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Dynamics of Organic Carbon and Predictive Management Indices in Contrasting Land Use Types on Weathered Soils of Eastern Tanzania

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Abstract: This study examined carbon footprint as an indicator of soil health at spatiotemporal scales with different land use types and varying soil depths in Morogoro, representing the eastern agroecological zone of Tanzania. Soils are highly weathered and acidic. The specific objectives were twofold: (1) To quantify soil organic carbon (SOC) at varying soil depths (0–15 cm, 15–30 cm) in contrasting land use types, including tractor cultivated, hand-hoe cultivated, ranch land, and reserved/bare land type; (2) To predict carbon management indices (CMI) of the studied land use types through regresses SOC, carbon pool index (CPI), and lability index (LI) at varying soil depths. Composite soil samples were based on transects of three main plots each (replicates) of 20 m by 50 m. Results showed that land use types and soil depths significantly (P <0.001) affected SOC (3.4%) and CMI (126.3). Hand hoe cultivated land at 0–15 cm recorded CMI of 259.8. Regression analysis showed an increase in CMI ranging from 97% to 99%, with standard error ranging from 2.177 to 46.096. Similar trends, but with disparity magnitudes in regressed parameters provide useful insight into transformations of organic carbon in contrasting land use types.

Keywords: carbon sequestration; conservational land use soil health; sustainable agroecosystems; soil nutrient management; Tanzania

1. Introduction

Different land use types and the accompanying types of vegetation cover influence the dynamics of organic carbon as these situations cause significant disturbance to the soil. Land uses and management options with little disturbance to the soil are likely to increase soil organic carbon but intensive disturbance decrease soil organic carbon and as a results cause degradation of soil ecosystem [1]. The changes of an ecosystem to a cultivated/cropped land or ranch land from its natural form, for example of grassland/forest, may result in a loss of 50% of soil carbon [2–5]. Furthermore, vegetation growth on a cropped land facilitates carbon sequestration though capturing of atmospheric CO_2 during photosynthesis as well as storing CO_2 in soil for a long period [1,6]. Surface disturbances through cultivation may reduce carbon contents in soils along with reduction of carbon input and increased mineralization with synthetic fertilizers [7]. The effect of land use types on soil carbon is always never uniform as it varies with soil types [1]. According to Yeasmin et al. [1], soils are likely to vary in type, population and activity of microbes, type and amount of mineralogical composition, and native and/or inputs of organic matter. An accumulation of organic matter presents the most important factor for soil organic carbon contents [8]. Six et al. [8] indicated that native soil organic matter is an indicator of the balance of carbon inputs and losses under natural conditions where there are no anthropogenic interventions. Yeasmin et al. [1] reported that improved land use and crop management options result in additional carbon sequestration through more carbon input and/or low carbon harvest. The soil organic carbon in pastoral or ranch land, grassland, and cultivated/cropped agricultural land can even exceed their native soil carbon in conditions of proper land use and systems management options [1,9,10]. The fluxes of soil organic carbon in an ecosystem are influenced by land use and the types of vegetation cover as soil organic carbon depends largely

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on the quality of the litter material as well as deposition and turnover rate of the decomposing materials [9].

