



# Accumulation of SOC in relatively undisturbed tropical mountain foothills under climate change scenarios: The case of Uluguru Mountain, Tanzania

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## Abstract

Soil nutrients form an important part of agro-ecosystems in various landscapes, including mountainous areas. Most foothills in tropical mountains are heterogeneous in terms of the accumulation of soil nutrients due climatic location and ecological endowments. Since most mountain foothills have potential for the provision of environmental services, it is imperative to assess the salient soil nutrients including carbon in order to determine the amount. This study assessed the accumulation of soil organic carbon (SOC) in the relatively undisturbed foothills of Uluguru Mountains whose geology indicates that they were formed during cretaceous age (i.e.  $\approx 50$  million years ago). The study also determined the trends of rainfall and temperature because these elements of climate have important influence on carbon accumulation. In conducting this study, we sampled Kiroka Village (in Kiroka Ward) because it is found at the foothills of the Uluguru Mountain and most of its parts are relatively undisturbed. In this place, sixteen soil sampling points were established within one hectare and these points involved two soil depths (i.e. 0–20 cm and 20–40 cm) and two locations (i.e. lowland and upland). The Walkley–Black Method was used for SOC analysis while Mann–Kendall Test was employed for climate data analysis. The results exhibit that there have been significant variations in SOC accumulation under the two soil depths and locations. In the lowland areas, SOC was 1.1 and 0.43 MgC ha<sup>-1</sup> for the depths 0–20 cm and 20–40, respectively. Besides, in upland areas, SOC was 0.38 and 0.31 MgC ha<sup>-1</sup> for the depths 0–20 cm and 20–40, respectively. Most cereal crops require a considerable amount of SOC in the soil that ranges between 0.5 and 2 MgC ha<sup>-1</sup>. Additionally, the mean annual rainfall and temperature patterns from 1980 to 2020 declined and intensified at  $R^2 = 0.15$  and 0.19, respectively. Therefore, these results inform environmental experts, climate practitioners and other relevant stakeholders to endorse suitable and sustainable environmental management methods in the mountainous areas.

**Keywords** Anthropogenic activities · Conservation · Mountain foothills · Eastern arc · Soils

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## Introduction

The assessment of soil organic carbon (SOC) involves the estimation of stocks and net fluxes of carbon from different land use systems in a given area over a given period and under a given management system (Bationo et al. 2006; Smith & Fang 2010; Batjest 2011). This implies that various biomes or land use patterns can have an independent assessment of SOC for current and future use (IPCC 2000; Lal 2008; Talebi & Mostafazadeh 2021).

Naturally, the amount of carbon stored in soil is mostly determined by the balance of two biotic processes, these include (i) the production of organic matter by terrestrial vegetation and (ii) decomposition by soil organisms (Lal 2004; Hartemink et al. 2008; Mkonda & He 2018). Soil

organic matter, an important component for SOC accumulation, comes from the remains of plants and animals, and is created by many organic chemical components including carbohydrates, lipids and proteins. These components are very important sources of carbon used for optimizing the microbial activity of the soil.

It is obvious that in a relatively undisturbed ecosystem; SOC increases through the decomposition of soil organic matter and its stock serves various biological functions. Also, the SOC content has great impact on runoff generation and sediment production (Mostafazadeh et al. 2022). This fact was also rendered by Batjes (1996) who asserted that the accumulation of SOC is a key component aspect for any terrestrial ecosystem, and thus, any variation in its abundance and composition has important effect on many of the processes that occur within the system.

Various studies have been established on the SOC stock in climatic regions such as the tropics and semi-arid regions (Milne et al. 2007; Verburg et al. 2010). Some of these studies have assessed the influence of land use (especially agriculture and rangeland) on SOC accumulation (Wang et al. 2005; Ogle et al. 2004; Smith and Fang 2010; Talebi et al. 2022). However, there has been an increased demand for assessing SOC in the relatively undisturbed ecosystems including mountain areas.

Specifically, Tanzania is among the sub-Saharan countries with limited studies that explore the accumulation of SOC in mountainous areas. Some of these studies examined the accumulation of SOC either in general lands or in some cropping systems (Hartemink 1997, Glaser et al. 2001; Mäkipää et al. 2012; Kempen et al. 2019). Some of these studies determined the stability of organic matter and SOC on savanna soils, permanent acacia cropping, permanent sisal cropping, and the effects of manure in homestead fields on organic C and N mineralization. Very few studies such as those of Burgess et al. (1998) and Hartemink et al. (2008) have estimated SOC under natural ecosystems such as forestry and pasture lands but with limited information.

Tanzania has several mountains with different ecological potentials. Most of these mountains form the eastern arc mountains ranges of east Africa. The Uluguru Mountains, part of the eastern arc mountains, have significant potentials ranging from serving peoples' livelihoods to environmental conservation (Lovett 1998; Jung et al. 2021). The main portion of the mountains is a ridge running roughly from north to south and rising up to 2,630 m. Demographically, these mountains host over 50 villages with over 150,000 people. Despite the biological potentials of the mountains, there has been increased degradation in the area (Hall et al. 2009).

Explicitly, this degradation has been more pronounced in the mountain foothills (Khiavi & Mostafazadeh 2022). This situation has been exacerbated by climate change scenarios (Burgess et al. 1998; Mkonda 2022a). Most studies have

revealed that anthropogenic activities such as agriculture, deforestation and settlement establishment are some of the major drivers for environmental degradation in the area (Rossi 2009; Plaza-Bonilla et al. 2015).

