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Changes in Soil Carbon Storage Potential Following Conversion from Afromontane Forest to Plantations and Cultivated Land in Komto Watershed, Western Ethiopia

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Abstract
Forest ecosystem takes the lion share of soil C store compared to other land use systems. The study was aimed to examine the influence of land use change on soil C sequestration potential under varying soil layers. Heterogeneity in soil C storage was observed across land use types and along soil layers due to disparity in spatial distribution of soil C densities arising from the influences of variations in land cover types and management practices. The average soil C stock varied from 14.16 Mg ha^{-1} for the cultivated land to 35.24 Mg ha^{-1} for the natural forest, and 21.48 Mg ha^{-1} for of plantation forest to a depth of 60 cm. The average soil C loss rate after 25 years period of conversion from Afromontane forest to plantations and cultivated land were estimated to be 0.55 and 0.84 Mg ha^{-1} yr^{-1}, respectively. Encroachment of native forests coupled with unwise agricultural management practices contributed to SOC depletion and subsequent CO_2 emission. Integrated land use systems that combine trees and agricultural crops can increase C sequestration potential while giving multiple products for the land users.
Keywords: Land use change, Afromontane forest, soil carbon storage, soil carbon loss, climate change

1. Introduction

Soil is the largest sink and store of global terrestrial C and an important part of the biosphere in sequestering C (Lal, 2002). It has a higher potential to store C compared to vegetation and atmosphere (Bellamy *et al*., 2005). The global soil C pool is 2300 Pg, which is 3 times the size of atmospheric C (770 Pg) and 3.8 times the size of biotic pools (610 Pg) (Lal, 2001). However, the idea of SOC sequestration did not get adequate recognition due to inadequate understanding of the role of soil in global C cycle and climate change. So far, mitigation of climate change was linked widely with reducing CO_2 emission from industries giving little emphasis to the vast C pool in the soil system. Nowadays, with an increasing concern about anthropogenic global warming mostly due to CO_2 emissions, the storage and dynamics of soil organic carbon (SOC) under different land uses has received even more attention due to the significant potential of soils to act as a sink or source of atmospheric CO_2 (Lal, 2004).

The SOC sequestration is mainly influenced by land use dynamics, management practices, soil depth, land security and other soil variables like bulk density. Land use dynamics governs the fate of SOC storage potential on global basis thereby determining the state of climate change. Changes in land use result in significant changes of net primary production, species composition, stand age, rooting distribution and quantity of litter (Jackson *et al*., 2000), and these factors affect SOC storage dynamics, either mitigating or aggravating climate change. Forest ecosystems store more than 80% of all terrestrial aboveground C and more than 70% of all soil C (Batjes, 1996). Forests can be both sources of atmospheric CO_2, when disturbed by natural or human causes, and sinks, when vegetation and soil C accumulate after disturbance. An area of native forest in Ethiopia that had 40% land cover during the beginning of 20th century according to Pohjonen and Pukkala (1990) was estimated to be 2.2% in 2002 (Berry, 2003) and not better at present. Population growth induced gradual encroachment of native forests by cultivated land has been occurring everywhere. Expansion of cultivated land at the expense of natural forest not only reduced diversity of plant species but also diminished the organic carbon (OC) storage potential of Ethiopian soils exacerbating climate change. A review conducted by Girmay *et al.* (2008) concluded that topsoil C stock decline upon land use conversion from natural forest to crop land, to open grazing, and to plantation. Another study in Ethiopia showed that OC and total N of the top 0–10 cm soil layer declined significantly and exponentially with increasing years under cultivation following deforestation (Lemenih *et al*., 2005). Generally, land use change that involves deforestation and conversion into cultivated land is the principal source of CO_2 in Ethiopia. The study was aimed to assess C storage potential of soils after land use conversion from Afromontane forest to plantations and cultivated land at varying depths in Komto watershed located in humid tropics of western Ethiopia. Gain or loss in SOC storage due to land use change was used to depict the quantity of CO_2e sequestered in or emitted from the system.

