Soil organic carbon stock and retention rate among land uses along Didessa toposequence in humid Western Ethiopia

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Research

Keywords: Agroforestry, arable cropping, fallowing land, grassland sugarcane plantation

Posted Date: September 18th, 2020

DOI: https://doi.org/10.21203/rs.3.rs-75409/v1

Version of Record: A version of this preprint was published on November 24th, 2020. See the published version at https://doi.org/10.1186/s40068-020-00199-w.

Abstract

Background

There is scarcity of scientific information on stocks and retention rate of soil organic carbon (SOC) among mixed farming systems in humid Western Ethiopia. The objectives of study were to determine the SOC stocks and retention rates along a 53-km long toposequence of Didessa watershed. The study was conducted in mixed farming systems (annual arable cropping, grazing, fallow, grassland, coffee agroforestry, Eucalyptus agroforestry and mechanized irrigated sugarcane production) within an elevation range of 1273 to 2543 meter above sea level.

Results

The results revealed that land use types greatly affected SOC stocks and retention rates in the upper 20 cm soil depth. The SOC stocks ranged from 9.27 to 13.5 Mg C ha^{-1} (0-20cm) while the retention rates were 0.11, 0.2, 0.28, 0.31 and 1.14 Mg C ha^{-1} yr^{-1} for coffee agroforestry, fallow, grazing, Eucalyptus agroforestry and irrigated sugarcane production systems, respectively.

Conclusion

The retention rates demonstrated that the different farming systems are potential source of C sinks. The study indicated that the farming systems are efficient in sequestering SOC and their benefits can be further adopted for their economic values, social significance, restoration of degraded land and sequestration of C in humid tropical Western Ethiopia.

1. Introduction

Emission of CO_2 since the industrial revolution of 1750 and land use change have increased the amount of atmospheric carbon (C) by 31% (ESA 2000; Lal 2004a). The soil system is the largest reservoir of C pool which is 3.3 times the size of atmospheric C and 4.5 times the size of biotic C pool (Lal, 2005; Lal 2006). African soils have an estimated soil organic carbon (SOC) stock of 166 397*10^6 tons (0-100cm). This corresponds to 9% of the global SOC stocks and 68% of the terrestrial C pool of Africa (Henry et al., 2009). Ethiopia has an estimated SOC stock of 6459*10^6 tons (0-100cm) and it is the third largest SOC stocks in East Africa next to Tanzania and Zambia (Henry et al., 2009). However, conversion of natural ecosystem to agriculture in the tropics could cause loss of 75% or more of SOC (Lal, 2005). Increased global C storage through sequestration into aboveground terrestrial biome and belowground stocks are feasible methods for reducing CO_2 concentration in the atmosphere (ESA, 2000; Lal 2004a; Lal 2005). Global agricultural and degraded soils have high C sink capacity which could be in the order of 50 to 66% of 42 to 78 gigatons (Gt) of the historic C lost to atmosphere (Lal, 2005). Soils of African continent have an estimated 30% of total global C sequestration potentials (Henry et al., 2009). The SOC sequestration has the potential to increase agricultural production and reduce CO_2 concentration in the atmosphere (ESA, 2000; Lal 2004b).

Topography and climate vary along landscape positions and affect SOC sequestration capacity of terrestrial ecosystems. Several studies in Ethiopia have been carried out to quantify effect of vegetation, land uses and climate on SOC concentrations (Wakene, 2001; Dawit et al., 2002; Mulugeta and Fisseha, 2004; Abraha et al., 2012; Kilic et al., 2012; Achalu et al., 2013; Nega and Heluf *et al.*, 2013; Getahun and Bobe, 2015). They compared the effect of conversion of native vegetation to agricultural land uses and reported higher SOC concentration from forests and grasslands compared to arable cropping and grazing land uses. However, they could not make any account of the effect of different land uses under mixed farming systems along topographic elevation over broader landscape positions on SOC stocks and retention rates.

Population pressure has pushed agriculture in Ethiopia to expand into forest on hillsides and slopping lands (Sima et al., 2011). Native vegetation is being changed into arable cropping lands with slight or no conservation measures and there has been a decreasing trend of forest coverage and SOC stocks. From 1990 to 2010 alone, 1.16Gt of C stocks from forest biome and 1.83Gt of SOC stocks were lost at country level (FAO, 2010). Over grazing, fuel woods and production of charcoal, poor governance and land tenure system are some of the underlying causes for depletion of aboveground and belowground C stocks in Ethiopia (Sima et al., 2011). The inherent fragile soil properties coupled with low input agriculture have caused decline in the soil fertility within short term after conversion of marginal lands to agricultural land. Smallholder farmers fallow their field plots for three to four years until the soil fertility has partially restored. During the fallowing, controlled grazing is usually practiced. Land use changes from native vegetation to agriculture and the vice versa are the source and the sink for atmospheric CO_2. Land misuses and mismanagements are the source for atmospheric while adoption of restorative land uses and recommended management practices reduces rate of CO_2 emission to atmosphere, improve food security, water quality and the environment (Lal, 2004a). Alley cropping system (Oelbermann *et al.*, 2004), coffee garden and agroforestry systems (Xavier and Mendo, 2011; Hombegowda et al., 2015), farm forestry and agroforestry systems (Prasad et al., 2012; Murthy et al., 2013), conversion of pasture and grazing land to sugarcane plantation and silvo-pasture (Junior et al., 2012; Ensinas et al., 2015), soybean and maize intercropping (Junior et al., 2012) and preservation of vegetal biomass of sugarcane sequester C and increase SOC stocks.