The world population is rapidly growing and it was around 7 billion people by 2020 and is expected to reach 9.1 billion people by 2020 [11]. With this increase, food production will be required to increase by 70% while land, water, and energy resource are increasingly becoming the limiting factors [11]. The Tanzanian population was around 56 million in 2018 and it is expected to reach 129 million people by 2050 [12,13]. Furthermore, the impact of climate change complicates the sustainability of resources for food production due to increased incidence of reducing factors (e.g., disease, insect, weeds), poor distribution and intensity of rains, and increased heat stress [14,15]. Intensification of food production systems such as agriculture and animal keeping has increased the use of mechanized options, improved varieties, and agrochemicals (fertilizers, herbicides, fungicides, etc.) but compromising other ecosystem services. The countries of the Global South (Africa, Asia, Latin America, and Oceania Pacific, have been increasing food production systems (agriculture and animal keeping) through transforming forest and/or natural grasslands to farming lands while threatening the biodiversity with loss in habitats and fragmentation [16,17]. Increased detrimental effect resulting from different land use types is consequently reported to cause a differential loss of soil organic carbon, especially in lands disturbed by production activities [18,19]. Besides these negative impacts, the production of paddy rice, for example, has been reported to increase accumulation of soil organic carbon but with the expense of relatively high methane (CH_4) emissions since flooding in fields limits the complete degradation of soil organic matter [20–23]. Sanderman et al. [24] also reported that farming activities have contributed to a net loss of the global soil organic carbon. Furthermore, the dynamics of nitrogen and phosphorus in soils as a result of changes in soil organic carbon are widely reported [24,25]. Studies have also indicated that soil organic carbon affects the physical characteristics of soils including compaction and bulk density [13,24]. Therefore, it is important to assess dynamics of soil organic carbon footprints as an indicator of soil health under different land use types as this has impact on environmental conservation and mitigation of climate change through carbon sequestration.

Soil organic carbon is an important indicator of physical characteristics of soils with various land use types. Contents of soil organic carbon have been reported to range from 0.55 to 10.8% in bush land and forest plantations in the plain and plateau, 1.03 to 6.34% in cultivated mid-slopes and lower slopes of the plateau, and around 4.5% in the vegetable growing valley bottoms in Tanzania [26]. Carbon sequestration mitigates climate change as one of the multiple ecosystem services for healthy soil [27]. Despite the wide documentation of the importance of carbon sequestration and soil organic carbon in provision of health environmental services, the dynamics of soil organic carbon and the associated drivers across various land use types of smallholder farmers in Tanzania are rarely understood. Land use types on the settings of smallholder farms have interconnecting services that have to be clearly documented. Land use types, changes and poor agronomic practices are responsible in depleting soil organic carbon [27].

Continuous disturbances posed on lands by various land use types are a major cause for a decline in soil organic carbon stocks in highly weathered tropical soils [28]. However, the information on the dynamics of soil organic carbon in the country is highly uncertain due to lack or shortage of reliable data [27,29]. Also, there is no reliable documentation of the dynamics of soil organic carbon with soil depths and at the spatial scale of land use types in eastern Tanzania. Furthermore, there are no studies on the dynamics of soil organic carbon as influenced by the interactions of soil depths with the spatial (altitudinal) scale of land use types. Therefore, this study evaluated the dynamics of soil organic carbon as influenced by different land use types with varying soil depths and at spatial scale. Findings from this study are expected to shed light on the soil health, inferring to soil organic carbon, with feasible options for environmental conservation under different land use types. In overall, the present study examined soil organic carbon footprint as an indicator of soil health at spatiotemporal scales with different land use types and varying soil depths. The specific objectives of this study are twofold: (1) To quantify soil organic carbon at varying soil depths (0–15 cm, 15–30 cm) in contrasting land use types, including tractor cultivated, hand-hoe cultivated, ranch land, and reserved/bare land type; (2) To predict organic carbon management indices of the studied land use types through regresses soil organic carbon, organic matter, carbon pool index, and lability index at varying soil depths.

2. Materials and Methods

2.1. Description of the study area

Experimental soils were collected from farms of the Sokoine University of Agriculture in Morogoro, eastern Tanzania. It is located on the northern foot-slopes of Uluguru Mountains at latitude 6.84763 °S and longitude 37.65570 °E at an elevation exceeding 536 m above sea level. The study accommodated various land use types including tractor cultivated land, hand hoe cultivated land, and grazed/ranch land compared against land reserved (bare) for over 13 years without any use (typical grass/shrub land). Rainfall of Morogoro region is bimodal, with long rains often starting in March to May but short rains are experienced in October through December. Rainfall is normally average of 861 mm while the mean monthly temperature is between 20 °C and 26 °C in the months of November and December [30].