Batjes (2011) stipulated that, in most instances, SOC stocks under undisturbed native vegetation are usually considered to be in dynamic equilibrium with other terrestrial carbon pools because they are mainly controlled by climate, terrain, vegetation, soil mineralogy, particle size and their interactions.

Recognizing the urgency of finding sustainable solutions, it is imperative to make a carbon inventory assessment in the area in order to estimate the stocks and net fluxes of soil carbon. The assessment of SOC is very important because its stock is mainly determined by land use systems in a specific area over a given period and under a given management system. Since land disturbance is progressively high at the foothills of Uluguru Mountain, it is vital for scientists to document SOC in the area.

Based on this established background, it is clear that there is very limited information about SOC in most mountainous areas of Tanzania. Basically, what needs to be specifically established is the actual assessment of SOC accumulation in relatively undisturbed tropical mountains under climate change scenarios (Lal 2015; Mkonda 2022b). This establishment is particularly important because it determines the SOC stock under the natural environment and provides ecological potential for environmental services. Besides, a sufficient amount of SOC available in the area provides suitable environmental conditions for diverse living organisms including soil microbes. Consequently, increased replenishment of natural environments would significantly intensify the capacity of the area to provide environmental services (Glaser et al. 2001; Johannes et al. 2017).

Therefore, the current study aims at; (1) estimating SOC accumulation in the relatively undisturbed environment at different soil depths; and (2) evaluating the relationship between SOC in lowland and upland areas. This will in turn provide insights to climate practitioners and environmental advocacy groups on how such an environment can be managed. In this study, the lowland is regarded as the area found in the low altitude of the mountain foothills compared to the upland areas and vice versa. Both lowland and highland are found within the study area.

## Materials and methods

### Site descriptions

The study site is located in Kiroka village at latitude ( $6^{\circ} 49' 59''$  S) and longitude ( $37^{\circ} 49' 0''$  E), with an altitude of 468 m (1,535 feet) above sea level (a.s.l.), Morogoro Rural

District, Morogoro Region, Tanzania. The site is located at the foothills of the Uluguru Mountain specifically the Uluguru Nature Forest Reserve with an area of 24,115.09 ha that form an important chain of the East Arc Mountains. As applied to other areas of the tropic, this site is also among the vulnerable zones to climate variability and change Fig. 1.

A field experiment was conducted between January and February, 2022 in Kiroka Village (sites), (GPS-6.83333, 37.81667). The detail of the design and sampling procedures is described in the soil sampling section. The relatively undisturbed areas are viewed as all areas which have not been under intensive cultivation for the past ten years. Demographically, Kiroka Village, Kiroka Ward in Morogoro District of Tanzania is home to nearly 5,800 people.

We selected the relatively undisturbed lands for our study because the changes in land use and management directly affect the input and decomposition of organic matter in the soil and thereby influence soil organic carbon dynamics (Bationo et al. 2006). For this study, it was essential to understand whether soil was considered to be relatively undisturbed (i.e., under natural vegetation), or

under cultivation, pasture, or degraded). This biophysical scenario was preempted at the time of profile description and sampling (FAO 2006).

### Farming situation in the area

In the area, agriculture is the main source of income and people grow a range of crops including maize, rice, beans, sweet potatoes, cassava, peas and tropical fruits. Monoculture, a dominant farming system in the area, has resulted to exhaustion of soil quality around the study area. In addition, the tillage system in the area involves both conventional and conservation (Glaser et al. 2001; Mkonda & He 2018). In turn, conventional tillage has affected the agro-ecosystems and the environments at large. Essentially, agricultural practices can have both direct and indirect impacts in the entire area due to ecological connections (i.e. mountains, slopes and vegetation). Therefore, the assessment of the farming situation was essential because of their influence on the study site.

