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Soil organic carbon losses following conversion of natural forests into agriculture: Insights from Eritrea

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Abstract: Conversion of natural forests into conventional agricultural lands may lead to significant soil organic carbon losses. Soil organic carbon stock assessment for such land use changes is very crucial for appropriate land use management, soil fertility improvement, ecosystem restoration and climate-change mitigation measures. However, information on the status of soil organic carbon stocks for such land use types is limited in Eritrea and in the Horn of Africa. Thus, the study aimed to assess soil organic carbon stocks for natural forests, continuous cropping, shifting cultivation, and grazing land use types. Fifty-one surface soil samples were collected from these four types of land use around Adi Hakin, Laelay Gash, Eritrea, and analysed. One-way analysis of variance (ANOVA) test results showed that land use changes had highly significant effect on soil organic carbon stock ($p < 0.001$). The natural forest and continuous cropping land use types recorded the highest (51.69 $Mg \cdot ha^{-1}$) and lowest (21.23 $Mg \cdot ha^{-1}$) mean soil organic carbon stocks, respectively. Grazing and shifting cultivation had 22.74 and 23.57 $Mg \cdot ha^{-1}$ soil organic carbon stocks, respectively. Conversion of natural forest into continuous cropping, grazing, and shifting cultivation in the study area in the long run resulted in losing 58.93, 56.00 and 54.40% of soil organic carbon stocks, and emitting 111.79, 106.25 and 103.20 $Mg \cdot CO_2 \cdot ha^{-1}$, respectively, to the atmosphere. Thus, the study concludes that conventional agriculture contributes to the atmospheric CO_2 concentration through soil carbon emission. On the contrary, conservation of natural forests is crucial for soil carbon sequestration and atmospheric CO_2 mitigation endeavors.

Keywords: land uses; soil organic carbon; natural forest; shifting cultivation; grazing.

Потери органического углерода из почвы в результате перевода естественных лесов в сельскохозяйственные земли: Опыт Эритреи

Резюме: Преобразование естественных лесов в сельскохозяйственные угодья может привести к значительным потерям органического углерода в почве. Оценка запасов почвенного органического углерода при таких изменениях в землепользовании важна для рационального использования земель, повышения плодородия почв, восстановления экосистем и разработки мер по смягчению последствий изменения климата. Однако информация о состоянии запасов почвенного органического углерода при таких видах землепользования в Эритрее и в регионе в целом весьма ограничена. Таким образом, целью исследования была оценка запасов почвенного органического углерода в естественных лесах, при непрерывном и переложном земледелии и на пастбищах. Пятьдесят один образец из верхнего слоя почвы был отобран из четырех вариантов землепользования в окрестностях Ади Хакин, Лаэлай Гаш, Эритрея, и проанализирован. Результаты однофакторного дисперсионного анализа (ANOVA) показали, что изменения в землепользовании сильно влияют на запасы почвенного органического углерода ($p < 0.001$). В почвах под естественным лесом и при непрерывном земледелии зарегистрированы максимальные (51.69 Мг·га$^{-1}$) и минимальные (21.23 Мг·га$^{-1}$) значения средних запасов почвенного органического углерода соответственно. На пастбищах и при переложном земледелии запасы почвенного органического углерода составили 22.74 и 23.57 Мг·га$^{-1}$ соответственно. Преобразование естественных лесов в участки непрерывного земледелия, в пастбища и в угодья переложного земледелия на исследуемой территории с течением времени привело к потере 59, 56 и 54% запасов почвенного органического углерода и выбросу в атмосферу 112, 106 и 103 Мг CO_2·га$^{-1}$ соответственно. При традиционном сельском хозяйстве в атмосферу выбрасывается больше углерода, чем при остальных видах землепользования. Напротив, сохранение естественных лесов имеет решающее значение для секвестрации углерода и борьбы с выбросами CO_2 в атмосферу.

Ключевые слова: землепользование; почвенный органический углерод; естественный лес; переложное земледелие; выпас скота.