2.2. Experimental design and soil sampling

Soil samples for the study were collected from paired sites of a bare (reserved) land for over 13 years and major land use types (tractor cultivated land, hand-hoe cultivated land, and grazed/ranch land). The composited soil samples were based on transects of three main plots each (replicates) of 20 m by 50 m (1000 m^2) demarcated within each site. Composite soil samples in each site were replicated at three altitudinal zones (> 400 m; 400–500 m; > 500 m above sea level) and with respect to soil depths. Two composite soil samples were obtained from 0–15 cm (top-soil) and 15–30 cm (sub-soil) in each plot. To obtain a composite soil sample in each demarcated plot, the soils were sampled at an equidistance of every 100 m^2 making total of 10 sampling spots and samples (Appendix A). There were total of 6 composite soil samples under each land-use type and reserved forest, making total of 48 composite soil samples for the study.

Soil organic matter in each soil was fractionated following procedures described by Camberdella & Elliott [31]. Air-dried soil sub-samples were sieved and 20 g of each placed in 250 mL plastic bottle. Then, 70 mL of sodium hexa-metaphosphate solution ($Na_6[(PO_3)_6]$) was added and the mixture shaken for 15 h on an end to end electrical shaker. The contents of mixtures were passed through series of sieves (2 mm, 250 and 53 μ) and the fractions collected dried at 50 °C for 48 h in an air oven. The 53–250 μ fractions were referred to as labile soil organic matter. All the materials that passed through 53 μ sieve were collected in a flask, swirled to mix thoroughly and a sample of 100 mL taken and oven-dried. This sample was regarded as the stable soil organic matter. The oven-dried fractions were ground using mortar and pestle to very fine material, sieved through 0.149 mm sieve and analysed for soil organic carbon [9].

The enrichment ratio or lability index (LI) of the labile carbon was calculated by dividing it (carbon) by the total organic carbon of the same land use [9]. Several soil organic carbon indices in the disturbed sites (tractor, hand hoe and ranch) were calculated to evaluate spatial dynamics of carbon content with various land use types. Carbon management index (CMI) as an assessment model that shows how a particular land use affects soil quality relative to reference land use soil (forest or undisturbed land) was calculated as described by Sainepo et al. [9] as shown in Equations 1–4.

$$\mathrm{CMI} = \mathrm{CPI} \times \mathrm{LI} \times 100 \tag{1}$$

where CMI is carbon management index, CPI is the carbon pool index, and LI is the lability index of the soil under a particular land use.

$$\mathbf{CPI} = \frac{\text{Organic carbon in soil of specific land use type (\%)}}{\text{Organic carbon in the reference soil of reserved land (\%)}} \tag{2}$$

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$$\mathrm{LI} = \frac{\text{L in soil of specific land use type}}{\text{L in the reference soil of reserved land}} \quad (3)$$

where, L is carbon lability of the soil.

$$\mathbf{L} = \frac{\textbf{Content of labile C}}{\textbf{Content on non} - \textbf{labile C}} \quad (4)$$

Uncultivated land (bare) was used as reference land use type in this study due to persistent rehabilitation for the past 13 years and it is enclosed from grazing and other anthropogenic disturbances (Appendix B). Carbon management index higher than the reference land use type suggests better management [32].