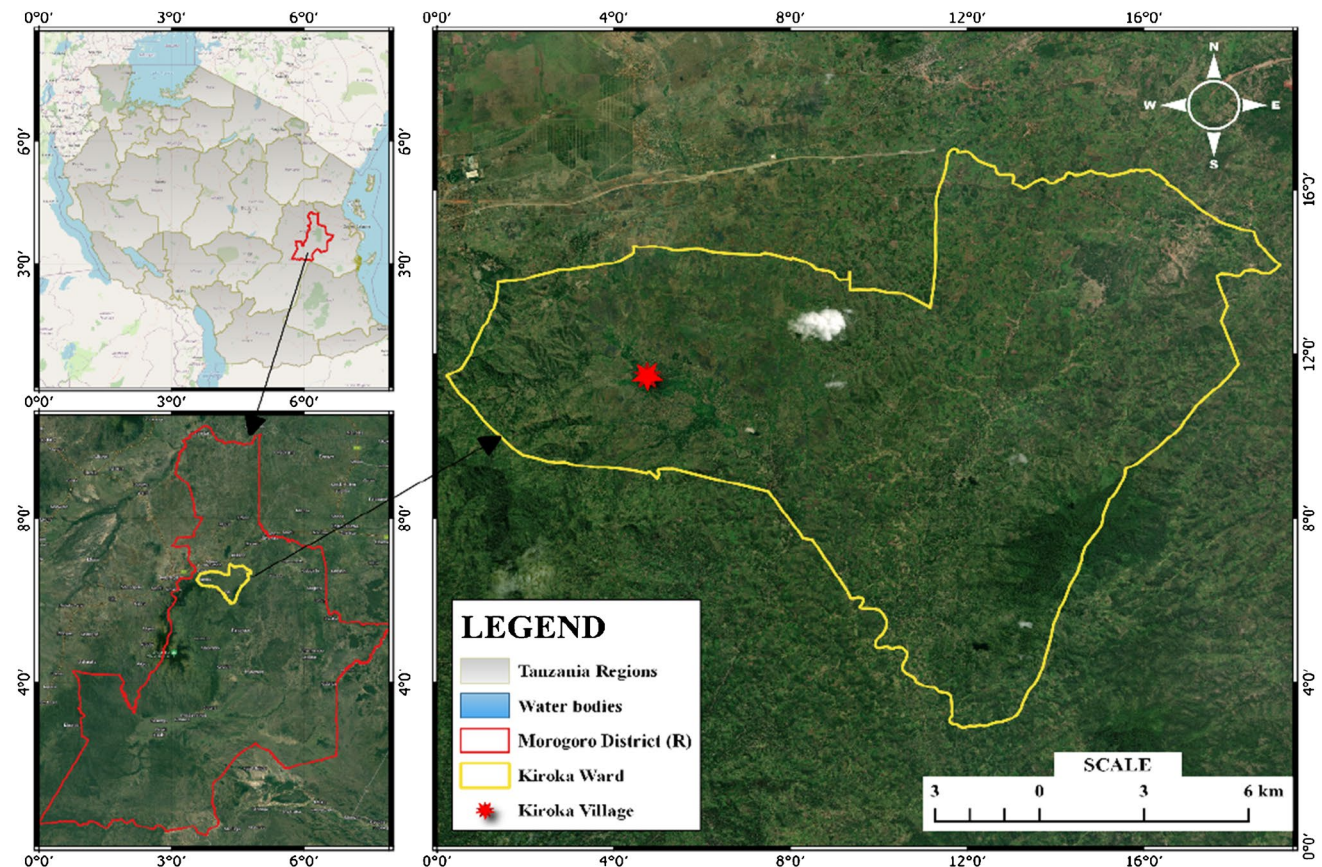


Fig. 1 Study Area

## Soil sampling and analysis

This study was carried out between January and February 2022 in Kiroka village. Soil was sampled according to FAO guidelines for soil description (FAO 2006). The sampling of soils involved two locations (i.e. upland and lowland) whereas, in each location; two sites (A and B) were established as seen in Table 1. Overall, we sampled a total of 128 soil cores in locations, sites and depths. Explicitly, sixteen soil sampling points were established within each site (i.e. with an average of a hectare). Overall, each sampling involved two soil depths (i.e. 0–20 and 20–40 cm) and locations whereas, for each depth, we selected randomly the field to establish four soil ditches ( $W \times L \times D = 40 \times 50 \times 40$  cm) as seen in Table 1. The determined depths were sufficient as the area was relatively undisturbed by anthropogenic activities.

Then, using a 150 mL volumetric soil sampler (6 cm diameter & 5.3 cm height), we sampled four soil cores in each established ditch as seen in Table 1. In this respect, volume-specific samples at 5 cm increments were collected in each soil profile without mixing horizons. These processes were done in replicate. The two soil sources were defined for more clarification. For the site to qualify as relatively undisturbed, it should have stayed without being under any form of cultivation for at least 10 years.

We established these depths because SOC vary with climate, soil type, land use, management practices, vegetation type, and soil depth. This is why the current study considered the level of disturbance and depth in the soil sampling. In addition, the standard operating procedure for electrical conductivity soil/water ratio of one to five (1:5) was adopted in this study.

Practically, the sampled depths were sufficient as the area was not significantly disturbed by anthropogenic activities. Geographically, the sites with fewer disturbances by anthropogenic activities, and easy accessibility were purposively sampled. Later on, soil analyses were done at the Department of Soil Sciences and Geological

Studies at Sokoine University of Agriculture, Tanzania. The Walkley–Black Method was used for SOC analyses.

Despite the potentials of the study area, this kind of research suffered from serious challenges especially field exploration (visit) as most of these areas are hilly in nature.

## Laboratory analyses and computation of SOC and other soil nutrients

Soil analyses were done in March 2022 in the Department of Soil Sciences and Geological Studies at Sokoine University of Agriculture. The Walkley–Black Method was used for SOC analyses (Walkley & Black 1934). The analysis considered the locations (lowland and upland) and depths. The current procedure considers the Revised Legend (FAO-UNESCO 1988) and clusters the corresponding soil profile data into two (0–20 cm and 20–40 cm). The analysis was also done according to FAO guidelines (FAO 2006).

Apart from SOC, we also analyzed other major soil nutrients such as nitrogen and phosphorus. Based on Wilke (2005), we analyzed the total soil nitrogen using a modified Kjeldahl procedure while available phosphorus (P) was extracted using Bray 1 method and determined by spectrophotometric procedure. Alongside, other soil parameters such as pH, electrical conductivity (EC) and exchange capacity (CEC) were determined as supporting elements.

For an individual profile with  $k$  layers, the equation of Batjes (1996) was used to calculate the amount of organic carbon in the whole soil profile:

$$\text{SOCd} = \sum_{i=1}^k \text{SOC}_i = \sum_{i=1}^k \rho_i \times P_i \times D_i \times (1 - S_i)$$

$$\text{SOC}_i = \rho_i \times P_i \times D_i \times (1 - S_i)$$

where  $k$  is the number of horizons,  $\text{SOC}_i$  is soil organic carbon concentration ( $\text{Mg m}^{-2}$ ),  $\rho_i$  is the bulk density ( $\text{Mg m}^{-3}$ ),  $P_i$  is the proportion of organic carbon ( $\text{gC g}^{-1}$ ) in layer  $i$ ,  $D_i$  is the thickness of this layer (m), and  $S_i$  is the volume fraction of fragments  $> 2$  mm.