Traditional land use systems across various ecological regions and elevation gradients are practiced in Ethiopia since immemorial (Bishaw et al., 2013). Traditional smallholder and oxen drawn arable cropping, Eucalyptus and coffee agroforestry, woodlots, protected forest, fallowing, grassland systems and mechanized sugarcane plantation are some among many mixed land use systems practiced in the humid tropical Western Ethiopia. The indigenous and traditional land use systems could be restorative land use systems compared to continuous cropping with limited inputs and biomass return to the soil system. The indigenous but traditional land use systems have been practiced for centuries and could be stable systems that could reduce CO_2 emission and positively impact food production, income generation, livelihoods and energy sources (Bishaw et al., 2013). Mechanized irrigated sugarcane plantation was recently introduced into Didessa watershed. However, there is scarcity of available research information on the effect of indigenous land uses and mechanized irrigated land use systems practiced along toposequence on SOC stocks and retentions on intermediate to highly weathered soils of humid tropical Western Ethiopia. Thus, the dynamics of SOC stocks and rates of retention in indigenous land use systems, and mechanized irrigated sugarcane plantation along elevation gradient forming land use catena are lacking in the horn of Africa in general and Ethiopia in particular.

Therefore, the objectives of this research were to quantify SOC stocks and retention rates of indigenous land uses systems, recently introduced modern mechanized irrigated sugarcane production system in sequestering SOC stocks and retention rates in humid tropical environment of Western Ethiopia. We hypothesized that indigenous land uses of mixed farming systems along elevation gradients were more efficient restorative systems of sequestering atmospheric CO_2 compare with modern mechanized cropping system and their efficiencies vary along elevation gradients.

2. Materials And Methods

2.1. Location

Didessa watershed is located in humid tropical Western Ethiopia. The topographic map of the 52 km long study transect extends from 9°06’12.7180”N, 36°28’22.1868”E to 8°40’1.9920”N, 36°25’13.0308”E. Didessa watershed drains an area of about 9,486 km^2 and agro-ecology indicated in Fig. 1. Didessa River is the tributary of Blue Nile that flows into North Western Ethiopia. The watershed covers about 5.4% of the total area of Blue Nile and contributes 6.86 km^3 annual discharges which accounts to 10.7% of the total annual discharge of Blue Nile (Conway, 2000). The location of study land use systems along the same toposequence is indicated in Fig. 2.

2.2. Topography and climate

Elevation of the watershed range from 845 to 2685 meter and characterized by sequence of contrasted landforms. Three broad categories of topographic positions are found in study transect. These include lowland, midland and highland with elevation ranges between 845–1500, 1500–2000 and 2000–2685 masl, respectively. Analysis of twenty years of weather data of twelve metrological stations in and around Didessa watershed showed that the mean annual rainfall of the watershed ranged from 1400 mm to 1920 mm per annum. The rainfall in the watershed has a unimodal pattern of distribution. The watershed has three types of length of growing period (LGP) that ranges from 165 to 210 days, from 210 to 240 days, and from 240 to 300 days. The annual average temperature varies from 19 °C in the highlands to 23 °C in the lowland.

2.3. Agro-ecologies and vegetation

The agro-climatic zones (ACZ) of the watershed were derived from twenty years of twelve metrological stations and topographic elevation from digital elevation model. According to Hurni (1998) classification system, three agro-climatic zones were identified namely warm sub-humid lowland (180–240 LGP, 20-27.5 °C, 500–1300 masl), tepid sub-humid midland (180–240 LGP, 15–20 °C, 1500–2000 masl) and tepid humid highland (240–300 LGP, 15–20 °C, 2000–2685 meter). Grassland vegetation dominated the lowland topographic position. Mixed woodland and grassland dominated the midland position while woodland dominated the highland topographic position. As one move from lowland to highland, there are shifts in vegetation types and land use systems along the study transect.

2.4. Farming system of Didessa toposequence

The farming systems are predominantly subsistent mixed crop-livestock (mostly cattle, sheep and goat) production system. In the mixed farming system, cattle provide inexpensive and easily accessible inputs required for cultivation such as draught and threshing power, while crop production supplies crop residue as feed supplement for the livestock. However, most of the grazing is carried out on communal grazing and fallow lands. Manures from calves, sheep and goats are mainly used for homestead gardens. Farm fields away from home gardens often receive manure of cattle and equines (donkeys, horses, and mules) through kraal (cattle pen during night) rotation. Tillage involves oxen plowing with simple plows that cultivate the soils to shallow depths of 15 cm on average (oral communication with the farmers and personal observation).

Major crops grown in the lowland (less than 2000 meter) of the transect include maize, sorghum, finger millet and noug while above this elevation highland potato, teff, field pea, faba bean and noug are common crops. Combination of manure and inorganic fertilizers are used for crop production but the amount of fertilizer applications is low. Farmers use di-ammonium phosphate (DAP) in combination with urea. The recommended rate of application is 100 kg ha^{-1} $year^{-1}$ for both DAP and urea. However, some farmers use sometimes half of recommended amount and often none mainly due to economic reasons. The farming systems have traditional agroforestry system with scattered trees in the farm and grazing lands, eucalyptus woodlots at edge of farmlands, homestead coffee under shade trees. Farms of similar management history were selected by interviewing farm owners and village elders.