2. Methodology

2.1. General ecological description

The study was conducted in Komto watershed which is situated between 9.084768 and 9.111881N and 36.609009 and 36.630832E in humid tropics of western Ethiopia, with an elevation ranging from 2139−2500 m asl. The mean annual rainfall is 2140 mm while mean annual temperature is 18.7 ^{O}C. Before 1990s, the watershed was once entirely covered with intact natural forest; namely Komto forest. The forest was classified under Afromontane moist evergreen forest comprised of tree species such as *Ilex mitis, Ficus sur*, and *Syzigum guinesis*, *Croton macrostachyus, Pouteriaadolfi-friederici, afromontanum, Apodytes dimidiata, Prunus africana, Albizia gummifera* and shrubs including *Maesa lanceolata* and *Teclea nobilis.* Komto forest was proposed as a forest reserve area in 1976 and demarcated as a state forest in 1990 as one of the 58 National Forest Priority Areas (NFPA) in Ethiopia (EFAP, 1994 as cited in Fekadu *et al*., 2012). Nevertheless, the forest and its wildlife were severely threatened due to deforestation for agricultural expansion, timber and charcoal production. Though efforts made so far to reforest degraded areas with *Cupressus lusitanica* and *Eucalyptus globulus* plantations have shown good insight to forest restoration, significant portion of the watershed is yet covered with cultivated land consisting of cereals such as *Teff* (*Eragrostis tef*), millet (*Panicum miliaceum*), wheat (*Triticum aestivum*), sorghum (*Sorghum bicolor*), maize (*Zea mays*), barley (*Hordeum vulgare*) and legumes such as horse bean (V*icia faba*) and ground nut (*Arachis hypogaea*). Nitisol is the most dominant soil type in the study area.

2.2. Watershed delineation and LULC classification

The watershed was delineated by using Arc GIS 10.1 software. Supervised LULC classification of a cloud free Landsat TM image was carried out using ERDAS Image 11 software. Geometric correction and image enhancement were conducted using ERDAS 9.2. Accordingly, four land cover types were identified in the watershed (Fig. 1). Categorizing the four land cover types into present use of the land, three main land use types were defined in the watershed (viz. natural or afromontane forest, plantation forest and cultivated land). Komto watershed has a total area of 361.92 hectares (ha); out of which natural forest, plantation forest and cultivated land accounts for 221.24, 9.78, and 130.90 ha of land, respectively.

2.3. Soil sampling, preparation and analysis

Firstly, each of the three land uses was stratified into two homogeneous sampling units or strata. Hereafter, six composite samples each formed from 8 subsamples were prepared for every single stratum using systematic sampling technique. This implies that twelve soil samples were collected for individual land uses and each soil layers (0–20, 20–40 and 40–60 cm). To account for the volume of coarse fragments in the sample during SOC estimation, freshly collected soil samples were initially air dried, and then the sample mass was recorded. Samples were then passed through a 2 mm sieve and the mass of material retained on the sieve (> 2 mm) was recorded and removed. In this case, both the > and < 2 mm materials were air dried after sieving prior to recording their respective masses. Following sample preparation, bulk density was determined by core method (Blake and Hartge, 1986). The soil OC was determined by Walkley–Black oxidation method (Walkley and Black, 1934).

2.4. Estimation of soil organic carbon storage

The SOC content of soil per hectare was estimated using Jonathan *et al.* (2011) equation:

$$SOC_{di} = OC * \rho b * d * GCF * CFU * (1 - Prt) \quad (1)$$

Where SOC_{di} is the amount of OC stored per unit hectare of land (Mg ha^{-1}) to specified soil depth (di) i.e. 0–20 cm, 20–40 cm 40–60 cm, OC is organic C concentration (mg $(g < 2\ mm)^{-1}$) from soil analysis result for each soil layers, ρ_b is bulk density of the soil (g cm^{-3}), 'd' is soil thickness or depth (cm), GCF is gravel correction factor (g < 2 mm) (g^{-1} soil), CFU is correction factor for units (10^8 cm^2 ha^{-1} * 10^{-9} Mg mg^{-1}) and 'Prt' is the proportion of the land area within the sampling unit allocated to rocks and/or trees (i.e. correction for rocks and trees). The gravel correction factor (GCF) is used to incorporate OC in the coarse soil fragments not passing 2 mm mesh size sieve that was not accounted during chemical analysis of OC in the laboratory.

Based on the OC content of each soil layer per hectare (Mg C ha^{-1}), the amount of SOC stored in soils per specific area of land was estimated as follows:

$$SOC_s = \sum (SOC_{di} * A_i) \quad (2)$$

where SOC_s is the OC stored in soils per specified area (Mg), SOC_{di} is Mg ha^{-1} of OC stored in the i^{th} soil depth (i.e. 0–20, 20–40 and 40–60 cm), and A_i is area of the land (ha).