However, global calculations of the pool of carbon in the soil are complicated by a number of factors. According to Batjes (2011), these factors include: (1) there is still limited knowledge of the extent of different kinds of soils (b) there is limited availability of reliable, complete and uniform data for these soils (c) there is considerable spatial variation in carbon and nitrogen concentration, stoniness and bulk density of soils that have been classified similarly; (d) and also there is confounding effects of climate, relief, parent material, vegetation and land use. In addition, climate data were gathered from Tanzania Meteorological Agency.

**Table 1** Soil sampling per site

Locations	Depth (cm)	No. of samples (Site one-A)	No. of samples (Site two-B)
Lowland areas	0–20	16	16
	20–40	16	16
Upland areas	0–20	16	16
	20–40	16	16
Total		64	64
		(A + B) = 128	

**Source:** Field Soil Sampling

### Climate data analysis

Climate data from the study area were analyzed using Mann Kendall Test (Fig. 2). This analysis was particularly important because rainfall and temperature are very important aspects in determining SOC accumulation in the natural environment. Alongside, the two elements determine various physical and biological processes that determine the provision of environmental services.

### Results

#### SOC and other important soil nutrients

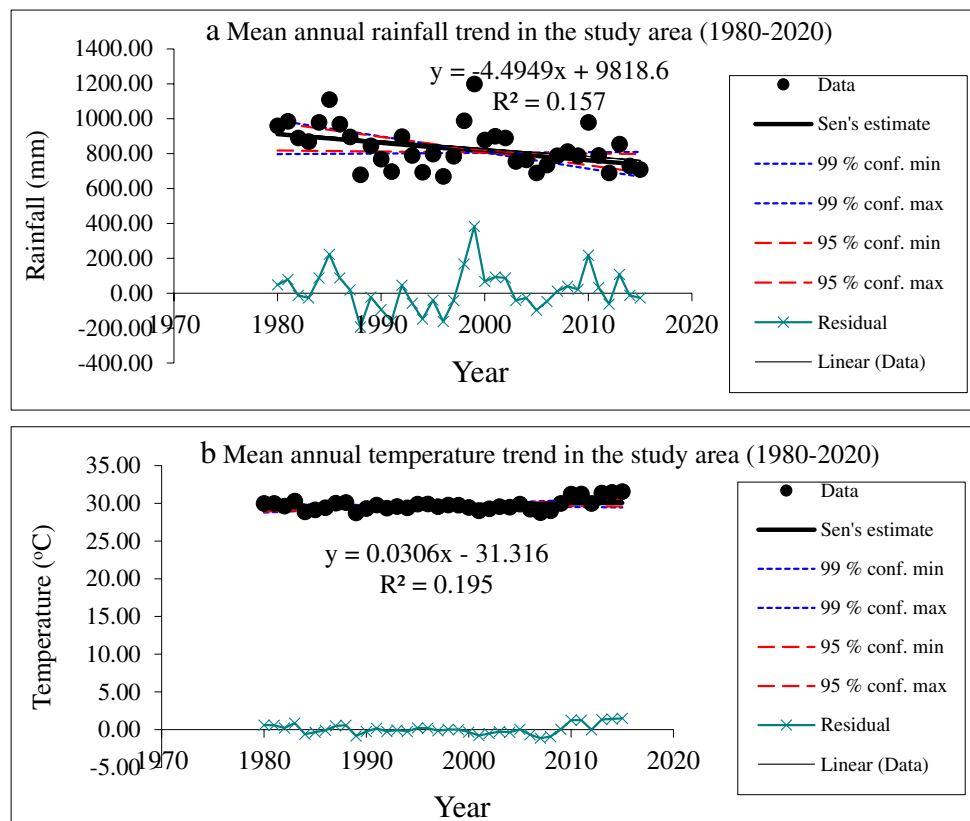
Table 2 provides results of SOC accumulation in relatively disturbed areas around the Uluguru Mountain. The results also reflect the real situation in relatively undisturbed areas

in various tropical areas. These results will be discussed in line with the global SOC framework.

The results in Table 2 indicate that SOC was significantly greater in lowland (1.1 and 0.43 MgCha<sup>-1</sup> at soil 0–20 cm and 20–40 cm depth) than in upland (0.38 and 0.31MgCha<sup>-1</sup> at 0–20 cm and 20–40 cm), and decreased with increasing soil depth ( $p < 0.05$ ). Under both situations, SOC was highest on the surface (0–20 cm) and diminished with increasing soil depth (Table 2).

This scenario happens possibly because in lowland areas there is a sufficient accumulation of soil nutrients including SOC in the upland area. Besides, as what happens in the lowland, the concentration of soil nutrients in the topsoils was higher than in the layers beneath. However, the difference in SOC accumulation between 0–20 and 20–40 cm was non-significant differences ( $p > 0.05$ ). Alongside, Table 3 shows the results of other important nutrients such as EC, zinc and magnesium that form an important entity of soil nutrients.