2.5. Sampling sites and land uses selection

Soil samples were collected at five sampling sites along the toposequence. The sampling sites were Fayinera, Dune Kane, Balho, and Lugama and Sugar plantation. At Fayinera and Dune Kane sampling sites, soil samples were collected from annual cropping land, fallow land and eucalyptus agroforestry (woodlots) that were in close juxtaposition (at edge of farmland). At Balho sampling sites, soil samples were collected from grazing and annual cropping lands. At Lugama sampling site, soil samples were collected from arable land, grazing land and home homestead coffee agroforestry. While at sugar plantation, soil samples were collected from grazing and mature sugar plantation. The soil samples collected from the distinct sampling farms (land uses) at the four sampling sites were close to each other within a distance of 10 meters to 50 meters from the edge of the respective land uses. Each of the sampling sites were rigorously checked for uniformity of soil types by augering and field characterization of physical and chemical properties, slope angle, length and aspects before sampling of soils from respective land uses and sampling sites. Flow directions of materials from farm lands at each of sampling farms and sampling sites were also considered for uniformity to aid interpretation of the results. Auger point observations to the depth of 120 cm were made and described according to FAO (2006) soil description field guide and checked uniformity of soil types, physically observable pedogenic features and processes. The results of field observation and description were used to verify the similarity in soil types among farms. These selection criteria, however, did not allow us to find farmlands of very similar land use characteristics, land configuration, and land management history along all the sampling sites.

2.6. Soil sampling from four sampling sites

Soil samples were collected from four representative subsistent mixed farming systems identified along the Didessa toposequence. Thirty samples were collected from each of a uniform field from cropping land, fallow land and agroforestry land at Fayinera and Dune Kane sampling sites, from cropping and grazing land at Balho sampling site, from cropping, homestead coffee agroforestry and grazing land at Lugama sampling sites, and mature sugar plantation and grassland at sugar plantation sites. All the samples were collected from 0–20 cm depth with an auger. The thirty samples collected from each land use were bulked to form homogenous composite samples. Generally, 360 samples were collected and then twelve composite soil samples were made out of them following standard soil sampling and bulking procedure. From each of the composite samples, representative subsamples were collected into plastic bags for analysis of soil physical and chemical properties. Foreign materials such as coarse fragments, plant roots, and leaves were removed. The samples were air dried, ground, and sieved to pass through a 2 mm sieve.

2.7. Analysis of soil physical and chemical properties

The air dried, sieved to pass through 2 mm, and oven dried equivalent soil samples were analyzed for distribution of particle size determination according to modified sedimentation hydrometer procedure of Bouyoucos (Kroetsch *et al.*, 2006). The samples were pretreated with hydrogen peroxide to destroy organic matter and treated with sodium hexametaphosphate solution $(NaPO3)_6$ to disperse other soil cementing agents. The proportions of sand, silt and clay sized particle size fractions were determined. The textural classes of soils were determined from textural triangle. The pH of the soils was measured in supernatant suspension of soil to liquid mixture of 1:2.5 ratios. The liquids were distilled water (pH_{H2O}) and 1M KCl (pH KCl) (Reeuwijk 1992). The SOC was determined according to the Walkley-Black procedure (Reeuwijk, 1992). Soil organic matter (SOM) was estimated from SOC by assuming that SOM contains 58% of SOC (Reeuwijk, 1992).

The bulk density (ρb, gcm^{-3}) of soils were calculated as the dry weight of the soil divided by volume of soil core sampler. The SOC stocks were calculated as Mg ha^{-1} by multiplying the concentration (%) of SOC by the respective bulk density (g cm^{-3}) and multiplied by the depth from which samples was collected (20 cm). The total SOC stocks of soil profiles were determined by summing up of the SOC stocks from the respective horizons and expressed as Mg C ha^{-1}. The retention rates of SOC stocks were calculated as SOC stocks of the land use systems minus the SOC of the reference land use divided by the duration of the land use systems. The SOC stocks of crop land and grassland were used as reference SOC stocks with their respective indigenous land uses systems wherever available.

2.8. Statistical analysis

The map of Didessa watershed was prepared by use of ArcGIS software version 10.1 and three dimensional topographic map of study transect of Didessa toposequence was constructed using Global Mapper version 13. Soil data from similar land uses at sampling sites were treated as replications. SPSS statistics version 20 was utilized to carryout statistical analysis to determine effect of sites on SOC stocks and retention rates by. P-values of 0.01 and 0.05 were used for the identification of statistically highly significant and significant differences, respectively.