2.3. Statistical data analysis

In assessing the effects of factors land use types (spatial variability) and soil depths (vertical variability) on soil organic carbon, organic matter or carbon management index the fixed main effects were the sites (bare/reserved land, ranch land, tractor cultivated land, and hand hoe cultivated land) and soil sampling depths (0–15 cm and 15–30 cm), whereas replicate transects were treated as random effect [33]. A split-plot design of analysis of variance was performed and the factor effects model is as shown in Equation 5. Land use types were subjected to the whole plot category and sampling depths to the sub-plot at a single combination of their effect on soil organic carbon, organic matter and/or carbon management index. Significant means were compared through least significant difference (LSD), whereas interaction effects were compared through standard errors of differences of means (S.E.D.) at 5% threshold by Tukey's post-hoc multiple comparisons.

$$\mathrm{Y}_{ij} = \mu + \alpha_i + \beta_j + \beta_i\alpha_j + \varepsilon_{ij} \quad (5)$$

where Yij is the observed soil organic carbon, organic matter and carbon management index in the *ijth* factors; μ is the overall (grand) mean; α_i and β_j are the main effects of the factors land use types and soil depths, respectively; $(\alpha\beta)_{ij}$ is the two-way interactions between the factors; εij is the random error the *ijth* factors.

In addition, soil organic carbon, organic matter and carbon management index were assessed at each specific sampling depth (not considered as a factor – single pool) and land use types (considered as a factor) through one-way analysis of variance and the factor effect model is as shown in Equation 6. Significant means were compared through standard errors of differences of means (S.E.D.) at 5% threshold by Tukey's post-hoc multiple comparisons.

$$\mathbf{Y}_i = \mu + \boldsymbol{\alpha}_i + \boldsymbol{\varepsilon}_i \quad (6)$$

where Yi is the observed soil organic carbon, organic matter or carbon management index in the *ith* factor; μ is the overall (grand) mean; α_i is the effect of land use types; εi is the random error associated with *ij* factors.

Multiple linear regressions analysis was performed to evaluate the relationship of carbon management index (response variate) with soil organic carbon, organic matter, carbon pool index, and lability index (explanatory variates) at soil depths 0–30 cm, and the fitted model is shown in Equation 7. Regression analysis was performed for each land use type without combining, but the data from bare land (reference) was excluded from this analysis.

$$\mathbf{Y}_{ijkl} = \boldsymbol{\beta}_i \boldsymbol{X}_1 + \boldsymbol{\alpha}_j \boldsymbol{X}_2 + \boldsymbol{\sigma}_k \boldsymbol{X}_3 + \boldsymbol{\gamma}_l \boldsymbol{X}_4 + \mathbf{C} \quad (7)$$

where Y_{ijkl} is the predicted carbon management index in the *ijklth* factors, β_i, α_j, σ_k, and γ_l are the coefficients or slopes, and C is the intercept.

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3. Results

3.1. Effect of land use types and soil sampling depths on organic carbon and carbon management index

Soil organic carbon differed significantly ($P < 0.001$), with a soil depth of 0–15 cm displaying higher value (3.16%), which is higher than that (2.23%) recorded at a soil depth of 15–30 cm (Tables 1 and 2). Main effect of land use types on the measured variables also differed significantly (P <0.001), with the highest values of all three parameters recorded in tractor cultivated land (SOC = 3.4%; SOM = 5.8%; CMI = 126.3), but statistically similar with bare (reference) land (SOC = 3.1%; SOM = 5.3%). In contrast, there was no significant effect of land use types on carbon management indices (Table 1). However, in-depth analysis using Shapiro-Wilk test for Normality shows that residuals for carbon management indices were normally distributed (Test statistic W: 0.9796; probability: 0.562). Variances were also homogenous based on Bartlett's test for homogeneity of variances (Chi-square 142.09 on 7 degrees of freedom: probability = 0.081). Results showed that ranch land use type recorded the lowest carbon management index (77.1) as opposed to tractor cultivated land (126.3), hand hoe cultivated land (204), and bare (100) land (Figure 1). Interactions of land use types and soil depths had higher soil organic carbon, soil organic matter and carbon management index in tractor cultivated land, which are comparable to bare land at a soil depth of 0–15 cm. However, hand hoe cultivated land at a soil depth of 0–15 cm showed the highest carbon management index of 259.8 (Table 2; Figure 2).