**Fig. 2** Trend of mean annual rainfall (a) and temperature (b) in the area from 1980 to 2020. **Source:** Tanzania Meteorological Agency, 2022



**Table 2** Analyses result of the major soil nutrients from the study area

Field ref	Depth (cm)	No. Samp	TN-Kjeld	SOC-BlkW	Ext.P (mg/kg)	CEC (cmolKg <sup>-1</sup> )		
			Mgha <sup>-1</sup>	MgCha <sup>-1</sup>	PBry-1	CEC	Ca <sup>2+</sup>	K <sup>+</sup>
Lowland	0–20	32	0.47	1.1	2.43	37	15.71	3.42
Lowland	20–40	32	0.18	0.43	2.18	29	12.4	2.21
Upland	0–20	32	0.07	0.38	0.19	35	8.2	1.40
Upland	20–40	32	0.06	0.31	0.08	26	6.3	0.72

**Source:** Lab soil analyses at Sokoine University of Agriculture (SUA), 2022

Correspondingly, total nitrogen (TN) and phosphorus (TP) were significantly higher ( $p < 0.05$ ) in the lowland than in the upland and decreased from 0.47 and 2.43 Mg (0–20 cm) to 0.18 and 2.18 Mg (20–40 cm), respectively (Table 2). In addition, other important soil nutrients such as calcium ( $\text{Ca}^{2+}$ ), potassium ( $\text{K}^+$ ) and magnesium ( $\text{Mg}^{2+}$ ) behaved the same way as seen in (Tables 2 and 3).

The pH value of the soil increased significantly ( $p < 0.05$ ) from upland to lowland areas (Table 3). The soil pH was neutral as it ranged from 5.82 to 7.03 under both situations (Bokhorst et al. 2017). Nonetheless, the least attention was given to the trace elements as the study intensely focused on SOC.

Alongside this, we determined soil bulk density (BD). The BD was normally expressed as the mass of an oven-dry sample of intact soil per unit volume. Lal (2008) revealed that BD is among the most important soil physical property which is essential for assessing carbon stocks. The BD determines the cumulative SOC in large area, therefore, it was important also to calculate SOC in a large area (hectare) using the BD.

In the lowlands, the calculated BD was  $0.9 \text{ g cm}^{-3}$  and  $1.0 \text{ g cm}^{-3}$  for 0–20 cm and 20–40 cm, respectively. Besides, the BD in uplands was  $1.1 \text{ g cm}^{-3}$  and  $1.2 \text{ g cm}^{-3}$  for 0–20 cm and 20–40 cm, respectively. Since SOC was 1.2 and 0.68 in lowlands and uplands, respectively, then, SOC accumulation was calculated by the following formula:  $\text{SOC} = \text{Depth (cm)} \times \text{Bulk density (g cm}^{-3}) \times \text{Organic carbon (\%)}$ .

Hence, the calculated SOC per hectare is determined as follows hereunder;

i) SOC (0–20 cm)

- A. Lowlands =  $20 \text{ cm} \times 0.9 \text{ g cm}^{-3} \times 1.1 \text{ MgC ha}^{-1} = 19.8 \text{ Mg ha}^{-1}$
- B. Uplands =  $20 \text{ cm} \times 1.1 \text{ g cm}^{-3} \times 0.38 \text{ MgC ha}^{-1} = 8.36 \text{ Mg ha}^{-1}$

ii) SOC (20–40 cm)

- A. Lowlands =  $20 \text{ cm} \times 1.0 \text{ g cm}^{-3} \times 0.43 \text{ MgC ha}^{-1} = 8.6 \text{ Mg ha}^{-1}$
- B. Uplands =  $20 \text{ cm} \times 1.2 \text{ g cm}^{-3} \times 0.31 \text{ MgC ha}^{-1} = 7.44 \text{ Mg ha}^{-1}$

### Climate data

Since climate has a significant influence on organic soil nutrient amendments. Therefore, it was worthwhile to depict climate information alongside SOC accumulation in the study area. Overall, the results indicate that for the past 40 years (1990–2020) there have been climate fluctuations in the area as seen in Fig. 2. The result indicates there have been a considerable decrease and increase in the mean annual rainfall and temperature, respectively.

The mean annual rainfall and temperature patterns from 1980 to 2020 declined and intensified at  $R^2 = 0.15$  and  $0.19$  respectively (Fig. 2). These climate curves increased the vulnerability of biological processes. The temporal variability of rainfall patterns had significant attributions to the onset and cessation, intensity, frequency, and amount of rain. Although the study concentrated on the relatively undisturbed areas, the results had significant impacts on farming calendar for most farmers around the area (Mkonda & He 2017).

The results from Fig. 2 give a general exploration of the trend of rainfall in the study area based on the annual amount. It displays a wider context on long-term variability that explores the general situation on the ground. The result indicates that the intra-climatic variation was more pronounced during the growing season.

### Discussion

This study establishes a discussion on the measurable assessment of SOC in the relatively undisturbed environments as seen in Tables 2 and 3. As established in the background and findings, this study is among the fewest studies which have estimated SOC stock in the mountain foothills. For example, Rossi (2009) established SOC in the Soil Scapes of Southeastern Tanzania while Hartemink (1997) established soil nutrients including SOC under permanent cropping in north-eastern Tanzania. In addition, a study by Mäkipää et al. (2012) estimated SOC in the general lands. At least the study by Kempen et al. (2019) mapped SOC of the topsoil in Tanzania whereas, it found

**Table 3** Analyses result of the minor soil nutrients from the study area

Field ref	Depth (cm)	No. Samp	Soil pH (1:2:5) (in $\text{H}_2\text{O}$ ) (%)	$\text{CaCl}_2$ (%)	EC (200 $\mu\text{S/cm}$ )	Zn (mg/kg)	Mg (mg/kg)
Lowland	0–20	32	5.82	5.17	33	0.82	5.93
Lowland	20–40	32	6.13	5.28	31	0.78	3.56
Upland	0–20	32	6.87	4.29	29	0.31	2.53
Upland	20–40	32	7.03	3.73	25	0.22	1.51

**Source:** Lab soil analyses at Sokoine University of Agriculture (SUA), 2022

that among the areas with high SOC concentration are along the eastern arc mountains, Lake Tanganyika and north-western Tanzania.