2.5. Statistical analysis

Descriptive statistics were used to illustrate mean and standard deviation of the measured parameters. Mean separation was carried out using least significant difference (LSD) at $P < 0.05$.

3. Results and Discussion

3.1. The SOC concentration across land uses and soil depths

Variations in SOC concentration across land uses and with soil depth were observed in the watershed (Table 1). Compared with the natural forest, SOC concentration in the cultivated land was approximately 60.2% less for the upper 0–20 cm depth. Cereal cropping, especially *Teff* was considered an extreme case in relation to SOC depletion. Exhaustive grazing and traditional crop residue burning after harvest were the main causes for extremely low SOC content of cultivated lands. Soils under plantation forests specifically *Eucalyptus globulus* and *Cupressus lusitanica* were exposed to prolonged human interference which had imposed unfavorable condition for SOC accumulation. Generally, the SOC content of any land use was governed by the level of biomass, species diversity, quantity of litter fall and management condition (Mulugeta *et al*., 2005). The Afromontane forest harbors many plant species and better rooting distribution and; as a result showed relatively higher SOC concentration than other land uses at respective depth classes. The data presented in (Table 1) shows the mean SOC concentration was relatively highest for Afromontane forest in the upper 0–20 cm soil layer and lowest for cultivated land in the bottom 40–60 cm layer.

The mean SOC content consistently decreased with depth for all land uses where rate of decrement from 0–20 to 20–40 cm was comparatively highest for soils of the plantation forest (25%) followed by cultivated land (17%) and Afromontane forest (16%). The rate of decrement was 41%, 33% and 24% for each move from 20–40 cm to the underlying 40–60 cm layer in soils of the cultivated land, plantation forest and Afromontane forest, respectively. It could be due to decrease in abundance of plant litter and root distribution with depth. Topsoil stored more OC and plays significant role in governing C cycles than subsoil. Conversion of Afromontane forest to other land uses greatly affected the OC concentration in the topsoil. In this regard, change from Afromontane forest to plantations reduced SOC concentration by 2.84 mg g^{-1}, 2.68 mg g^{-1} and 2.27 mg g^{-1} whereas change of Afromontane forest to cultivated land depleted SOC concentration by 3.84 mg g^{-1}, 3.24 mg g^{-1} and 2.81 mg g^{-1} for 0–20 cm, 20–40 cm and 40–60 cm depths, respectively. The OC loss was relatively higher for cultivated land than plantation forest at respective depth classes. The result showed that bulk density was less variable than SOC (Table 1). The mean bulk density of Afromontane forest soil was low compared with other land uses which could be attributed its higher organic matter content.

3.2. Impact of land use dynamics and soil depth on SOC stock and CO_2e flux

Soil C stocks were highly heterogeneous across land uses due to disparity in spatial distribution of soil C densities arising from the influences of variations in land cover types, soil depth and management practices. The mean SOC stock of the natural forest was significantly different from the other land uses for respective soil layers at $p < 0.05$ (Table 2). Nevertheless, the mean SOC stock of the cultivated land was significantly different from plantation forest at 40–60 cm soil layer alone. Likewise, the mean SOC stocks of the three depth classes within each land use were significantly different at $p < 0.05$. Compared with other land uses, production of larger quantities of biomass makes the Afromontane forest to be more efficient in promoting SOC sequestration. As a result, the mean SOC storage decreased in order of Afromontane forest > plantation forest > cultivated land for respective soil layers (Table 2). The impact of land use change on SOC storage can be depicted when mean SOC stock was reduced from 11.45 Mg ha^{-1} for Afromontane forest to 4.96 Mg ha^{-1} for cultivated land. Hence, conversion from Afromontane forest to cultivated land over the past 25 years had caused for loss of about 6.49 Mg ha^{-1} SOC which was comparable to the report of Xiaorong *et al*. (2014). Study by Mulugeta *et al*. (2005) revealed depletion of 23.50 Mg ha^{-1} SOC within 33 years of continuous cultivation after deforestation of tropical forest in highlands of Ethiopia. Conversion of natural vegetation to agricultural land results in the mineralization of SOC, thus reducing SOC stocks and increasing atmospheric CO_2 concentrations as indicated by Don *et al*. (2011). Besides, plantation forests had stored lower SOC than Afromontane forest owing to disturbances by anthropogenic factors. Gautam and Mandal (2016) pointed that due to forest disturbance, C sequestration capacity reduced which reflects the higher C emissions or losses.