3. Results And Discussion

3.1. Soil physical and chemical properties

Some soil physical and chemical properties of surface soils are presented in Table 1 and Table 2. The clay contents of upper 0-20cm soil layers ranged from 16 to 34% and soil texture ranged from sandy clay to loam. Soils on more inclined surface had lower clay and higher sand contents due to surficial soil erosion. The soil pH H_2O in the highlands ranged from 4.48 to 5.62 and pH KCl ranged from 3.56 to 4.73. The pH H_2O in lowland ranged from 5.07 to 7.37. The pH KCl ranged from 3.69 to 6.31 that is an indication of difference in exchange acidity of soils. The large variation in pH in the highland and lowland soils was due leaching of basic cations from the highland and the formation of secondary calcium carbonate in the lowland soils (Abdenna et al. 2018). The soil bulk density ranged from 0.83gcm^{-3} in coffee agroforestry to 1.44gcm^{-3} in mechanized irrigated sugarcane plantation. Within coffee agroforestry the soil bulk density varied within a narrow range (0.83 to 0.88gcm^{-3}). The bulk density in smallholder Eucalyptus agroforestry system ranges from 0.99 to 1.22 g cm^{-3} while in cultivated land use system, the bulk density ranged from 1.08 to 1.3 g cm^{-3}. The bulk density in short fallow land use also varied with very narrow ranges and comparable with the bulk density of cultivated land uses. Grasslands and mature sugarcane plantation had comparable soil bulk density that ranged from 1.15 to 1.32 g cm^{-3}. The higher soil bulk density found sugar plantation could be due to compaction of Vertisols by heavy machineries during land preparation and harvesting of canes.

Table 1
Soil textures and pH in land uses of mixed farming systems of Didessa toposequence

Districts	Sites	Land Uses	Sand	Silt	Clay	Texture class	pH H2O	pH KCl
Guto Gidda	Fayinera	Coffee Agroforest	61	23	16	SC	5.08	3.58
		Eucalyptus agroforest	57	23	20	SL	4.78	3.61
		Cultivated land	53	27	20	SL	5.01	3.85
		Short Fallow	47	27	26	SCL	4.91	3.71
Guto Gidda	Dune kane	Coffee Agroforest	61	23	16	SL	5.06	3.72
		Protected forest	55	23	22	SCL	4.89	3.81
		Eucalyptus agroforest	53	25	22	SCL	4.71	3.59
		Cultivated land	45	29	26	L	4.85	3.69
		Short fallow land	43	31	26	L	5.11	3.83
Diga	Jirata	Eucalyptus agroforest	43	27	30	SCL	5.11	3.83
		Cultivated land	45	25	30	CL	5.05	3.73
		Short fallow	49	35	16	SCL	4.49	3.75
		Coffee agroforest	43	25	32	L	4.48	3.49
Leka Dulacha	Catholic	Cultivated land	47	19	34	CL	5.12	3.93
		Eucalyptus agroforest	37	37	26	SCL	5.01	3.58
		Short Fallow	53	29	18	L	4.79	3.64
Leqa Dulacha	Balho	Grazing land	63	29	8	SL	4.93	3.67
		Forest land	41	33	26	SL	5.16	3.91
		Cultivated land	57	21	22	L	5.62	4.73
Bedele	Sugar plantation	Sugarcane at harvest	57	21	22	SCL	5.07	3.69
		Grassland	55	19	26	SCL	6.06	4.67
		Sugarcane plantation	49	21	30	SCL	6.17	4.76
Jimma Arjo	Sugar plantation	Grassland and forest	41	25	34	L	6.13	4.52

Districts	Sites	Land Uses	Sand	Silt	Clay	Texture class	pH H2O	pH KCl
		Sugarcane at harvest	49	17	34	SCL	7.37	6.31
		Sugarcane plantation	53	17	30	SCL	6.63	4.75

Table 2
Some chemical properties of soils and durations of land use catena being in study transect

Districts	Sites	Land uses	Duration (yr)	C (%)	ρb, gcm-3	C stocks, Mg ha-1
Guto Gidda	Fayinera	Coffee agroforestry	50	7.31	0.83	12.18
		Eucalyptus agroforestry	10	6.41	1.12	14.29
		Cultivated land	40	4.75	1.08	10.27
		Short fallow	3	5.20	1.07	11.13
	Dune Kane	Coffee agroforestry	22	6.33	0.87	11.01
		Protected forest	22	5.92	1.02	12.07
		Eucalyptus agroforestry	15	5.67	1.12	12.71
		Cultivated land		4.39	1.08	9.49
		Short fallow land	3	4.52	1.09	9.83
Diga	Jirata	Eucalyptus agroforestry	15	4.85	1.12	10.81
		Cultivated land	2	4.58	1.12	10.29
		Short fallow	3	4.71	1.08	10.19
		Coffee agroforestry	15	5.14	0.88	9.00
Leka Dulacha	Near Catholic	Cultivated land		4.03	1.26	10.14
		Eucalyptus agroforestry	15	4.24	0.99	8.42
		Short fallow	3	4.61	1.19	10.94
	Bal'o	Grazing land	8	6.16	1.24	15.21
		Forest land	12	8.44	0.74	12.43
		Cultivated land	40	5.69	1.13	12.88
Bedele	Sugar plantation	Sugar plantation at harvest	3	4.46	1.49	13.31
		Grassland		3.39	1.32	8.93
		Sugarcane plantation	3	3.49	1.29	9.04
Jimma Arjo	Sugar plantation	Grassland		4.17	1.15	9.60

Districts	Sites	Land uses	Duration (yr)	C (%)	ρb, gcm-3	C stocks, Mg ha-1
		Sugar plantation at harvest	3	4.18	1.44	12.03
		Sugar plantation	3	2.75	1.25	7.41

The stocks of SOC in the upper 0-20cm soil surface layers from five locations in the mixed farming systems along Didessa toposequence are presented in Table 3. The stock of SOC ranged from 10.54 Mg ha^{-1} at lowland in mechanized irrigated sugarcane production system to 14.045 Mg ha^{-1} at the highland topographic position at Balho site. The observed difference in stock of SOC Balho was significantly different from other sites along Didessa toposequence. The higher SOC stock at Balho was due to cooler weather and longer growth periods.