Embarking to the study findings, the results on SOC accumulation in the relatively undisturbed environment indicate that the accumulation of SOC was on the top soils (0–20 cm) than on sub-soils (20–40 cm) because of most organic matter decomposition and deposits in that top layer (Tables 2 and 3). Besides, in terms of locations; SOC was higher in the lowland than in upland environments. This situation happens because in lowland areas there are more deposits of soil nutrients, from various sources, than in upland areas (Mkonda 2023).

Considerably, the variations in SOC stock over location within such a small-scale are attributed by some differences in microclimate, topographic position, parent material, soil texture, soil drainage, soil nutrient status, salinity and vegetation type (Batjes 2011; Mkonda and He 2018; Mkonda et al. 2018).

These results are even evident from other established studies such as those by Mkonda and He (2018), Mäkipää et al. (2012), Bationo et al. (2006) and Batjes (2011). On top of that, the findings are also reflected in the FAO guidelines (FAO 2006). On this basis, the present study can be set as a baseline for the forthcoming studies in the same area or similar environments.

Empirically, the findings of this study are fairly important to the replenishment of various biological processes including the functions of arbuscular mycorrhizae in intensifying the capacity of nutrient uptake by various plants (Hartemink 1997; Mkonda & He 2018). Based on the findings, especially the biological advantages of SOC, the lowland areas benefit more compared to the uplands. Alongside, in most incidences, it is a mandatory measuring unit for soil carbon assessment in clean development mechanisms.

Besides, the results indicate that there had been a serious decline in SOC in the upland areas (Table 2). Among other things, the slope and other erosion agents have been more pronounced in the upland areas compared to the counterpart (Mkonda 2023). This exactly indicates the essence of the same ecosystems (i.e. foothills of the mountain) having low SOC deposits in the upland than in the lowland. The implications of this study include; we expect more active biological processes in the lowlands than in the uplands due to differential SOC deposits.

Furthermore, in lowlands, the ability of organic matter to retain cations for plant utilization while buffering them from leaching was higher than in uplands (Ellert et al. 2002; Rossi 2009). The cation exchange capacity of organic matter is mainly due to negative charges created as hydrogen ions are removed from weak acids during neutralization (IPCC 2000). Besides, organic matter

also reduces or buffers the change of pH in the soil when acids or bases are added to the soil. If this situation happens; there might be improved vegetation in the area when other factors are kept constant. These implications are also determined in the studies by Burgess et al. (1998), Glaser et al. (2001), Hall et al. (2009), Johannes et al. (2017) and Kempen et al. (2019).

Similarly, the findings reveal that there have been increased differences in the water content of soil between the lowlands and uplands (Mkonda & He 2018). Lowland soils appeared to have high retaining water capacity than uplands because of high organic matter contents which buffer moisture that would get lost through leaching (Lal 2004; Hartemink et al. 2008).

Since SOC is resilient from losing moisture, the vegetation fields especially in the lowlands act as a sink for the first, second, and third largest greenhouse gases which are carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>), and nitrous oxide (N<sub>2</sub>O), respectively. By sinking these greenhouse gases, we are mitigating climate change impacts (Araujo et al. 2017; IPCC 2013; Haoa et al. 2016). To support this, several studies have specified that the amount of sequestered carbon is equivalent to that found in biomass ( $p < 0.05$ ). Therefore, soil restoration always leads to carbon sink and vice versa (UNFCCC 2007; IPCC 2013; Haoa et al. 2016).

In terms of climate (Fig. 2), appropriate rainfall plays a substantial role in the process of accumulating carbon in the soil as it facilitates various biological processes. Contrary, extremely low rainfall leads to the excessive drought that limits the production of plant biomass and the formation of organic matter. Principally, the change in moisture regime affects the decomposition of biomass the soil (Glaser et al. 2001; IPCC (2000)). Various studies have realized that there is an exponential correlation between SOC accumulation and precipitation (Mäkipää et al. 2012; Bationo et al. 2006; and Batjes (2011).

In terms of moisture, most literature stipulates that the moisture content in the lowlands is higher than in the upland. It is obvious that this difference reveals that the function of the soil biological process is more significant in the lowland than in the upland. Therefore, this situation also indicates that the two locations have different capacities in the provision of environmental services (Wilke 2005).

On the other hand, the increase in temperature and decrease in rainfall is likely to reduce the Net Primary Productivity and Net Ecosystem Productivity though it may not be easy to quantify the magnitude. Therefore, in this aspect, it can be concluded by asserting that there is a significant correlation between climate and SOC accumulation as also established by the United Nations Framework Convention on Climate Change (UNFCCC 2007).

## Conclusions

The present study has established the amount of SOC around the foothills of the Uluguru Mountain. Empirically, this study revealed that the amount of SOC in the lowlands was almost two times that of the uplands. These happened despite the fact that both environments were relatively undisturbed and were not very far apart. The quantified amount has significant implications to the environment and livelihood of the people. The findings of this study can be applied in various lowly elevated areas especially in the eastern arc mountains of east Africa. This study suggests that the lowly elevated areas or/and areas near the mountain foothills need substantial conservation to limit disproportionate erosion that might be caused by run-off. Based on the findings and discussion, this study poses insight on environment especially on how to design, plan and implement various environmental projects in areas with different ecological gradients.