In all land uses, more OC was stored in the topsoil because of the logarithmic nature of C with depth. Comparable to the finding of Nantumbwe (2005), the study result indicated that majority of C was found above 40 cm soil layer for all land uses and more than 40% in the top 20 cm for cultivated land and plantation forest. Most probably due to better root distribution in Afromontane forest soils, SOC distribution with depth was nearly normal and hence, the top 20 cm layer contained about 37% of the total SOC in the 60 cm depth. Conversion from Afromontane to plantation forest had apparently lost 4.16 Mg ha^{-1}, 4.93 Mg ha^{-1} and 4.96 Mg ha^{-1} SOC while change from Afromontane forest to cultivated land had lost 6.48 Mg ha^{-1}, 6.37 Mg ha^{-1} and 6.61 Mg ha^{-1} SOC for 0–20 cm, 20–40 cm and 40–60 cm depths, respectively (Table 2). This was attributed to low OC input at subsoil and the modifying effect of bulk density. Thomas *et al*. (2015) reported that converting tropical forest to plantations reduced SOC by 12.70 and 10.10 Mg ha^{-1} in the 0–10 cm and 0–30 cm layers, respectively, in Harapan region of Jambi province in Indonesia.

When the total SOC stock (Gg) (Table 3) was estimated on per hectare basis, the average SOC storage capacity varied from 35.24 Mg ha^{-1} in soils of the Afromontane forest to 14.16 Mg ha^{-1} in soils of the cultivated land, in between was 21.48 Mg ha^{-1} in soils of plantation forest (Fig. 2). The average SOC stock of Afromontane forest in the current study falls in the range between the average carbon stocks of 34.56 and 44.93 Mg ha^{-1} (0–60 cm) reported by de Blecourt *et al*. (2013). The SOC stock in cultivated land of the present study is lower than the finding of Solomon *et al.* (2002) who reported SOC stock of 36.80 Mg ha^{-1} for cultivated soils after conversion of humid tropical forest to maize (*Zea mays*) cultivation in southeastern Ethiopia and a little bit higher than 11 Mg ha^{-1} reported by Vagen *et al*. (2005). The average CO_2e sink was 129.32 Mg ha^{-1}, 78.82 Mg ha^{-1} and 51.97 Mg ha^{-1} in soils of the Afromontane forest, plantation forest and cultivated land, respectively. The result was in accordance with the conclusion of Wakene and Heluf (2004) who reported that intensive and continuous cultivation forced oxidation of OC, and thus resulted in reduction of SOC. Furthermore, Bonell (2011) specified that variation of SOC across land uses could be attributed to the number of trees, tree species, size of trees and other disturbances. Our study indicated that after 25 years of conversion from Afromontane to plantation forest (*Eucalyptus globules and Cupressus lusitanica*) and cultivated land, about 39.1% (13.76 Mg ha^{-1}) and 59.8% (21.08 Mg ha^{-1}) SOC was lost from depth of 60 cm, respectively, depicting highest loss from the cultivated land. Study conducted in the southwestern highlands of Ethiopia showed that clearing of natural forest followed by cultivation of crops resulted in a loss of 43% (75.4 Mg ha^{-1}) SOC after nearly 75 years within the 0–50 cm soil layer (Lemma *et al*., 2006). The average rate of soil C loss due to conversion from Afromontane forest to plantations and cultivated land in the present study were estimated to be 0.55 and 0.84 Mg ha^{-1} yr^{-1}, respectively. Mulugeta *et al.* (2005) reported average soil C loss rate of 1.58 Mg ha^{-1} yr^{-1} within 33 years of continuous cultivation following deforestation in highlands of Ethiopia. Congruent to the present study result, the finding of Thomas *et al*. (2015) indicated average rate of 0.46 Mg ha^{-1} yr^{-1} C loss due to conversion of tropical forest to plantations in Harapan region, Jambi province of Indonesia.

