2 sequestration. The implication of high dependency of communities on rain-fed farming has aggravated soil degradation

and, hence, better management is urgently needed to reverse the process before the soils lose their ecosystem services.

Table 4: Soil organic carbon stocks (Mg C ha^{-1}) in farmland management systems

Farm management system	Number of observations (%)	Range	Median	Mean
Rainfed farm	18 (81.82)	13 - 94.9	25.75	31.60
Irrigation farm	4 (18.18)	21.95 - 102	28.5	45.23

Dynamics of soil carbon stocks in agricultural land use types

The analyses confirmed that the trend of mean soil carbon storage in agricultural land use types was: agroforestry (153.57 Mg C ha^{-1}) > grazing land (34.61 Mg C ha^{-1}) > cereal cultivation (24.18 Mg C ha^{-1}) up to 1 m depth (Table 5).

Table 5: Spatial distribution of SOC stocks in agricultural land use

Land use	Observations*	Range	Mean SOC stock (Mg C ha^{-1}) in Ethiopia	Globally SOC stocks (Mg C ha^{-1}) and references
Agroforestry	9	49.41 - 256.3	153.57	30 - 300 (Nair et al., 2010)
Cereal cultivation	20	36.6 - 102	24.18	50 (Lal, 2004)
Grazing land	3	22 - 41.03	34.61	100 (Silver et al., 2010)

* = See appendix for details.

Table 5 clearly indicates that agricultural land use influences SOC and implies that the values are minimal compared with organic carbon stocks across other land use types. SOC stocks can vary spatially across agricultural land use type (World Bank, 2012). Effects of agricultural land use could contribute to variations of SOC stocks in spatial scales of agroecosystems. For the analyses of agricultural land use, three main land use types were distinguished, of which crop cultivation was the dominant land use type.

Soils of cereal cultivation

SOC stock potential in cereal cultivation ranged from 13 Mg C ha^{-1} in the sub-humid agroecosystems to 102 Mg C ha^{-1} in humid mid-highland agroecosystems with a mean value of 24.18 Mg C ha^{-1}. Lal (2004) stated that achievement of 50 Mg C ha^{-1} stocks in soils of cropland is important for global conservative concerns and, thus, cropland management should be integrated for restoring degraded soil organic matter. The most prominent cereal cultivation includes maize, teff and barely in the studied

sites. Low carbon input in the form of cereal crop residue, reduced tree cover and continuous cultivation resulted in the lowest stocking potentials while the largest carbon stocks potential was observed in farmlands with a combination of farm management systems, modest climatic condition and dominant soil types. Many studies also explained that land use influences SOC stocks (Mekuria et al., 2009; Gebremariam and Kebede, 2010; Abera and Belachew, 2011; Habtamu et al., 2014; Haile et al., 2014) and quality of the environment (Lal, 2004; Ndor and Ioruka, 2013).

A variety of local factors including climatic condition, soil properties as well as land use and management practice can contribute to the change of soil carbon stocks. Accordingly, lower amounts of organic carbon storage have been found in soils of cereal cultivation than other land use systems. Continues cultivation might contribute to the reduction of carbon storage in this land use. This suggests the need for sustainable cropping systems and management to improve soil carbon storage. Therefore, improvement of crop residues, reduce tillage operation, improvement of fertilizer application, choice of crop for carbon management and irrigation systems have a potential for improvement of soil fertility and restoration of degraded areas (Lal, 2004; Srinivasarao et al., 2013). Such land management can adjust soil carbon stocks to varying degrees (Lal, 2004; Singh et al., 2008; Srinivasarao et al., 2013).

Soils of **agroforestry systems**

Agroforestry is one of the land-use systems that involves growing of trees or other woody perennials on agricultural crops and pastures. The purpose of this land use system is to improve productivity of agricultural land and pastures, and utilize the ecological and economic interactions of different components (Srinivasarao et al., 2013). The agroforestry systems studied showed higher potential of carbon storage capacities in the soils of humid agroecosystems up to 1m depth (36.6 - 256.3 Mg C ha^{-1}). In particular, complex agroforestry systems, such as coffee, enset and enset-coffee agroforestry practices harbor high levels of carbon stocks. Similarly, Nair et al. (2010) found that carbon stored in the soils range from 30 to 300 Mg C ha^{-1} up to 1 m depth in agroforestry systems which could be attributed as distinct feature of agroforestry practices from other forms of agriculture. Similar studies concluded that soils of agroforestry practices sequestered higher amounts of organic carbon (Haileslassie et al., 2006; Singh et al., 2010; Nair et al., 2010; Haile et al, 2014; Negash and Starr, 2015; Mulualem, et al., 2015) due to addition of organic matter with litter decomposition and management, including high organic matter inputs (Haileslassie et al., 2006) than cereal-based systems.