**Data availability** These will be available at the request.

## Declarations

**Ethics approval** Not applicable.

**Consent to participate** Not applicable.

**Consent for publication** Not applicable.

**Competing interests** The authors declare no competing interests.

## References

- Araujo M, Zinn Y, Lal R (2017) Soil Parent Material, Texture and Oxide Contents Have Little Effect on Soil Organic Carbon Retention in Tropical Highlands. *Geoderma* 300:1–10. <https://doi.org/10.1016/j.geoderma.2017.04.006>
- Bationo A, Kihara J, Vanlauwe B, Waswa B, Kimetu J (2006) Soil Organic Carbon Dynamics, Functions and Management in West African Agro-Ecosystems. *Agric Syst* 94(1):13–25. <https://doi.org/10.1016/j.agsy.2005.08.011>
- Batjes NH (1996) Total carbon and nitrogen in the soils of the world. *Eur J Soil Sci* 47:151–163
- Batjes N (2011) Soil organic carbon stocks under native vegetation: Revised estimates for use with the simple assessment option of the carbon benefits Project system. *Agric. Ecosyst. Environ.* 142(3):365–373. <https://doi.org/10.1016/j.agee.2011.06.007>
- Burgess N, Fjeldsa J, Botterweg R (1998) Faunal importance of the eastern arc mountains of Kenya and Tanzania. *J East Afr Nat Hist* 87:37–58
- Ellert BH, Janzen HH, Entz T (2002) Assessment of a Method to Measure Temporal Change in Soil Carbon Storage". *Soil Sci Soc Am J* 66:1687–1695. <https://doi.org/10.2136/sssaj2002.1687>
- FAO (2006) Guidelines for Soil Description, 4th edn. FAO, Rome, p 97
- FAO-UNESCO (1988) Soil map of the world, revised legend, with corrections and updates. (World Soil Resources Report 60). FAO, Rome (reprinted with updates as Technical Paper 20, ISRIC, Wageningen, 1997, The Netherlands)
- Glaser B, Lehmann J, Führböter M, Solomon D, Zech W (2001) Carbon and Nitrogen Mineralization in Cultivated and Natural Savanna Soils of Northern Tanzania. *Biol Fertil Soils* 33:301–309. <https://doi.org/10.1007/s003740000324>
- Hall J, Burgess N, Lovett J, Mbilinyi B, Gereau R (2009) Conservation implications of deforestation across an elevational gradient in the Eastern Arc Mountains, Tanzania. *Biol Cons* 142:2510–2521
- Haoa Q, Jianga C, Chaia X, Huang Z, Fana XD, He X (2016) Drainage, No-Tillage and Crop Rotation Decreases Annual Cumulative Emissions of Methane and Nitrous Oxide from a Rice Field in Southwest China. *Agr Ecosyst Environ* 233(2016):270–281. <https://doi.org/10.1016/j.agee.2016.09.026>
- Hartemink AE (1997) Soils Fertility Decline in Some Major Soil Groupings under Permanent Cropping in Tanga Region, Tanzania. *Geoderma* 75:215–229. [https://doi.org/10.1016/S0016-7061\(96\)00087-0](https://doi.org/10.1016/S0016-7061(96)00087-0)
- Hartemink AE, Veldkamp T, Bai Z (2008) Land Cover Change and Soil Fertility Decline in Tropical Regions. *Turk J Agric* for 32:195–213
- Intergovernmental Panel on Climate Change (2000) Land use, land use change and forestry. In: Watson RT, Noble IR, Bolin B, Ravandranath NH, Verardo DJ, Dokken DJ (eds) A special report of the IPCC. Cambridge University Press, Cambridge
- Intergovernmental Panel on Climate Change (2013) Climate change 2013: the physical science basis. In: Stocker TF, Qin D, Plattner GK, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V, Midgley PM (eds) Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge
- Johannes A, Matter A, Schulin R, Weisskopf P, Bavey P, Boivina P (2017) Optimal Organic Carbon Values for Soil Structure Quality of Arable Soils. Does Clay Content Matter? *Geoderma* 302:14–21. <https://doi.org/10.1016/j.geoderma.2017.04.021>
- Jung M, Arnell A, de Lamo X, Visconti P (2021) Author Correction: Areas of global importance for conserving terrestrial biodiversity, carbon and water. *Nat Ecol Evol* 5(11):1–1. <https://doi.org/10.1038/s41559-021-01569-y>
- Kempen B, Dalsgaard S, Kaaya AK, Chamuya N, Ruipérez-González M, Pekkarinen A, Walsh MG (2019) Mapping topsoil organic carbon concentrations and stocks for Tanzania. *Geoderma* 337:164–180. <https://doi.org/10.1016/j.geoderma.2018.09.011>
- Khiavi HT, Mostafazadeh R (2022) The spatiotemporal dependencies of terrain indices with soil characteristics in a steep hillslope mountainous area. *Arab J Geosci* 15:937. <https://doi.org/10.1007/s12517-022-10220-4>
- Lal R (2004) Soil Carbon Sequestration Impacts on Global Climate Change and Food Security. *Science* 304:1623–1627. <https://doi.org/10.1126/science.1097396>
- Lal R (2008) Soil Carbon Stocks under Present and Future Climate with Specific Reference to European Ecoregions. *Nutr Cycl Agroecosyst* 81:113–127. <https://doi.org/10.1007/s10705-007-9147-x>
- Lal R (2015) Sequestering carbon and increasing productivity by conservation agriculture. *J Soil Water Conserv* 70(3):55A–62A. <https://doi.org/10.2489/jswc>
- Lovett JC (1998) Importance of the Eastern Arc Mountains for Vascular Plants. *J East Afr Nat Hist* 87(1):59–74
- Mäkipää R, Liski J, Guendehou S, Malimbwi R, Mäkipää A (2012) Soil Carbon Monitoring Using Surveys and Modeling General Description and Application in the United Republic of Tanzania. FAO, Rome
- Milne E, Adamat RA, Batjes NH, Bernoux M, Bhattacharyya T, Cerri CC, Cerri CEP, Coleman K, Easter M, Falloon P, Feller C, Gicheru P, Kamoni P, Killian K, Pal DK, Paustian K, Powlson DS, Rawajfih Z, Sessay M, Williams S, Wokabi S (2007) National and sub-national assessments of soil organic carbon stocks and changes: the GEFSOC modelling system. *Agr Ecosyst Environ* 112:3–12
- Mkonda MY (2022a) Awareness and adaptations to climate change among the rural farmers in different agro-ecological zones of