The result presented in Table 4 shows that the results reported by some authors were close to the results of the present study. Mugagga *et al*. (2015) suggested that the largest land use conversion in East Africa over the last fifty years has been the expansion of agriculture. After 25 years of shift from Afromontane forest to cultivated land, nearly 77.35 Mg ha^{-1} of CO_2e had emitted from the soil to a depth of 60 cm. That means, a total of 10.13 Gg of CO_2e was emitted when 130.9 hectares of land was changed from native vegetation to cultivated land. On annual basis, rate of CO_2 emission from soil owing to such conversion was averagely 3.09 Mg ha^{-1} yr^{-1}. However, conversion from Afromontane to plantation forest released nearly 50.50 Mg ha^{-1} CO_2e from the soil to a depth of 60 cm which accounts to emission of 0.50 Gg of CO_2e from 9.78 hectares of land. On annual basis, this averagely released 2.02 Mg ha^{-1} yr^{-1} CO_2. This implies that soils of plantation forest had saved about 1.07 Mg ha^{-1} yr^{-1} of CO_2e that would have been emitted if Afromontane forest conversion was all into the cultivated land. Despite its lower SOC storage potential compared with forest land, the importance of cultivated land in storing SOC should not be underestimated as the vast areas of arable land contain significant quantities of SOC on global basis. It is possible to maintain SOC levels of cultivated lands fairly close to that under forest through improved management systems including fallowing and conservation tillage.

3.3. Major causes of low SOC in cultivated lands of Ethiopia

The SOC in most cultivated lands of Ethiopia in general and the study site in particular is very low and usually less than 3% resulting in a very low productivity. This is mainly due to continuous cultivation, complete removal and burning of crop residues, soil erosion and land right issues. Continuous cultivation or lack of fallow period reduces the regeneration potential of the soil and deteriorates SOC. Population growth driven limitation of land puts the existing farmland on relentless cultivation giving little chance for the land to rest and accumulate SOC. Kotto-Same *et al.* (1997) reported re-accumulation rates in recovering fallows to be approximately 9.4 Mg ha^{-1} yr^{-1} in a 6 years fallow period. Complete removal and annual burning of crop residues are other explicit causes for low SOC in the cultivated lands of Ethiopia. After harvesting the required products, crop residues are exhaustively collected for homestead energy use and livestock feed, leaving a few portion of residues left in the field to be burned annually thinking as if it enhances soil fertility. Unlike continuous tillage, zero tillage and stubble retention increased SOC by up to 8% according to the report of Robertson *et al*. (2015). Esteban and Robert (2000) findings pointed out that the low SOC storage in soils of the cultivated land resulted from reduced C input (due to annual harvest, removal of crop residue, low litter, etc), high OM decomposition (due to frequent tillage) and increased soil erosion (due to low surface cover). Prolonged cultivation coupled with frequent burning of crop residues have been accelerated the rapid turnover rates of organic materials (Yacob, 2015). Kiya (2015) reported that annual soil burning during winter season in central Ethiopia decreased SOC averagely by 78%. Management systems that leave the soil devoid of crop residues accelerate soil erosion leading to loss of all components of SOC including the one in the aggregates. Although estimates of soil C loss through soil erosion by water in sub-saharan Africa are few, other studies from west, east and southern Africa estimated losses of C through soil erosion from 0.2 to 0.7 Mg ha^{-1} yr^{-1} (Gachane *et al*., 1997; Moyo, 1998). Besides, land insecurity creates lack of confidence and trust in farmers and acts as push factor to sustainable land management practices.

4. Conclusions

The study result demonstrated that land use dynamics greatly governs the SOC sequestration potential. The good understory and litter biomass associated with Afromontane forest makes it to contain better SOC concentration than all other land uses at respective soil layers. The SOC content was consistently decreased with depth under each land use types due to decrease in abundance of primary and secondary sources of SOC. The average SOC storage capacity of the Afromontane forest soil was about 2 times higher than soils of the cultivated land and about 1.5 times higher than soils of the plantations. Conversion from Afromontane forest to other land uses over the past two and half decades had led to emission of CO_2 from the system as manifested by loss of SOC. Annual burning and complete removal of crop residues and continuous tillage are the major causes for low SOC in cultivated soils. In croplands, the critical issue in increasing SOC sequestration is the addition of crop residues, avoiding residue burning, manuring, and the reduction in soil disturbance through conservation tillage or no-till systems. Therefore, improved management practices like conservation tillage or zero-tillage, fallowing, residue incorporation, tree-crop agroforestry combined with addition of animal and farmyard manures can improve the SOC stock of the cultivated soil and helps to mitigate climate change. Moreover, models portraying SOC balance of mono-cropping systems need to be developed to clearly deal with the impact of traditional cultivation systems on land degradation and climate change.