INTRODUCTION

Natural forest ecosystems are determinants of environmental sustainability (Ibrahim et al., 2022). Globally, forest soils store more than 40% of the total organic carbon (C) in the terrestrial ecosystems (IPCC, 2007; Wei et al., 2014). However, forests are threatened by conversion for agricultural purposes, especially in less-developed regions (Ibrahim et al., 2022). For example, in Africa, agricultural expansion is solely responsible for 70–80% of forest loss (Olorunfemi et al., 2021). Conversion of natural forests into agriculture and grazing lands reduces SOC stocks and consecutively increases atmospheric CO_2 concentrations (Pringle et al., 2014; Schulz et al., 2016; Tolimir et al., 2020), and such emissions were reported by Don et al., (2011) as 25–30% of the total global greenhouse gas emissions. A review by Wei et al., (2014) shows that the SOC stock reductions due to conversion of forests into agricultural lands in temperate, tropical and boreal regions amounted to 52, 41 and 31%, respectively. Studies reveal significantly lower SOC stocks in continuous cropping, grazing, shifting cultivation, and managed plantation lands compared to lands covered by natural forests (Chen et al., 2016; Choudhary et al., 2016; Nuguse et al., 2019; Beillouin et al., 2023). Thus, it is high time for agricultural intensification to increase land productivity instead of agricultural expansions (Adolph et al., 2023).

Likewise, in Eritrea, rapid population growth, along with very low agricultural productivity, has led to the rapid expansion of agricultural lands (Berhe, 2018), and vast areas of natural forests have been converted into agricultural and grazing lands since the 1970s. Ghebrezgabher et al. (2016) reported an annual forest cover loss of 62 km^2 from 1972 to 2014. Measho et al. (2019) also revealed that 57.1% of the country was in a significantly decreasing annual normalised difference vegetation index (NDVI) trend from 2000 to 2017. Land degradation is widespread in the country (Tesfay et al., 2020) due to non-sustainable agriculture, overgrazing, overexploitation of forests, urbanisation and resettlement, and some natural causes (Berhe, 2018).

Conventional cropping and grazing are the dominant land use types in Eritrea. Agriculture employs more than 75% of the population (Tesfay et al., 2024) though the crop productivity is very low – below 0.7 $t \cdot ha^{-1}$ (Tesfay et al., 2018). Food is provided by subsistence farming and grown under erratic rainfall and recurrent drought spells. Albeit the efforts of the government to stop agricultural land expansions and increase productivity per unit of land, the agricultural sector could not be promoted, and agricultural expansion, though reduced, is still continuing. For example shifting cultivation is still practiced to some extent in some parts of the country, especially in the southwestern parts. Livestock rearing is very common by sedentary farmers/agropastoralists, and pastoralists. Grazing practices are traditional and uncontrolled where, in most cases, livestock freely and continuously overgraze communal lands (Tesfay et al., 2024). As Eritrea is found in the Sahel region, vegetation is scarce, especially in the dry seasons, for about 9 months. Nomadic livestock herders always migrate from place to place in search of grass and water for their animals.

Therefore, the impact of forestland conversion, land degradation, deforestation, unmanaged agricultral lands, and uncontrolled grazing practices on SOC loss is obvious. However, systematic study on the status and losses of SOC stocks in such converted different land use types is absent in Eritrea and in the Horn of Africa.

Thus, the study aimed to assess SOC stock in continuous cropping, grazing and shifting cultivation lands as compared to natural forest lands in Adi Hakin, Laelay Gash, Eritrea. Assessing the effects of such land use conversions on the SOC stock is crucial for informed policy decisions in case of soil fertility improvement, ecosystem restoration and climate-change mitigation plans. So that the study is supposed to be a useful asset for researchers, land use planners, and decision-makers for identifying and devising approprate strategies for natural forest conservation, soil C management in agricultural and grazing lands, and climate change mitigation actions.

MATERIALS AND METHODS

Study Area

The study was carried out in Adi Hakin, Laelay Gash, Eritrea, which is located in the southwestern part of the country within the moist lowlands agroecological zone. The study area extends from 14°36’00’’ to 14°48’36’’ N and 37°34’12 to 37°41’24’’ E, which covers around 25,000 ha of land with an average altitude of 1070 m above mean sea level. The average monthly temperature, annual rainfall and evapotranspiration rate are 25.8 °C, 599.04 mm and 1953.96 $mm \cdot yr^{-1}$, respectively. Laelay Gash subzone is known for its extensive rain-fed cropping and pastoralism. The major rain-fed crops are sorghum, millets, maize, beans and sesame. Farmers also rear cattle, goats, sheep, camels and donkeys. The area is home to different acacia species, *Adansonia digitata*, *Ziziphus spina-Christi*, *Balanites aegyptiaca*, *Tamarindus indica*, etc. Patches of acacia forests, and riverine forests (mainly *Hyphaene thebaica*) are also common. It is also home to a variety of wildlife animals like elephants, baboons, vervet monkeys, antelopes, dorcas gazelles, warthogs, hyenas, foxes, bushbucks, honey badges, and a wide range of birds and reptiles (Naty, 2002). The area has been transformed from forest-dominated in the 1970s to farming-dominated in the current time. According to Berhe (2018), the area was mostly classified as the declining land productivity category where the agricultural and agro-pastoral lands prevailed. Measho et al. (2019) also reported a hot spot decreasing annual NDVI trend from 2000 to 2017 in that area.