Table 3
Soil carbon stocks along a transect toposequence in Didessa watershed

Sites	SOC Stocks, Mg ha^{-1}	
	Mean*	Std. Error
Balho	14.045b	1.188
Catholic	10.540a	1.188
Dune Kane	10.760ab	0.84
Fayinera	11.968ab	0.84
sugar plantation	10.967ab	0.84
*Means in column followed by the same small letter are not statistically significant at P = 0.05 using Tukey test		

The stocks of SOC among the seven land use systems along the toposequence of Didessa watershed in mixed farming systems were presented in Table 4. The stocks of SOC ranged from 9.27 Mg ha^{-1} in grassland at lowland topographic position to 13.5 Mg ha^{-1} in Eucalyptus agroforestry system in the highland. The observed differences in stocks of SOC among the land uses were statistically significant. In the highland, stocks of SOC were was lower in annual arable cropping system compared to other land use systems. In the lowland, stocks of SOC were lower in pristine grassland system compared to mechanized irrigated sugarcane production system. The lower the stocks of SOC in the highland topographic position are caused by effect of continuous cultivation that induced mineralization and removal of plant biomass that decreased the inputs of organic residue to the soil system. The higher the stocks of SOC in mechanized irrigated sugarcane plantation were in agreement with the several reports from Brazilian sugarcane production system (Junior et al., 2012; Aline et al., 2013; Ensinas et al., 2015). They reported that cultivation of sugarcane plantations increased the stocks of SOC. Similar ranges of stocks of SOC in sugarcane plantations were also reported by Junior et al. (2012). However, higher stocks of SOC in smallholder irrigation based fruit production system were reported by Aweke et al. (2014). Moreover, they reported comparable SOC stock in rain fed arable cropping land in Northern Ethiopia. They reported stocks of SOC 17.47 Mg ha^{-1} in irrigated fruit production system and 9.8 Mg ha^{-1} in rain fed annual arable cropping system in the upper soil surface of 0-20cm. The reason for the lower SOC stocks in irrigated sugarcane plantations could be due to the humid regional climate which facilitated mineralization of soil organic matter. Moreover, Alfisols and Ultisols of the humid tropical regions had inherently low C storage capacity (Lal, 2004a). Aweke et al. (2014) stated that the climate in North Western Ethiopia was semiarid with mean annual precipitation of 558 mm with Arenosols and Cambisols developed on alluvial deposits and Adigrat sandstone parent materials. The lower stocks of SOC in our study thus could be due to high mineralization as favored by longer period of wet season and the residue quality returned to the soil system.

The mean stocks of SOC in *Eucalyptus* agroforestry system were higher than the stocks of SOC in annual arable cropping system in the highland topographic position. The higher the stocks of SOC under *Eucalyptus* agroforestry could be explained by higher biomass productions, higher C:N ratios, higher soil bulk density, and production and release of allelochemicals. Eucalyptus species produce and release allele-chemicals into rhizosphere which inhibit the growth, development and functioning of microbes (Bezuidenhout and Mark, 2006). Most *Eucalyptus species* also produce large quantities of litter material with high C:N ratios, high lignin and phenolic content (Snowdon et al., 2005; Silva ,2012). Mulugeta et al. (2004) also reported higher C:N ratios of surface soils under *Eucalyptus saligna* as compared to natural forests in Southern Ethiopia. Poultouchidou (2012) also reported increased stocks of SOC in soils from *Eucalyptus species* and Silva (2012) also reported increased soil compaction, bulk density and stocks of SOC as the result of conversion of pasture land into *Eucalyptus* agroforestry in Brazil which are in agreement with our finding.

The mean stocks of SOC from coffee agroforestry system were higher than the nearby stocks of SOC from annual arable cropping system (Table 4). The mean SOC stocks in coffee agroforestry system from our study were lower than stocks of SOC of 21 Mg ha^{-1} from 32 years old coffee agroforestry established on Andosols in Central Rift Valley of Ethiopia (Girma and Woldel-Meskel, 2012). The low stocks of SOC stocks in coffee agroforestry in Didessa toposequence as compared to Central Rift Valley of Ethiopia could be due to difference in the soil types (Luvisols and Alisols) which inherently have lower sequestration capacity of SOC stocks, and the favorable humid tropical climate of Western Ethiopia for mineralization. While, Andosols from Central Rift valley of Ethiopia favor stocks of SOC through decreasing mineralization due to moisture deficiency. Lal (2004a) also reported that Andosols sequester more SOC than Luvisols and Alisols. Moreover, Xavier and Mendo (2011) also reported higher stocks of SOC ranging from 28.5 to 31.4 Mg ha^{-1} in 0-10cm soil layer from Brazilian coffee agroforestry system as compared to our report of stocks of SOC from coffee agroforestry system. The SOC stocks of 0-20cm in this coffee agroforestry system could be even much higher than the SOC stocks in the current study coffee agroforestry system. Higher value of SOC stock of 32.24 Mg ha^{-1} in small holder coffee agroforestry system in Western highlands of Gautama was also reported (Michaela *et al.*, 2012).

