Soil organic carbon stock assessment for soil fertility improvement, ecosystem restoration and climate-change mitigation

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Abstract. Food insecurity, land degradation, desertification, and climate-change are prevalent in Eritrea. Though SOC stock is very crucial for soil fertility improvement, ecosystem restoration and climate-change mitigation, the status of it in different land uses in Eritrea is unknown. Thus, the study collected 64 surface soil samples from rainfed, irrigated, enclosure and grazing land uses from Keren subzone, Eritrea, and analysed for SOC. The ANOVA test results showed that land uses had very highly significant effects on SOC stock ($p < 0.001$). Rainfed and irrigated cropping recorded the minimum and maximum mean SOC stocks, 6.57 and 25.29 Mg ha^{-1}, respectively. This implies that shifting from rainfed to irrigated agriculture would not only contribute to soil fertility improvement, increased yield, and food security but also to climate-change mitigation. Converting the 2500 hectares rainfed land in the study area to irrigated, would store 46,800 Mg C and offset 171,756 Mg CO_2 emission. Grazing and enclosure land uses with 18.53 and 18.92 Mg SOC stocks ha^{-1}, respectively, had no significant difference between them (Tukey test) which indicates poor enclosure management. Thus, the study realizes that irrigated agriculture with good agronomic practices is helpful to improve soil quality and mitigate climate-change.

1 Introduction

Soil is a very crucial resource for its significant roles in food, feed and fiber production, ecosystem restoration and climate-change mitigation [1, 2]. However, in the past decades, soil has been exploited intensively without its security for the future; it has been and continues to be lost at rates greater than mechanisms that replenish it [3]. Globally, soils have lost 116 Pg of C due to land cultivation [4]. As a result, soil erosion, fertility decline, land degradation, decertification, and C emission from soils have increased. Nowadays, attention is paid to our land use practices as they heavily influence the C balance in soil through C sequestration and/or emission, and may lead to either depletion or accumulation of C depending on the type and respective management practices employed.

In Eritrea, land degradation is widespread, which is caused by, among others, soil erosion, deforestation, drought, traditional rain-fed farming, and overgrazing [5]. Although the country is fighting against land degradation through tree planting, soil and water conservation structures construction, enclosures establishment, investments in green energy, etc, land degradation is still a threat to the national development. More than 75% of the population is employed in agriculture in which traditional subsistence rain-fed farming, under erratic rainfall and recurrent drought spells, accounts for more than 88% of total farmlands. Each year, about 500,000 ha of land is cultivated under rainfed conditions but its productivity is below 0.7 t ha^{-1}. Consequently, food insecurity and poverty prevail within the farming communities [6]. [7] argues that the rain-fed production system in Eritrea cannot ensure food security and land use sustainability; irrigation should be intensified. For example, if irrigated agriculture, which is only 4.5% is raised to 25% (150,000 ha), it would substantially contribute to food self-sufficiency. Irrigated land uses, with good agronomic practices, enhance soil and water conservation, increase cropping intensity and income [8, 9], sequester C and offset CO_2 emissions [10-12], and mitigate sensible heat [9]. However, the effects of different land uses on soil health is unknown in Eritrea.

Improper land uses degrade soils and their C storage capacity. In grazing lands, prolonged high livestock stocking can lead to significantly poor SOC and soil fertility [13, 14] and other nutrients, degrade vegetation and may enhance erosion and runoff [14]. Grazing practice in Eritrea is traditional and uncontrolled. As a result, most of the grazing land is graded due to overgrazing. The country's efforts of establishing enclosures in different parts of the country for natural regeneration is also facing challenges due to the uncontrolled grazing and peoples' energy dependency on biomass.

Bearing in mind the discussed problems, assessment of the effects of different land uses on soil health is very crucial in the country for informed-policy decisions dealing with soil health improvement, food security, ecosystem restoration and climate-change mitigation. Thus, the study evaluated SOC stocks (as an indicator of soil health) and other some soil properties in different land uses namely rainfed, irrigated, grazing and enclosure.

2 Materials and Methods

2.1 Study Area

The study was conducted in Keren subzone, $15^0$44'55''-$15^0$51'05''N and $38^0$20'02''-$38^0$30'30''E, which is located within the arid lowlands agroecological zone of Eritrea at an average altitude of 1430 m above mean sea level with 23 ºC mean monthly air temperature, 398.69 mm average annual rainfall and 1669.44 mm yr^{-1} potential evapotranspiration rate. Mixed (rainfed cropping and livestock raring) subsistence farming is the main livelihood stay where more than 90% of the annual rainfall is occurred from the last week of June to the first week of September under very erratic situations. Irrigation practices are still very limited. The major rainfed crops are sorghum and pearl millet and to some extent groundnut. The major livestock are goats, sheep, cattle, camels and donkeys. The soils of the study area are leptosols, which are eroded, sandy, stony and poor. Mountains, valleys and plains characterize the topography, and granite rocks dominate the geology of the area.