Agroforestry systems also provide opportunities for conservation of diverse biological species (Schroth et al., 2004; Richards and Mendez, 2014) due to inclusion of coffee, enset and other tree species into the agricultural landscapes. Agroforestry systems perform key roles in conservation of diverse biological species by providing supplementary habitat for species, reducing rates of conversion of natural habitat and creating networks between habitats and modified forest remnants. Agroforestry-based systems are among bio-farming systems that can be used by small holder farmers to minimize external inputs and, hence, are recommended to sustain agricultural production on slopy lands (Lin et

al., 2011; Simane et al., 2013). This contributes to improve agro-ecosystems by reducing soil erosion, thereby, reducing losses of water and nutrients.

Soils of grazing lands

The grazing lands accumulated higher mean SOC than cereal cultivated lands, but they exhibited lower mean SOC than agroforestry practices (Table 5). Addition of organic input from cow dung may contribute to slight increment of organic matter in the grazing lands compared with cultivated lands (Mekuria et al., 2009; Haile et al., 2014; Mekuria et al., 2014), but overgrazing may cause degradation of soil organic matter compared with agroforestry systems (Haile et al., 2014). Many findings have shown that grasslands can fix organic carbon in the soil reaching up to 100 Mg C ha^{-1}) (Silver et al., 2010). For instance, conversion of free grazing lands to area exclosures have shown potential of increasing carbon stocks in the area (Mekuria et al., 2009), and if continued, this strategy may contribute to achieve equilibrium state in carbon sequestration.

Effects of dominant soil types on carbon storage

Soil types are important for crop production and storage of organic carbon. Soil organic stocks across soil types varied from 13 Mg C ha^{-1} in Andosols to 102 Mg C ha^{-1} in Vertisols with similar agricultural land use (Table 5).

Table 6: Soil organic carbon stocks in dominant soil types

Soil class *	Taxonomy *	Sub-tropical dry to sub-tropical moist (Mg C ha^{-1}) **	Soil types**	Range of carbon stocks (Mg C ha^{-1}) in Ethiopia
High activity clay soils	Vertisols, Mollisols, Inceptisols, Aridisols and high base status Alfisols	42 - 57	Vertisols	18.7 - 102
			Lithosols (Leptosols)	23.7 - 34.9
			Cambisols	25 - 49
Low activity clay soils	Ultisols, Oxisols, acidic Alfisols and many Entisols	39 - 47	Nitisols	65.2
Sandy soils	Any soils with greater than 70% sand and less than 8% clay (often Entisols)	33 - 50	Andosols	13 - 27

* = IPCC (2006); and ** = FAO (2001).

Dominant soil types are found from sub-humid to humid area of the country (FAO, 1984). Vertisols are responsible for the highest range of SOC stocks in the study sites. This is because of their relatively

better fertility compared with the other major soils. Vertisols are dominant soil types in highland areas, specifically on flat or gentle slopes. Andosols are mainly found in semi-arid and sub-humid areas, particularly in low land areas (see Appendix 1).

According to IPCC (2006), soils can be classified into three main classes. Each class consists of different soil taxonomy (Table 6). Six dominant soil types, i.e. Vertisols, Cambisols, Nitosols, Regosols, Leptosols and Fluvisols, cover half of the land mass of Ethiopia and are important as arable soils (Hurni et al., 2007). Out of these, five dominant soil types (Vertisols, Lithosols, Cambisols, Nitosols and Andosols) that affect distribution of organic carbon stocks were found on four agroecosystems.

Nitosols dominantly occur from sub-moist to humid areas, and these soils are highly weathered, acidic, high phosphorus fixing and well drained. However, Nitosols are vulnerable to erosion and leaching. Cambisols occur in the steep slopes and spread all over the country, but, mainly, they border the large areas of Nitosols in the highlands. They show wider variability than the other major cultivated soils in the country. Lithosols are also found in the highlands.

Results of previous studies also showed that dominant soil types affected carbon stocks in the ecosystems (Itanna et al., 2011). However, agricultural land use and management practices aggravated the change of SOC stocks. It should be noted that improvement of land use and management of agroecosystems can promote better carbon sequestration.