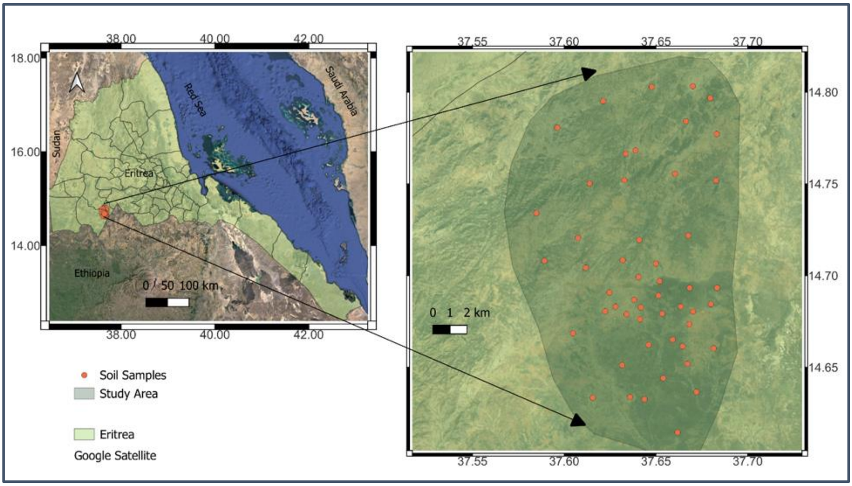

Fig. 1. Study area and soil samples location map.

Soil sampling and analysis

First systematic reconnaissance surveys were conducted on the whole study area in August 2023, and accordingly, four land use types were chosen namely natural forest, continuous and shifting cultivation, and grazing. These land use types were chosen to compare their SOC stocks and other soil properties, bearing in mind the the fact that grazing, continuous and shifting cultivation lands were previously forestlands but converted due to agricultural expansion in the 1970s. Fifty-one georeferenced composite surface (0–30 cm) soil samples were collected from natural forest, continuous cropping, grazing, shifting cultivation lands in September 2023 using stratified sampling technique. Samples were taken considering the four land use types, their adjacent coexistances, and homogenity of soil samples. Two of the authors (one being native to the area) have made enough care to minimize variability of soil samples when collecting. The soils are lixisols at the global scale.

To make one composite soil sample, 5 individual samples were taken using 30 cm deep auger within a radius of 10 m, well mixed, and around 1.5 kg of soil was packed in a plastic container, labelled, and GPS coordinates were recorded at the centre. Thus, for the total 51 composite soil samples, 255 individual soil samples were collected. Moreover, for bulk density determination, 51 undisturbed soil samples were also collected using core sampler. The soil samples were dried, grounded, sieved, and analysed following standard procedures in the soil laboratory of national agricultural research institute (NARI), Eritrea. Soil properties were analysed using respective methods: particle size distribution (hydrometer), soil textural classes (textural triangle), gravel (sieve and weigh), bulk density (core sampler), pH (pH meter), electrical conductivity (EC meter), and SOC (Walkley-Black) (FAO, 2019). The soil data were analysed using one-way ANOVA in the SPSS package to see the effects of land uses on the measured soil properties.

Carbon loss and CO_2 emission

Calculating the C content that could be lost with CO_2 emittion to the atmosphere due to the conversion of natural forests into continuous cropping, shifting cultivation, and grazing lands is crutial for informed-policy decisions for natural forest conservation, soil fertility management, ecosystem restoration and climate change mitigation. Here, calculations are made based on the mean SOC stocks, obtained in the continuous cropping, shifting cultivation, and grazing lands compared to that of the natural forests.

First, SOC stock (SOCs) was computed using equation 1, adopted after Tan and Lal (2004b):

$$\mathrm{SOCs} = \mathrm{SOC} \cdot \mathrm{BD} \cdot \mathrm{D} \cdot (1 - \mathrm{F}/100), \tag{1}$$

where SOCs is soil organic carbon stock ($Mg \cdot ha^{-1}$) in the 30 cm soil layer, SOC is soil organic carbon in %, BD is dry soil bulk density in $Mg \cdot m^{-3}$, D is sampled soil layer thickness in cm, and CF is > 2 mm coarse fraction in %.