2.2 Soil Sampling and Analysis

In order to select representative soil sampling areas, reconnaissance surveys were conducted in Keren subzone in July 2023, and finally, four adjacent land uses namely rainfed, irrigated, grazing and enclosure were chosen around Shnara, Lebeda, Ttri, Megarh, Adi Hashel, Waliku, Ona, and Begu farming villages and the Forto and Tinqulhaz enclosures. Ages of the conventional rainfed and grazing land uses were more than 100 years, irrigated 20-90 years and enclosures 7-20 years.

After the selection of soil sampling areas, 64 georeferenced composite surface (0-30 cm) soil samples were collected from the chosen land uses in Aug 2023. Undisturbed soil samples were also collected using core sampler for bulk density determination. The soil samples were dried, grounded and sieved following standard procedures. Particle size distribution was determined using hydrometer method, texture using textural triangle and bulk density using core sampler method. SOC was analysed using the Walkley-Black method [15] in the soil laboratory of the National Agricultural Research Institute (NARI), Halhale, Eritrea.

Soil laboratory results of particle size distribution and bulk density were interpreted using the guides given by [16], and SOM [17]. Descriptive statistics of soil properties were computed using descriptives and the effect of land uses on SOC stock and other soil properties were analysed using One-way ANOVA in the SPSS package.

2.3 C Sequestration and CO2 Mitigation

Calculating the C that could be stored and CO_2 mitigated by shifting from a poor land use to a better land use is very important for decisions in land use changes. In this study, calculations were done for shifting from rainfed to irrigated land use based on the results.

First, each SOC value was converted to SOC stock value by multiplying it by respective soil bulk density, sampling depth and gravel fraction; adopting the equation given by [18]. Then, C that could be sequestered by converting rainfed to irrigated land use was computed according to equation 1.

$$CS = (SOCSi - SOCSr)A \quad (1)$$

Where CS is C that could be sequestered, SOCSi is mean SOC stock in irrigated soils, SOCSr is mean SOC stock in rainfed soils (all in Mg ha^{-1}), and A is the total area of rainfed lands to be converted to irrigated lands (in ha).

Finally, CO_2 mitigation was computed by multiplying the total CS from equation 1 by the factor 3.67, adopted from IPCC fourth report [19], which is obtained by dividing the molecular weight of CO_2 to the atomic weight of C, considers the C isotopes.

3 Results and Discussions

3.1 Descriptive statistics of measured soil properties

The study notifies that the soils in the study area are course textured with loamy sand, sandy loam and sand representing 46.88, 34.38 and 18.74%, respectively. The soils are characterized with very high sand and very low silt and clay contents [16] with the averages of 81.25, 9.85 and 8.90%, respectively (Table 1). The average gravel (> 2 mm) content was 22.67%. The dry bulk density (BD), in Mg m^{-3}, ranged from 1.26 to 1.64 with an average of 1.41, which is moderate [16] for course textured soils. SOM values, in %, ranged from 0.05 to 1.53 with an average of 0.65, which is extremely low [17]. SOC stock values, Mg ha^{-1}, ranged from 1.21 to 34.27 with an average of 15.91. The dominant granite rocks in the area, soil erosion, poor soil fertility management, no/little organic matter input, heavy crop harvest off-take, use of animal dung, other vegetation and wood for energy needs and overgrazing might have contributed to the course texture, very high sand, very low silt and clay levels and extremely low SOM of the soils [5, 11].

Table 1: Descriptive statistics of measured soil properties

Soil Properties	Minimum	Maximum	Mean	*StdD	Skewness	Kurtosis
SOM, %	0.05	1.53	0.65	0.37	0.04	-0.97
SOCs, Mg ha^{-1}	1.21	34.27	15.91	8.46	-0.07	-1.02
BD, Mg m^{-3}	1.26	1.64	1.41	0.07	0.17	1.12
Clay, %	5.00	15.00	8.90	2.67	0.92	0.21
Silt, %	2.50	42.50	9.85	8.21	1.98	4.74
Sand, %	42.50	92.50	81.25	9.78	-1.85	4.16
Gravel, %	0.00	38.19	22.67	10.44	-0.42	-0.91