- Tanzania. *Manage Environ Qual* 33(5):1–26. <https://doi.org/10.1108/MEQ-10-2021-0241>
- Mkonda MY (2022b) Stakeholders' engagement in the process of adapting to climate change impacts, a case of central Tanzania. *Manage Environ Qual* 33(4):975–990. <https://doi.org/10.1108/MEQ-11-2021-0258>
- Mkonda MY (2023) Robust Variation in the Potentials of Tanzanian Soils under Sisal Plantation to Stabilize Organic Carbon and Nitrogen. A Case of Handeni District. *J Geog Nat Dis*. Vol. 13 Iss. 1. <https://doi.org/10.35841/2167-0587.23.13.260>
- Mkonda MY, He XH (2017) Are Rainfall and Temperature Really Changing? Farmer's Perceptions, Meteorological Data, and Policy Implications in the Tanzanian Semi-Arid Zone. *Sustainability*. 9 (8); <https://doi.org/10.3390/su9081412>
- Mkonda MY, He XH (2018) Accumulation of SOC under organic and no-fertilizations, and its influence on crop yields in Tanzania's semiarid zone. *Ecosystem Health Sustain*. <https://doi.org/10.1080/20964129.2018.1463146>
- Mkonda MY, He XH (2022) The Influence of Soil Organic Carbon and Climate Variability on Crop Yields in Kongwa District. *Tanzania Environ Manage*. <https://doi.org/10.1007/s00267-022-01592-0>
- Mkonda MY, He XH, Festin ES (2018) Comparing Smallholder Farmers' Perception of Climate Change with Meteorological Data: Experiences from Seven Agro-ecological Zones of Tanzania. *Weather, Clim Soc*. 10 (3). <https://doi.org/10.1175/WCAS-D-17-0036.1>
- Mostafazadeh R, Khiavi H, Ouri A, Golshan M (2022) Surface runoff and sediment yield response under the rainfall simulation condition controlled by soil variables of a semi-arid landscape. *Environ Dev Sustain*. <https://doi.org/10.1007/s10668-022-02569-z>
- Ogle SM, Conant RT, Paustian K (2004) Deriving grassland management factors for a carbon accounting method developed by the intergovernmental panel on climate change. *Environ Manage* 33:474–484
- Plaza-Bonilla D, Luis-Arrúe J, Cantero-Martínez C, Fanlo R, Álvaro-Fuentes A (2015) Carbon management in dryland agricultural systems. *Agron Sustain Dev* 35:1319–1334
- Rossi J (2009) Soil organic carbon in the soil scapes of southeastern Tanzania. PhD thesis K.U. Leuven University, Belgium
- Smith P, Fang C (2010) Carbon cycle: a warm response by soils. *Nature* 464:499–500
- Talebi KH, Mostafazadeh R (2021) Land use change dynamics assessment in the Khiavchai region, the hillside of Sabalan mountainous area. *Arab J Geosci* 14:2257. <https://doi.org/10.1007/s12517-021-08690-z>
- Talebi KH, Mostafazadeh R, Asaadi MA (2022) Temporal land use change and its economic values under competing driving forces in a diverse land use configuration. *Arab J Geosci* 15:1597. <https://doi.org/10.1007/s12517-022-10890-0>
- United Nation Framework Convention on Climate Change (2007) CDM-Executive Board 35. Annex 17: Tool for the demonstration and assessment of additionally in A/R CDM project activities. Bonn, Germany. <http://cdm.unfccc.int/EB/Meetings>
- Verburg PH, Neumann K, Nol L (2010) Challenges in using land use and land cover data for global change studies. *Glob Change Biol* 17:974–989
- Walkley A, Black IA (1934) An Examination of the Degtjareff Method for Determining Soil Organic Matter, and a Proposed Modification of the Chromic Acid Titration Method. *Soil Sci* 34:29–38. <https://doi.org/10.1097/00010694-193401000-00003>
- Wang X, He XH, Williams JR, Izaurralde RC, Atwood JD (2005) Sensitivity and uncertainty analyses of crop yields and soil organic carbon simulated with EPIC. *Trans Am Soc Agri Eng (ASAE)* 48:1041–1054
- Wilke BM (2005) Determination of Chemical and Physical Soil Properties. In: Margesin R, Schinner F (eds) *Manual for Soil Analysis – Monitoring and Assessing Soil Bioremediation*. Springer-Verlag, Berlin, pp 46–96

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