Then, the respective C content that is lost due to conversion of natural forests into continuous cropping, shifting cultivation and grazing lands was calculated using equation 2:

$$C_i = (SOCs_i - SOCs_f)A_i, \tag{2}$$

where C_i is the C that is lost from the ith land use type, $SOCs_i$ is the mean SOC stock in the i^{th} land use type, $SOCs_f$ is the mean SOC stock in natural forest soils, all in $Mg \cdot ha^{-1}$, and A_i is the area, in ha, that was converted from natural forest to the i^{th} land use type. Computation is done per unit – ha. If the result is negative, then it indicates C loss.

Finally, the emitted CO_2 (EC) from each land use was calculated using equation 3. The factor 3.67 is computed by dividing the molecular wieght of CO_2 by the atomic weight of C considering the C isotopes, adopted after IPCC (2007) fourth report.

$$EC_i = C_i \cdot 3.67, \tag{3}$$

where EC_i is the emitted CO_2 from the i^{th} land use type to the atmosphere, and C_i is the C that is lost from the i^{th} land use type.

RESULTS AND DISCUSSION

Effects of land use types on SOC stock and other soil properties

Sandy loam and loam soils are dominant in the study area. The mean SOC stocks ($Mg \cdot ha^{-1}$) in the continuous cropping, grazing, shifting cultivation lands, and natural forests were 21.23, 22.74, 23.57 and 51.69, respectively (Table 1). Land use type showed very high effect ($p < 0.001$) on SOC stock, soil organic matter (SOM), pH and gravel content; and high effect ($p < 0.005$) on clay and sand contents; and significant effect ($p < 0.05$) on bulk density and electrical conductivity, but not significantly affects silt content (Table 1). Many research findings also reported that land use types have great impact on SOC stock and other soil properties (Ciric et al., 2013; Choudhary et al., 2016; Chen et al., 2016; Nuguse et al., 2019; Ngatia et al., 2021;

Beillouin et al., 2023; Ghimire et al., 2023; Weldewahid et al., 2023; Lebedeva et al., 2024; Tesfay et al., 2024).

Table 1. Effect of land uses on some measured soil properties (mean values)

Soil Parameter	Continuous cultivation	Shifting cultivation	Grazing	Natural forest	p value
SOCs, $Mg \cdot ha^{-1}$	21.23	23.57	22.74	51.69	< 0.001
SOM, %	1.05	1.20	1.44	2.54	< 0.001
BD, $Mg \cdot m^{-3}$	1.31	1.28	1.25	1.24	0.04
pH (1 : 5)	8.36	7.74	8.22	8.25	< 0.001
EC (1 : 5), $dS \cdot m^{-1}$	0.07	0.07	0.05	0.08	0.044
Clay, %	26.62	36.36	13.85	27.75	0.003
Silt, %	27.79	27.50	31.35	33.00	0.471
Sand, %	45.59	37.05	54.81	39.25	0.004
Gravel, %	8.46	11.83	26.42	4.85	< 0.001

The mean SOC stocks in the mentioned above land use types were ordered in their magnitud: natural forest land > shifting cultivation > grazing > continuous cropping lands. Other researchers also found higher SOC stocks in natural forest lands and lower in continuous cropping, grazing, shifting cultivation, and managed plantations lands (Ciric et al., 2013; Choudhary et al., 2016; Chen et al., 2016; Nuguse et al., 2019; Beillouin et al., 2023). Conversion of natural forests into continuous cropping, grazing, and shifting cultivation lands in the study area through time caused SOC stock reductions by 58.93, 56.00 and 54.40%, respectively. These SOC stock losses are higher than the ones reported by Nuguse et al. (2019), where the SOC losses in grazing and continuous cropping lands were 43.24 and 37.84%, respectively, in the central parts of Eritrea; by Wei et al. (2014) the SOC stock reductions due to conversion of forest lands into agricultural in the tropical regions were 41%; and by Choudhary et al.

(2016) SOC in the managed plantation and shifting cultivation lands were by 51.68 and 48.55% less, than in the natural forests, respectively.

Natural forests are characterized by the highest mean SOC stock, and lowest bulk density, sand and gravel contents. On the contrary, continuous cropping lands had the lowest mean SOC stock, and highest bulk density. Natural forests contribute to C sequestration due to reduced soil erosion, continuous litter fall, root exudates, and minimal disturbances. Therefore, protecting natural forests from land conversion and deforestation is of greatest importance for C sequetration, soil fertility and quality improvement, ecosystem resilience and climate-change mitigation (Ivanov et al., 2021).