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Table 1. Mean and standard deviation (SD) for soil bulk density and OC concentration under different land uses and depth classes

Depth (cm)	**Land use type**	**Mean ± SD**	
		BD (g cm^{-3})	SOC (mg g^{-1})
0–20	Cultivated land	1.24 ± 0.04	2.54 + 0.54
	Plantation forest	1.24 ± 0.02	3.54 + 0.69
	Afromontane forest	1.01 ± 0.06	6.38 + 1.37
20–40	Cultivated land	1.27 ± 0.04	2.11 + 0.14
	Plantation forest	1.31 ± 0.05	2.67 + 0.20
	Afromontane forest	1.11 ± 0.04	5.35 + 1.08
40–60	Cultivated land	1.31 ± 0.01	1.25 + 0.17
	Plantation forest	1.44 ± 0.04	1.79 + 0.62
	Afromontane forest	1.24 ± 0.06	4.06 + 1.13

Table 2. Mean SOC storage potential of different land uses at varying depths

Land use type	**SOC storage (Mg ha^{-1})**		
	0–20 cm	20–40 cm	40–60 cm
Cultivated land	O6.26^{a} ± 1.15	♀5.35^{a} ± 0.47	Ϙ3.28^{a} ± 0.52
Plantation forest	O8.58^{ab} ± 1.46	♀6.79^{ab} ± 0.33	Ϙ4.93^{b} ± 1.58
Afromontane forest	O12.74^{c} ±1.95	♀11.72^{c} ±1.91	Ϙ9.89^{c} ± 2.18

Means within same column followed by different letters are significantly different at ($p < 0.05$)
Means within rows preceded by different symbols are significantly different at ($p < 0.05$)

Table 3. The SOC and CO_2e storage potential of different land uses to a depth of 60 cm

Land use type	Land area (ha)	SOC storage per land use (Gg)	Equiv. CO_2 sequestered per land use (Gg)
Cultivated land	130.90	1.85	6.80
Plantation forest	9.78	0.21	0.77
Afromontane forest	221.24	7.80	28.62

Key: 1Gg = 1000 Mg

Table 4. Percent loss of SOC after 20 to 40 years period of land use change as compared to other studies

Percent soil carbon lost due to conversion from Afromontane forest to plantations during the previous studies as compared to 39.1% loss under the present study		Percent soil carbon lost due to conversion from Afromontane forest to cultivated land during the previous studies as compared to 59.8% loss under the present study	
35.3%	Thomas *et al.* (2015)	60.0 %	Biyensa *et al.* (2016)
13.0%	Guo and Gifford (2002)	41.0 %	Wei *et al.* (2014)
40.0%	Ferre *et al.* (2014)	70.0%	Anikwe (2010)
32.0%	Poeplau *et al.* (2011)	22.0%	Murty *et al.* (2002)
19.3%	de Blecourt *et al.* (2013)	42.0%	Guo and Gifford (2002)
21.0%	Araujo *et al.* (2004)	30.0%	Davidson and Ackerman (1993)
50.0%	van Straaten *et al.* (2015)	59.0%	Solomon *et al.* (2002)