The mean stocks of SOC from grazing land use systems were higher as compared to the stocks of SOC from reference soils (arable cropping system) from the highland (Table 4). The mean stocks of SOC range from 14 to 26 Mg ha^{-1} are comparable to stocks of SOC in restrained grazing from Kobo district of Northern Ethiopia (Rimhanen et al., 2016) which has an elevation of 1600 m with hot to warm sub-moist agro-ecology, mean annual temperature ranging from 21 to 25 °C, and mean annual rainfall ranging from 900 to 1000 mm. Moreover, they reported higher stocks of SOC from grazing land use from Sire district of Central Rift Valley of Ethiopia with stocks SOC ranging from 18 to 59 Mg C ha^{-1} in the upper 30 cm surface soil layer. However, these correspond to 12 to 39 Mg ha^{-1} (Rimhanen et al., 2016) which is compareable to our finding from graizing lands. The stocks of SOC from grazing land use system of our study results are lower than the stocks of SOC of Kobo district of North Eastern Ethiopia. Moreover, the stocks of SOC in our results are in the lower margin of SOC stocks reported from Sire district of Central Rift Valley of Ethiopia (Rimhanen et al., 2016). The difference in precipitation, temperature and soil types is the cause of difference in stocks of SOC in both locations. Higher stocks of SOC of magnitude of 39.31 Mg ha^{-1} from open grazing land use from the upper 0-20cm in a semi-arid in Tigray of Northern Ethiopia was also reported by Aweke et al. (2014).

3.2. Soil organic carbon retention

The mean annual SOC retention rates in different land uses of mixed farming systems along Didessa toposequence are presented in Table 4. In reference to annual arable cropping (for midland and highland topographic position) and grassland (for lowland) systems, the annual retention rates ranged from 0.114 to 1.14 Mg ha^{-1} yr^{-1} and there were statistically significant differences among SOC retention rates ($p < 0.05$). The magnitudes of SOC retention rates revealed that retention rate in irrigated sugarcane production system > Eucalyptus agroforestry system > grazing land use system > fallow land use system. Mechanized irrigated sugarcane production at the lowland topographic position resulted in more retention of SOC as compared to the nearby reference pristine grassland system. The positive SOC retention rate in sugarcane production system was due higher sugarcane biomass production. The higher biomass production is due to fertilization of sugarcane planation, supplemental irrigation application during dry season, and incorporation of sugarcane residues into the soil system during harvesting of sugarcanes. Comparable and positive SOC retention rates of 0.67 Mg C ha^{-1} $year^{-1}$ in conventional tillage and 1.63 Mg C ha^{-1} $year^{-1}$ in zero tillage in Brazilian sugarcane production system with our finding in sugarcane production were reported by Aline et al. (2013). They attributed the positive retention rates of SOC to the sugarcane straw maintenance and incorporation to soils during harvesting of the cane. The annual retention rate of SOC in sugarcane plantation in our study was higher than the SOC retention rate of 0.56 Mg ha^{-1} yr^{-1} in smallholder irrigation fruit production system in semiarid Northern Ethiopia (Aweke et al., 2014).

The magnitude of SOC retention rate in Eucalyptus agroforestry system in Didessa toposequence is comparable to the SOC retention of 0.46 Mg C ha^{-1} yr^{-1} in *Faidherbia albida* silvopasture and 0.19 Mg C ha^{-1} yr^{-1} in *Faidherbia* albida agroforestry system in semiarid Northern Ethiopia (Aweke et al., 2014). The retention of SOC in eucalyptus agroforestry system is higher than the SOC retention rates of 1.2 Mg C ha^{-1} yr^{-1} in agroforestry system and 0.7 Mg ha^{-1} yr^{-1} in restrained grazing in Kobo district of Northern Ethiopia and Sire district of Rift valley of Ethiopia (Rihmanen *et al.*, 2016). In reference to annual arable cropping system, the SOC retention rate in grazing land use system was 0.279 Mg C ha^{-1} yr^{-1}. The magnitude of the SOC retention in the grazing land in our result was lower than the SOC retention of 0.73 Mg C ha^{-1} yr^{-1} in open pasture and 0.46 Mg C ha^{-1} yr^{-1} in silvopasture in semiarid Northern Ethiopia (Aweke et al., 2014). Moreover, the SOC retention rate in our finding was lower than SOC retention of 0.7 Mg C ha^{-1} yr^{-1} in restrained grazing in Kobo district of Northern Ethiopia and Sire district of Rift valley of Ethiopia (Rihmanen *et al.*, 2016). The lowest SOC retention rate in our finding is obtained from fallow land use system. The relatively small SOC retention rate in fallow land use system was due to short duration (< 2 years) from which the land could not get enough time for vegetation restoration that produces biomass the returns vegetal materials to the soil system.