Restoration based on agroecosystems and land use types

Agroecosystems provide a lens for adaptation that takes into account ecological element differentiation and farming systems (Simane et al., 2013). Restoration of soil organic pool and improvement in soil quality may become future solutions of climate change (Lal, 2004). Soil restoration depends on agroecosystem-based technologies. For instance, water harvesting structures for irrigation systems and vegetation cover have been shown to improve the SOC in semi-arid areas (Bateje, 1999). In addition, reclamation strategies become more effective in semi-arid areas that have been affected by salt during irrigation practices.

Restoration measures through management of livestock, improved species as well as fire and nutrient management would sustain grazing land condition, particularly, in semi-arid and sub-humid agroecosystems (Lal, 2004). Area exclosures are also passive restoration or rehabilitation strategy, particularly in grazing lands by reducing impacts from human activities, such as overgrazing and improve SOC stocks. Soil and water conservation is an important agroecosystem-based restoration strategy, particularly in humid areas. Cropland management could also be an important strategy in humid areas to enhance carbon sequestration through management of residues, proper tillage operations, and proper application of fertilizers and choice of crops having high carbon input, irrigation management and fallow systems (Lal, 2004). Moreover, intercropping systems of trees in the farmlands

of humid ecosystems have been proven as potential means of restoration of SOC (Singh, et al. 2010). This restoration of ecosystems could improve carbon sequestration in a sustainable manner.

Conclusions

The study confirmed that trends of mean carbon storage in the different agroecosystems in Ethiopia represent the following order: humid mid-highland > per humid highland > sub-humid > semi-arid. Comparatively, SOC stocks in these areas have shown lower amounts than in other tropical regions. This might have resulted from effects of land use, management and soil types. Soil types, agricultural land use and management practices play important role for spatial variation of organic carbon stocks in the soils of agroecosystems. The analyses also revealed that dominant soil types have greater mean carbon storage capacities than others. Agricultural land use types also contributed to the variations of organic carbon storage in the soil. SOC stocks are higher in agroforestry systems followed by areas with cereal and grazing lands. Therefore, agroforestry practices are the best strategies to increase sequestration of organic carbon, particularly in sub-humid and per-humid areas. Farmland management using irrigation system is also a promising strategy to improve SOC stocks. The study also showed that soil and water conservation in per-humid areas, exclosures in grazing lands and management of cereal cultivation are the best strategies for the restoration of soil carbon pools in agroecosystems. Therefore, it is recommended that possible solutions for improvement of organic carbon stocks would be the implementation of appropriate restoration strategies in agroecosystems.

Acknowledgements

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Appendix 1: Organic carbon stocks in agricultural land uses, farming management systems and dominant soil types in four agroecosystems in Ethiopia.

Agricultural land use	Farm Management system	SOC stocks (MgC ha^{-1})	Proportion (%) organic carbon	SOM (%)	Depth (cm)	Methods *	Dominant Soil types	Altitude (m)	Temperature and rainfall (meanyr^{-1})	Agro-Ecological Zone	Location of sample site	References
Cereal cultivation	Rain-fed	65.2	-	-	30	WB	Arcisol, Nitisol and Leptosol	1890-2100	1 4.2℃ -24.2℃ and 1800 – 2000mm	Humid mid Highland	Adjacent to Gera forest	Gedefaw and Bekele (2014).
Coffee-based cultivation	Rain-fed	94.9	-	-	30							
Cereal cultivation	Irrigation	28	1.2	2.04	80	WO	Vertisols, Cambisols, Regosols and Fluvisols	2300-2830	8-15 ℃	Humid highland	Maileba	Girmay and Singh (2012)
Cereal cultivation	Irrigation	79	1.0	1.7	80	WB	Cambisol, Leptosols and Vertisols,	2100-2160	20-30 ℃ 400-700 mm	Humid mid highland	Guma Selassa	
Enset cultivation	Rain-fed	49.41	3.09	5.3	15	WB	Cambisols	2100	27.7 ℃ and 6.5℃ and 1058 mm	Humid mid highland	Meskan	Haile et al. (2014)
Cereal cultivation	Rain-fed	27.58	1.50	2.55	15	WB						
Grazing land	Rain-fed	41.03	2.31	3.9	15	WB						
Cereal Cultivation	Irrigation	25.19	1.65	2.82	100	MW	-	1923-2300	-	Humid mid highland	Gumara	
Cereal cultivation	Rain-fed	13	1.6	2.72	30	DCA	Andosol	1643-1950	9.4℃ and 952mm	Sub-humid	Awassa	Abera and Belachew (2013)
Cereal cultivation	Rain-fed	27	2.8	4.9	30	DCA	Andosol	1643-1950	24℃ and 650mm	Semi-arid	Ziwaye	
Cereal cultivation	Rain-fed	22.65	1.28	2.28	50	WO	Sandy and infertile	800-1500	28.5 ℃	Semi arid	TahtayAdyabo	Gebremariam and Kebede (2010)
Grazing land	Rain-fed	22.41	1.60	2.72	50	WO	Sandy and infertile	800-1500	28.5 ℃	Semi arid		
Cereal cultivation	Rain-fed	14.4	8	14.24	20	DC-LC-2000A	Vitric Andosol	1920	700 -1000 mm	Sub-humid	Alaba	Itanna et al. (2011)
Cereal cultivation	Rain-fed	18.9	7	12.46	20		HaplicNitisol	1620	-	Sub-humid	Humbo	