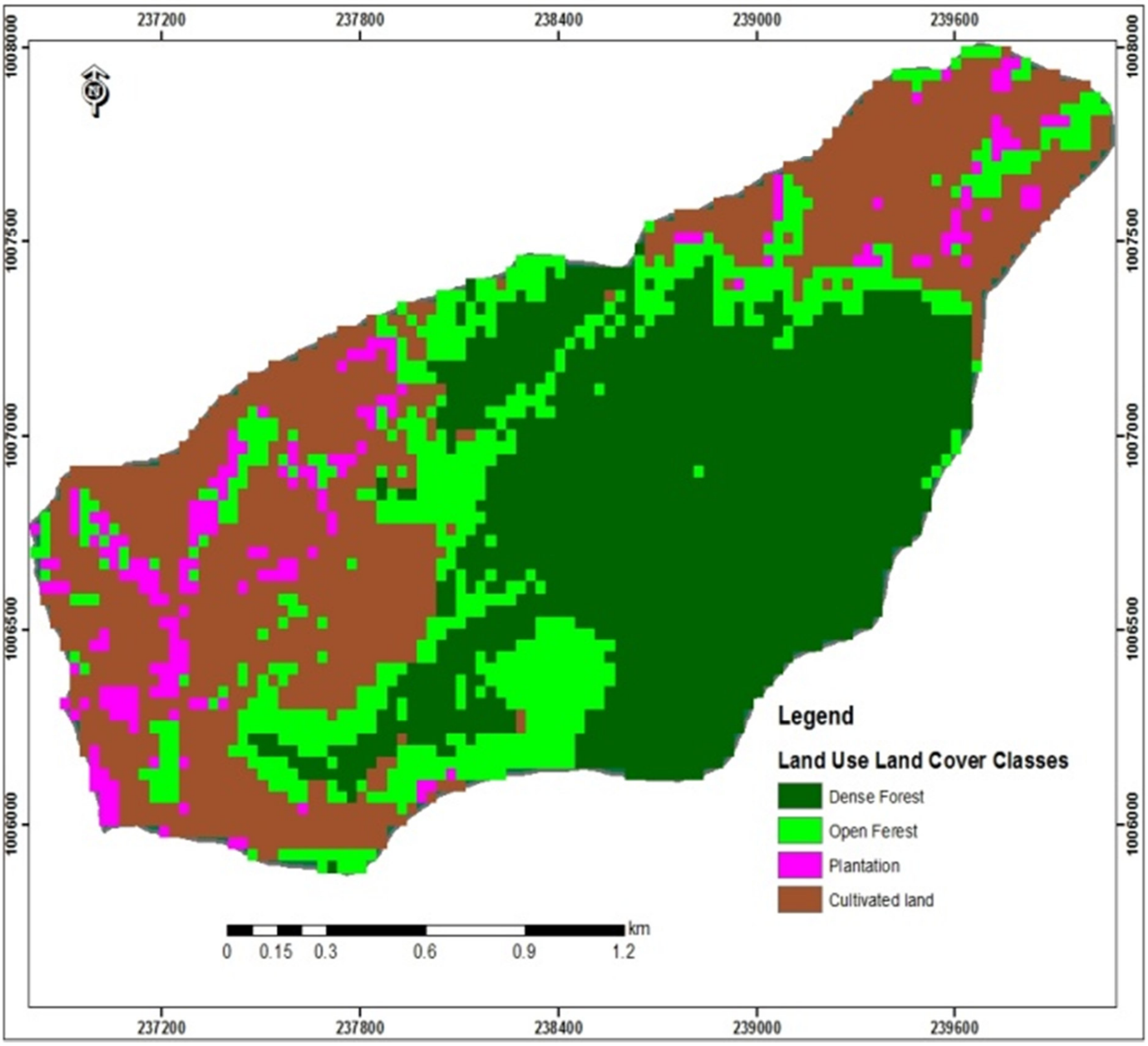

Fig. 1 Land use/land cover (LULC) map of the study area

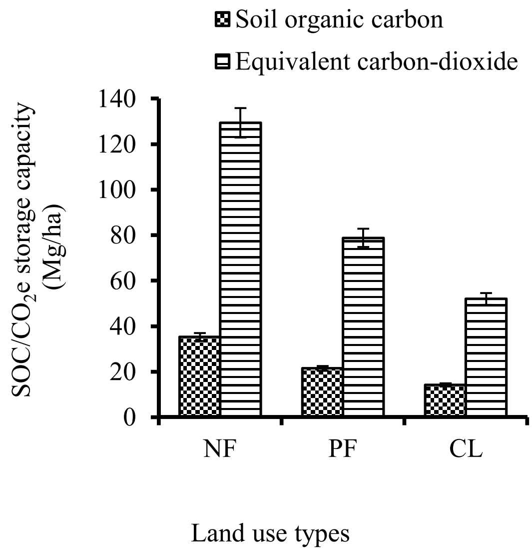

Fig. 2 Average OC and CO_2e storage potential of Afromontane or natural forest (NF), plantation forest (PF) and cultivated land (CL) soils to a depth of 60 cm