Table 4
Soil carbon stocks and retentions in a transect along a toposequence in Didessa watershed

Land Uses	**SOC Stocks, Mg ha^{-1}**		**SOC retentions, Mg ha^{-1} yr^{-1}**	
	Mean*	Std. Error	Mean**	Std. Error
Cropping land (reference-highland)	10.695ab	0.739	-	-
Grass land (reference-lowland)	9.265b	1.045	-	-
Coffee agroforestry	11.595ab	1.045	0.114b	0.073
Fallow land	10.48ab	1.045	0.200b	0.073
Grazing land	13.075a	1.045	0.279b	0.073
Eucalyptus agroforestry	13.5a	1.045	0.308b	0.073
Sugar plantation	12.67ab	1.045	1.135a	0.073
* Means in column followed by the same capital letter are not statistically significant at P = 0.05 using Dunken multiple range test				
**Means in column followed by the same small letter are not statistically significant at P = 0.05 using Tukey test				

4. Conclusion And Recommendation

Traditional coffee agroforestry, eucalyptus agroforestry, grazing land and irrigated sugarcane production system practiced in Western Ethiopia sequester SOC and moderate the loss of SOC stocks in the form of CO_2 into the atmosphere. Traditional coffee agroforestry, Eucalyptus agroforestry, and traditional grazing systems practiced by local communities and the recent introduction of mechanized irrigated sugarcane system into pristine grassland sequester and restore considerable amount of SOC stocks in the upper soil layers. The annual efficiency of SOC stocks sequestration potential followed the order of sugarcane plantation > Eucalyptus agroforestry > grazing land > short fallow land > coffee agroforestry systems. The annual SOC retention rates of these indigenous land use systems practiced along the toposequence and the recent introduced mechanized irrigated sugarcane plantation revealed that the systems are efficient in sequestering C and could be considered as SOC stock restorative land use systems. Thus, mixed land use systems restore SOC, besides sustainably provision of goods and services that have both economic and ecological significances. Adoption of these restorative land use systems could provide economic and social values, sequester SOC stocks, and restore degraded lands in humid tropical Western Ethiopia.

Abbreviations

ACZ = Agro-climatic zone; C = Carbon; CO2 = Carbon dioxide; Gt = Gigatone; LGP = Length of Growing Period; SOC = Soil Organic Carbon; SOM = Soil Organic Matter

Declarations

Authors' contributions

The research work was conducting to aid the interpretation of PhD dissertation of AD author at Haramaya University. AD who is the first author developed the concept note, conducted the research work and prepared the research manuscript for publication, while the co-authors (MY and MM) supported the write up and interpretation of the resulsts. The coauthors reviewed, commented and endorsed the manuscript for publication.

Consent for publication

Not applicable

Competing interests

The authors declare that they have no competing interests.

Availability of data and materials

Not applicable.

Funding

Wollega University and Ministry of Education of FDR Ethiopia funded the study

Ethics approval and consent to participate

The manuscript does not contain data or information from any person or individual apart from field and laboratory investigation. All data and information are generated and synthesized by first author and approved by the co-authors.

Acknowledgement

The authors would like to thank the Ministry of Education and Wollega University of the Federal Democratic Republic of Ethiopia for funding the research project. Wollega University was also acknowledged for provision of logistics and support during field works. Moreover, we extend our gratitude to Arjo-Didessa Sugar Development Enterprise for allowing us to collect soil samples and provision of vehicle and field guidance during field work, and Nekemte Soil Research Center for provision of support during soil laboratory analysis.