Table 1. Analysis of variance for the effect of land use types and soil depths on soil organic carbon, organic matter and carbon management indices.

		Measured Variables in Soils and Statistical Parameters								
		Soil Organic Carbon			**Soil Organic Matter**			**Carbon Management Index**		
Source of Variation	**d.f.**	**m.s.**	**v.r.**	***F pr.***	**m.s.**	**v.r.**	***F pr.***	**m.s.**	**v.r.**	***F pr.***
Replication	5	0.16	0.81		0.5	0.86		25681	1.65	
Land use types (T)	3	4.72	24.03	<0.001	14.15	24.23	<0.001	36571	2.36	0.113
Residual	15	0.2	1.33		0.58	1.33		15522	0.64	
Depth (D)	1	10.27	69.81	<0.001	30.24	68.99	<0.001	6596	0.27	0.607
T×D	3	0.35	2.36	0.102	1.06	2.41	0.097	13158	0.54	0.658
Residual	20	0.15			0.44			24210		
Total	47									

Key: d.f. =degrees of freedom; m.s. = mean sum of squares; v.r. = variance; *F pr.* = test-F probability.

Table 2. Means of soil organic carbon, organic matter and carbon management indices as affected by land use types, soil depths and their interactions.

Factors Evaluated	**Levels of Factors**	**Measured Parameters**		
		SOC (%)	**SOM (%)**	**CMI**
Land use types	Tractor cultivated	3.4^{a}	5.8^{a}	126.3^{a}
	Ranch land	2.3^{b}	3.9^{b}	77.1^{a}
	Hand hoe cultivated	2.1^{b}	3.6^{b}	204^{a}
	Bare land (Reference)	3.1^{a}	5.3^{a}	100^{a}
	P – value	<0.001	<0.001	0.113
	LSD (0.05)	0.4	0.7	108.4
	cv (%)	11.6	11.6	26.7
Sampling depth (cm)	0–15	3.2^{a}	5.4^{a}	139^{a}
	15–30	2.2^{b}	3.9^{b}	115^{a}
	P – value	<0.001	<0.001	0.607
	LSD (0.05)	0.2	0.4	93.7
	cv (%)	2.6	2.7	12.4

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Interactions	Tractor cultivated land (0–15 cm)	3.7^{a}	6.3^{a}	103.3^{a}
	Tractor cultivated land (15–30 cm)	3.1^{ab}	5.4^{ab}	149.2^{a}
	Hand hoe (0–15 cm)	2.5^{b}	4.2^{b}	259.8^{a}
	Hand hoe cultivated (15–30 cm)	1.7^{c}	2.9^{c}	148.2^{a}
	Ranch land (0–15 cm)	2.9^{ab}	5.0^{ab}	91.2^{a}
	Ranch land (15–30 cm)	1.6^{c}	2.8^{c}	63.1^{a}
	Bare land (Reference) (0–15 cm)	3.6^{a}	6.2^{a}	100^{a}
	Bare land (Reference) (15–30 cm)	2.5^{b}	4.3^{b}	100^{a}
	P – value	0.102	0.097	0.658
	S.E.D.	0.2	0.4	82.6
	cv (%)	15.2	14.3	21.3

Key: *Means in a category of comparison along the same column bearing different letter(s) differ significantly at 5% error rate. SOC = soil organic carbon; SOM = soil organic matter; CMI = carbon management index; LSD* = least significant differences of means; *S.E.D.* = standard errors of differences of means; *cv* = coefficients of variation.