Conversion of natural forests into continuous conventional cropping lands in the study area over time leads to significantly reduced and poor SOC stock. This is due to conventional tillage practices, continuous cultivation without fallow periods, mono-cropping, heavy crop residue harvest, heavy post-harvest grazing, no addition of organic matter, and water and wind erosion as the soil stay bare during the dry seasons. Other findings in the region also reported low organic matter in conventional rainfed cropping fields due to the aforementioned problems (Nuguse et al., 2019; Tesfay et al., 2020; Weldewahid et al., 2023; Tesfay et al., 2024). These all imply that conversion of forests into agricultural land depletes the natural organic matter reserve of the soils if appropriate land management practices do not take place to improve SOM storage and soil fertility. SOM and soil fertility can be improved through conservation practices like no/minimal tillage, cover cropping, crop residue retention, application of farmyard manure, irrigation, organic amendments, and integrated and diverse cropping/farming systems. Moreover, by introducing trees and incorporating exogenous C in the form of biochar or organic amendments, and reforesting back croplands to its natural vegetation by promoting agricultural production per unit area. Therefore, agricultural intensification, that promote increased productivity, should be planned and implemented carefully to protect agricultural expansion and conserve natural forests.

Conversion of natural forests into grazing lands over time leads to remarkably reduced SOC stocks in the study area. This is attributed to the uncontrolled traditional grazing practices which is characterized by continuous heavy livestock keeping. This results in vegetation clearance, soil erosion by water and wind, and land degradation. Other researchers also reported very poor SOC, soil fertility and other nutrients, degraded vegetation, enhanced soil erosion and runoff in grazing lands due to overgrazing (Mussa et al., 2017; Nuguse et al., 2019; Mosier et al., 2022; Kim et al., 2023; Tesfay et al., 2024). SOC and soil health of grazing lands can be improved through rotational grazing, applying right stocking rate, long rest periods for pastures, establishing enclosures and promoting cut and carry schemes, reseeding with legumes, and developing and using models for grazing rate management and SOC dynamics monitoring (Pringle et al., 2014; Ritchie, 2020).

Conversion of natural forests into shifting cultivation lands in the study area over time leads to significant reduction in SOC stocks; which is in line with other works (Chatterjee et al., 2022; Baul et al., 2023; Abrell et al., 2024). This is due to clearing and burning vegetation, conventional tillage practices, crop residue off-take, no addition of organic matter, heavy post-harvest grazing, reduction of fallow periods, water and wind erosion. Fallow periods were meant to give time for natural regeneration and C accumulation but fallowing time is shortened due to land shortages and poor agricultural productivity. In the area shifting cultivation is in transition; fallow periods are reduced, and in some cases fallow periods are cancelled. SOC and soil fertility in slash-and-burn shifting cultivation can be improved through proper management of cultivation and fallow periods, minimum tillage, zero burning, promoting legume crops, motivating farmers to invest in improved fallows, promoting agroforestry practices, and developing and using integrated farming systems models.

Carbon loss and CO_2 emission

Comparing the mean SOC stocks in natural forests and continuous cropping lands, the difference was found to be 30.46 $Mg \cdot ha^{-1}$. This implies that conversion of natural forests into continuous cropping lands in the study area over time contributes to a loss of 30.46 $Mg\ C \cdot ha^{-1}$ and an emission of 111.79 $Mg\ CO_2 \cdot ha^{-1}$ to the atmosphere.

Similarly, conversion of forests into shifting cultivation and grazing lands in the long run causes losses of 28.11 and 28.95 Mg C·ha^{-1} and emissions of 103.16 and 106.25 Mg CO_2·ha^{-1} to the atmosphere, respectively. This shows that improved management practices in the continuous cropping, shifting cultivation, and grazing lands are unattended. Thus, good land management practices need to be exercised, and more importantly, conservation of natural forests needs critical attention as they are very crucial for the well-being of our planet.

CONCLUSIONS

Land use types showed very high effect ($p < 0.001$) on SOC stock, soil organic matter, pH and gravel content and high effect ($p < 0.005$) on clay and sand contents, significant effect ($p < 0.05$) on bulk density and electrical conductivity.

Conversion of natural forests into continuous cropping, grazing, and shifting cultivation lands in the study area over time contributes to losses of 30.46, 28.95 and 28.11 Mg C·ha^{-1} and emissions of 111.79, 106.25 and 103.16 Mg CO_2·ha^{-1} to the atmosphere, respectively. Thus, the study concludes that conventional farming systems are potential contributors to the atmospheric CO_2 through SOC losses. On the contrary, natural forest soils have high potential to mitigate climate-change through SOC sequestration.

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