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Figures

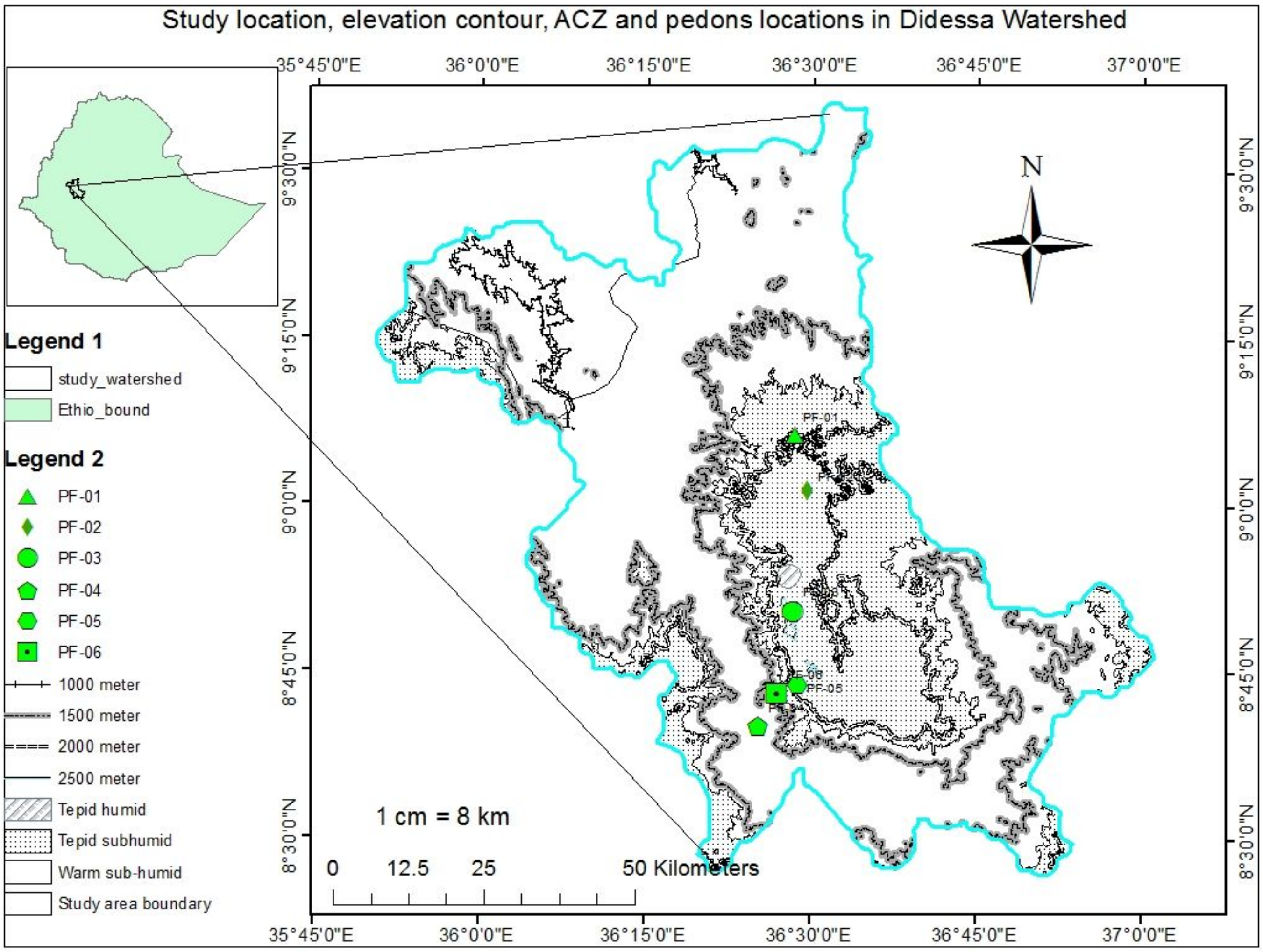
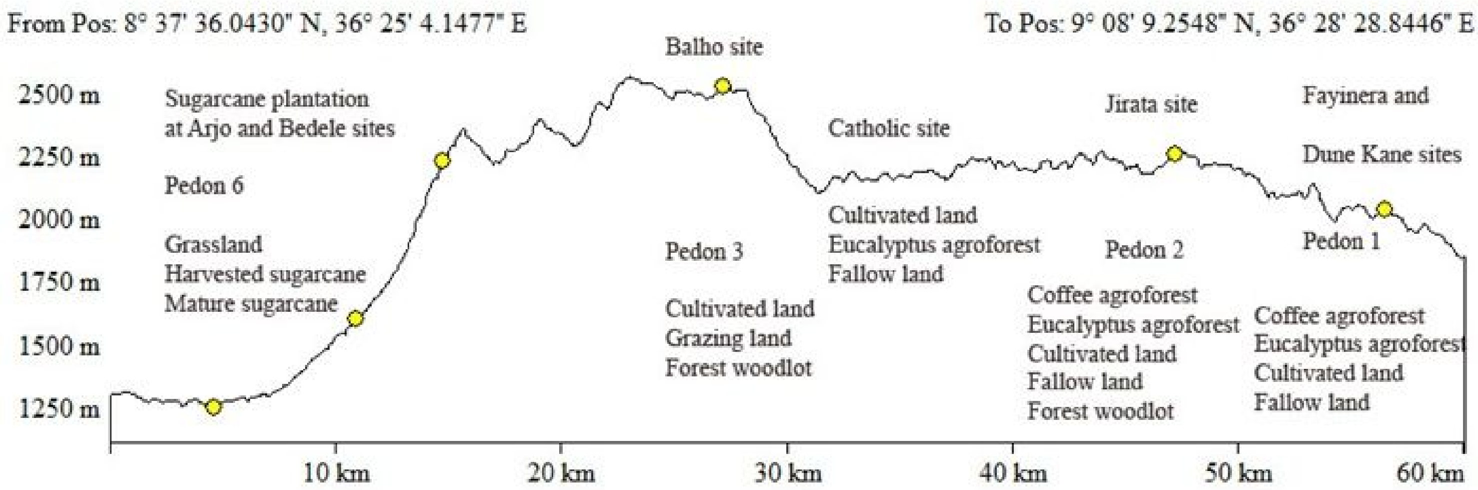


Figure 1

Location of Didessa watershed, pedons, elevation contour intervals and Agro-ecology of the Didessa toposequence)



Parameters	Study sites and characteristics along toposequence					
	Sugar plantation	*Balho*	*Catholic*	*Jirata*	*Dune Kane*	*Fayinera*
Moisture regimes	Udic	Udic	Udic	Udic	Udic	Udic
LGP	180-240	240-300	180-240	180-240	180-240	180-240
Temperature, °C	20-27	15-20	15-20	15-20	15-20	15-20
Temperature regime	Hyperthermic	Thermic	Thermic	Thermic	Thermic	Thermic
AEZ	Warm subhumid	Tepid subhumid	Tepid subhumid	Tepid subhumid	Tepid subhumid	Tepid subhumid
Vegetation	Grassland	Woodland	Woodland	Woodland	Woodland	Woodland
Topography	Lowland	Highland	Highland	Highland		Mid to highland
Soil classes	Pedon 6: Vertisols	Pedon 3: Alfisols/Luvisols	Pedon 2: Alfisols/Luvisols	Pedon 2: Alfisols/Luvisols	Pedon 1: Ultisols/Alisols	Pedon 1: Ultisols/Alisols

Figure 2

Topographic map of transect of Didessa toposequence, locations of land use systems and characteristics