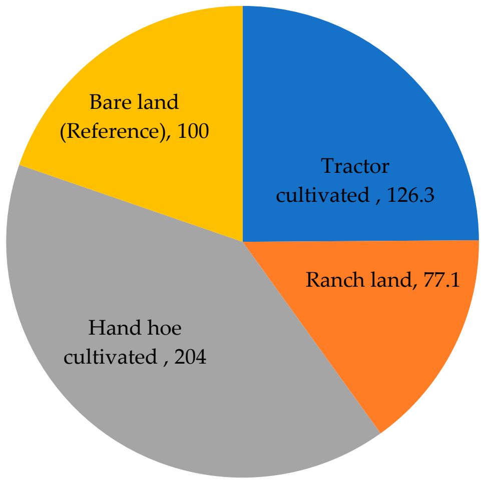

Figure 1. Organic carbon management indices of four different land use types.

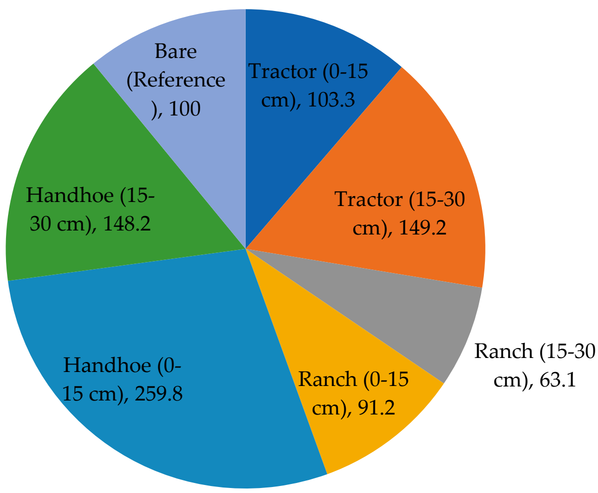

Figure 2. Carbon management indices distribution with land use types and soil depths (0-15 cm and 15-30 cm).

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3.2. Effect of land use types on organic carbon and carbon management index at 0–15 cm soil depth

Land use types had significant effect on soil organic carbon (*P* =0.002), organic matter (*P* =0.002) and carbon management indices (*P* =0.007) at a soil depth of 0-15 cm (Table 3; Figures 3 and 4). Tractor cultivated land and bare land had comparably similar higher soil organic carbon (3.7% by 3.6%) than the values (2.9% by 2.5%) recorded in hand hoe cultivated and ranch lands at a soil depth of 0–15 cm (Figure 3). Similar trend was observed in carbon management indices, where the highest values (115.7 by 100.9) were recorded in tractor cultivated and bare lands. Ranch and hand hoe cultivated lands recorded the lowest (67.9 by 53.9) carbon management indices at the same soil depth of 0–15 cm (Figure 4).

Table 3. Analysis of variance for the effect of land use types on soil organic carbon, organic matter and carbon management indices at a soil depth of 0–15 cm.

Source of Variation	Measured Variables in Soils and Statistical Parameters									
		Soil Organic Carbon			Soil Organic Matter			Carbon Management Index		
	d.f.	m.s.	v.r.	*F pr.*	m.s.	v.r.	*F pr.*	m.s.	v.r.	*F pr.*
Replication	5	0.067	0.26		0.1908	0.25		2405.6	2.95	
Land use types	3	1.994	7.66	0.002	5.9804	7.73	0.002	4911.9	6.03	0.007
Residual	15	0.26			0.7734			814.7		
Total	23									

Key: d.f. =degrees of freedom; m.s. = mean sum of squares; v.r. = variance; *F pr.* = test-F probability.