*StdD = standard deviation

3.2 Effect of Land Uses on Measured Soil Properties

The minimum-maximum ranges of SOC stock, in Mg ha^{-1}, for rainfed, grazing, enclosure and irrigated land uses were 1.21-20.68, 6.79-31.20, 10.75-27.38 and 14.44-34.26, and the mean values were 6.57, 18.53, 18.92 and 25.29, respectively. Land uses showed very highly significant effect on SOC stock, silt, sand and gravel contents ($p < 0.001$), highly significant effect on bulk density ($p=0.005$) and significant effect on clay content ($p=0.044$). Irrigated agriculture recorded the highest mean SOC stock, clay and silt contents, and the lowest bulk density, sand and gravel contents **(Table 2)**. The mean SOC stocks ordered in their magnitude were irrigated > enclosure > grazing > rainfed. In comparison, irrigated soils have the highest but rainfed soils the lowest mean SOC stock, owning to the relatively reduced tillage, crop residues return, farmyard manure application, crop rotations and soil moisture availability in the irrigated fields, which is supported by [11]. On the contrary, rainfed-cropping in Eritrea is characterized by conventional tillage, no/little organic matter application, heavy crop residue harvest, heavy post-harvest grazing [5] and no soil cover the entire dry season prone to water and wind erosion. The results of this investigation are in line with the works of [10, 11], they observed that shifting from rainfed to irrigated agriculture improved SOC stock and soil quality. In this study, irrigated lands increased SOC stock by 285%.

Enclosure and grazing land uses with 18.92 and 18.53 Mg ha^{-1} mean SOC stocks, respectively, had no significant difference between them (Tukey HSD test), which indicates poor enclosure management. This finding agrees with the finding of [20] but the opposite holds true with the reports of [21] both from Ethiopia. The first reported no difference but the latter reported that areas enclosure had significantly more 27.5% SOC compared to adjacent open grazing areas. This shows that enclosure management matters. It was observed during soil sampling that there were animals grazing and people cutting trees in some areas of the enclosures. If people do not have enough energy supply at their homes for cooking their food, they tend to cut trees. Investments in households' green energy projects is mandatory to reduce tree cutting and promote the recovery of enclosures. Awareness creation campaigns, community involvement, benefit sharing, cultivating cut and carrying system, etc are helpful for natural regeneration of enclosures.

Grazing is free and uncontrolled in the study area and in Eritrea in general. As a result, grazing land is poor and the SOC stock is poor. Grazing land management is very important to reduce land degradation and improve animal production. [13, 14] reported that shifting from continuous to alternative grazing improved SOC stock.

3.3 C Sequestration and CO2 Mitigation

Comparing the mean SOC stock of soils in irrigated (25.29 Mg ha^{-1}) and rainfed (5.57 Mg ha^{-1}) land uses, irrigated soils have stored extra 18.72 Mg SOC stock ha^{-1} than rainfed soils. Optimistically, the results of the study indicate that shifting from rainfed to irrigated agriculture would not only contribute to soil quality improvements, increased crop productivity and income–but also to climate-change mitigation through C sequestration. Therefore, converting the current 2500 ha rainfed land in the study subzone to irrigated agriculture would store, with the existing management, at least 46,800 Mg C and offset 171,756 Mg CO_2 emission. C storage can be enhanced with good agronomic practices. [11, 12, 22] also reported that irrigated land expansions with good agronomic practices have significant potential for climate-change mitigation through C sink.

Table 2: Effects of land uses on SOC stock and others soil properties

Land Use	SOCs, Mg ha^{-1}	BD, Mg m^{-3}	Clay, %	Silt, %	Sand, %	Gravel, %
Rainfed	6.57	1.44	9.75	6.63	83.15	17.03
Grazing	18.53	1.39	8.20	7.10	84.70	31.58
Enclosure	18.92	1.45	7.50	10.56	81.94	23.80
Irrigated	25.29	1.38	10.00	22.25	67.75	10.68
p value	<0.001	0.005	<0.044	<0.001	<0.001	<0.001

4 Conclusion

Course texture, high bulk density, and low SOM characterize the soils of the study area. Land uses had very high significant effect on SOC stock, silt, sand and gravel contents ($p < 0.001$), high significant effect on bulk density ($p=0.005$) and significant effect on clay content ($p=0.044$). Irrigated agriculture recorded the highest mean SOC stock, clay and silt contents, and the lowest bulk density, sand and gravel contents. Irrigated soils, owing better mean SOC stock, have stored 18.72 Mg SOC stock ha^{-1} than rainfed soils. SOC stock in enclosure and grazing land uses did not show significant difference owning to poor enclosure management. Thus, the study concludes that shifting from rainfed to irrigated agriculture would be beneficial for C sequestration, soil fertility improvement and climate-change mitigation.

The authors would like to express their heartfelt thanks to the Ministry of Agriculture (MoA), National Agricultural Research Institute (NARI), Hamelmalo Agricultural College (HAC), Eritrean Crops and Livestock Corporation (ECLC) and zonal and subzonal agricultural offices for their supports in advice, data provision, soil sampling and soil lab analysis.

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