Land use	Water				Depth	Method	Soil	Altitude	Climate	Agro-ecology	Location	Reference
Cereal cultivation	Rain-fed	20.3	9	16.02	20		CalcaricFluvisol	1600	400-700 mm	Semi-arid	Ziway	
Cereal cultivation	Rain-fed	21.9	9.7	17.3	20		HaplicSolonetz	1600	400-700mm	Semi-arid	Bulbula	
Cereal cultivation	Rain-fed	33.9	14	24.92	20		Pelli-EutricVertisol	1850	700-1000 mm	Sub-humid	DebreZeit	
Agroforestry	Rain-fed	174	-	-	100	WB	AndicPaleudalf	2137-2215	-	Humid mid-highland	Gambo District	Singh et al. (2010)
Agroforestry	Rain-fed	159	-	-	100	WB	AndicPaleudalf	2137-2215	26.6^{o}C and 10.4^{o}C, 973 mm	Humid mid-highland	Gambo District	
Enset Agroforestry	Rain-fed	232	-	-	60	WB	Nitisols	2100-2400	-	Humid mid-highland	Gedeo	Negash and Starr (2015)
Agroforestry	Rain-fed	255.2	-	-	60	WB	Nitisols	1900-2200	-	Humid mid-highland	Gedeo	
Fruit and coffee	Rain-fed	256.3	-	-	60	WB	Nitisols	1500-1900	-	Sub-humid	Gedeo	
Cereal (maize) cultivation	Rain-fed	26.3	-	-	10	DCEA	PlinthaquicPaleudalf	1900	18°C	Sub-humid	Wushwush	Solomon et al. (2002)
Cereal (maize) cultivation	Rain-fed	23.6	-	-	10	DCEA	TypicPalehumults	2100	19°C and 1250mm	Humid mid-highland	Munessa-Shashemene	
Enset-system cultivation	Irrigation	124.74	4.2	7.14	30	WB	Luvisols	2880–3095	-	Humid highland	Galesa watershed	Haileslassie et al. (2006)
Teff-system cultivation	Irrigation	102	3.4	5.78	30	WB	Vertisols, Leptosols	2320–2620	1117mm	Humid mid-highland	Gare watershed	
Cereal	Irrigation	21.95	5.9	10.03	30	DC	Arenosols, Regosols	1960-2000	15 °C and 30 °C, and 558mm	Sub-humid	Mandae watershed	Mulualem et al. (2015)
Cereal	Rain-fed	29.4	3.3	5.61								
Agroforestry	Rain-fed	36.6	6.4	10.9								
Cereal	Rain-fed	36.5	-	-	50	DC-IRS	Phaeozems	-	-	Sub-humid	Dambidolo	Vågen et al. (2013)
Cereal	Rain-fed	18.7	-	-			Leptosols	-	-	Humid highland	Kutaber	
Grazing land	Rain-fed	40.4	-	-	20	WB	Leptosol, Regosols	-	11-17 and 26-34°C	Semi-arid	Three districts of Tigray	Mekuria et al. (2009)

* WB = Walkley-Black method; WO = Wet Oxidation method; MW = Modeling and wet method; DC = Dry combustion; DCA = Dry combustion by Allison method; DC-LC-2000A = Dry combustion with LECO CNS-2000analyzer; Dry combustion elemental analyzer; and DC-IRS + Dry combustion and IR spectroscopy.