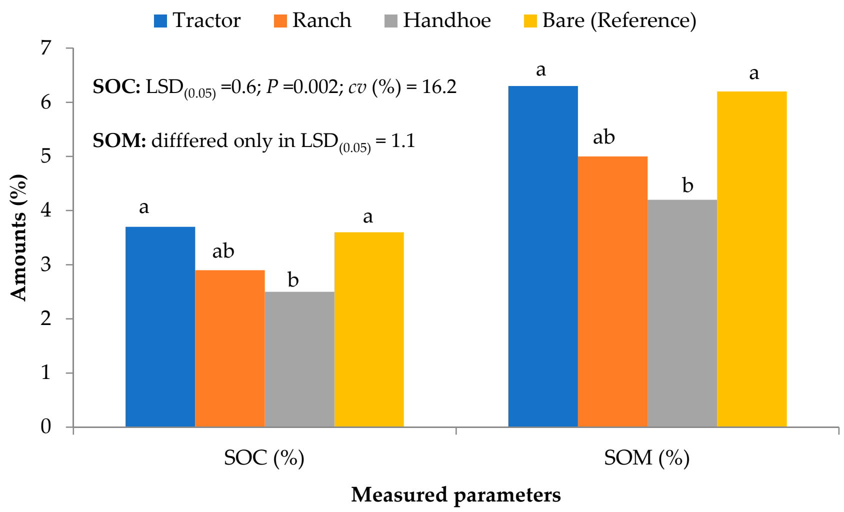

Figure 3. Soil organic carbon and organic matter distribution with land use types at 0–15 cm soil depth.

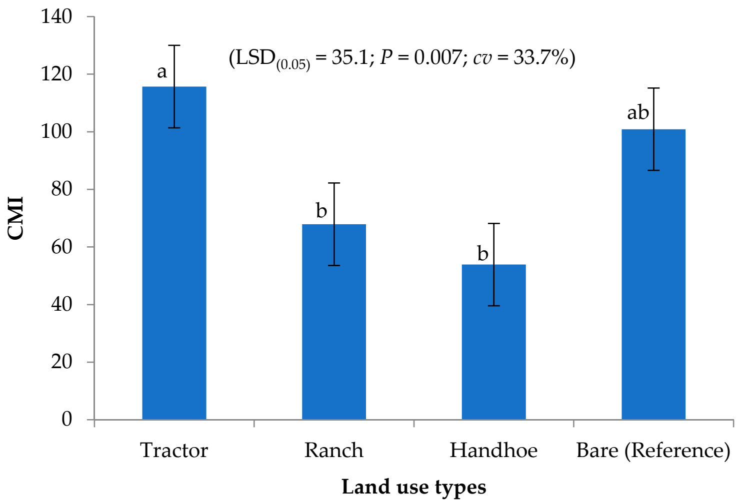

Figure 4. Carbon management indices distribution with land use types at 0–15 cm soil depth.

3.3. Effect of land use types on organic carbon and carbon management index at 15–30 cm soil depth

Soil organic carbon, organic matter and carbon management indices differed significantly ($P<0.001$) across land use types at a soil depth of 15–30 cm (Tables 4 and 5; Figures 5 and 6). Tractor cultivated land recorded the highest soil organic carbon (3.1%), organic matter (5.4%) and carbon management index (161.8). this trend was followed by bare land, hand hoe and ranch lands (Table 5).

Table 4. Analysis of variance for the effect of land use types on soil organic carbon, organic matter and carbon management indices at a soil depth of 15–30 cm.

Source of Variation		Measured Variables in Soils and Statistical Parameters								
		Soil Organic Carbon			Soil Organic Matter			Carbon Management Index		
	d.f.	m.s.	v.r.	*F pr.*	m.s.	v.r.	*F pr.*	m.s.	v.r.	*F pr.*
Replication	5	0.21	2.2		0.63	2.18		240.1	0.52	
Land use types	3	3.07	32.66	<0.001	9.22	31.9	<0.001	18127	39	<0.001
Residual	15	0.09			0.29			464.8		
Total	23									

Key: d.f. =degrees of freedom; m.s. = mean sum of squares; v.r. = variance; *F pr.* = test-F probability.

Table 5. Means of soil organic carbon, organic matter and carbon management indices at a soil depth of 15–30 cm as affected by land use types.

Land Use Types	Measured Parameters in Soils		
	Soil organic carbon	Soil Organic Matter	Carbon Management Index
Tractor	3.1^{a}	5.4^{a}	161.8^{a}
Ranch	1.6^{c}	2.8^{c}	45.1^{c}
Hand hoe	1.7^{c}	2.9^{c}	47.8^{c}
Bare (Reference)	2.5^{b}	4.3^{b}	101.1^{b}
P - value	<0.001	<0.001	<0.001
$LSD_{(0.05)}$	0.4	0.7	26.5
cv (%)	13.7	14	24.2

3.4. Regression analysis of the measured parameters

Regression analysis results indicated that soil organic carbon, carbon pool index, and lability index contributed significantly ($P<0.001$) in increasing carbon management indices at different land use types for the soil depth of 0–30 cm. In contrast, soil organic matter had negative effect on carbon management indices (Tables 7 and 8). The increase in carbon management indices accounted for by the regressed parameters ranged from 97% (0.973) to 99% (0.994), with standard error accounted for ranging from 2.177 to 46.096. Other factors not included in the model are likely to contribute 1 to 3% increase in carbon management indices in the studied land use types at a soil depth of 0–30 cm. Ranch land and tractor and hand hoe cultivated lands (Table 6). Both carbon pool index (P =0.02298) and lability index (P =0.01842) hand strongly positive and significant effect on increasing carbon management index in tractor cultivated land. Similar trend was observed in hand hoe cultivated land for lability index (P <0.001) and in ranch land for carbon pool index (P =0.00056) in increasing carbon management index (Table 8).

Table 6. Regression statistics between carbon management indices and soil organic carbon, carbon pool index, lability index, and soil organic matter in different land use types.

	Land Use Types		
Regression Statistics	**Tractor**	**Hand Hoe**	**Ranch**
Multiple R	0.997	0.991	0.998
R Square	0.993	0.983	0.996
Adjusted R Square	**0.989**	**0.973**	**0.994**
Standard Error	4.828	46.096	2.177
Observations	12	12	12

Table 7. Regressions analysis of variance between carbon management indices and soil organic carbon, carbon pool index, lability index, and soil organic matter in different land use types.

		Tractor			Hand Hoe			Ranch		
	df	*MS*	*F-stat.*	*Significance F*	*MS*	*F-stat.*	*Significance F*	*MS*	*F-stat.*	*Significance F*
Regression	4	5828.44	250.03	1.25E-07	210945	99.28	3.04E-06	2334.57	492.43	1.19E-08
Residual	7	23.31			2124.84			4.74		
Total	11									

Table 8. Regressions coefficients of carbon management indices regressed against soil organic carbon, carbon pool index, lability index, and soil organic matter for different land use types.

Land Use Type	*Fitted Parameters*	*Coefficients*	*Standard Error*	*t Stat*	*p-Value*	*Lower 95%*	*Upper 95%*
Tractor	**Intercept**	-109.67	14.52	-7.55	0.00013	-144.01	-75.33
	SOC	84.49	75.4	1.12	0.29945	-93.8	262.77
	CPI	100.52	34.66	2.9	**0.02298**	18.56	182.47
	LI	112.67	36.87	3.06	**0.01842**	25.5	199.85
	SOM	-48.91	44.04	-1.11	0.30345	-153.06	55.23
Hand hoe	**Intercept**	-214.91	113.41	-1.9	0.09993	-483.1	53.3
	SOC	147.65	1163.96	0.13	0.90263	-2604.7	2900
	CPI	223.28	196.7	1.14	0.2937	-241.8	688.4
	LI	97.17	11.81	8.23	**7.63E^{-05}**	69.2	125.1
	SOM	-80.57	676.47	-0.12	0.9085369	-1680.2	1519
Ranch	**Intercept**	-74.88	3.76	-19.93	0.0000002	-83.8	-66
	SOC	82.62	48.04	1.72	0.12914	-31	196.2
	CPI	170.5	28.58	5.97	**0.00056**	102.9	238.1
	LI	30.95	20.38	1.52	0.1725	-17.2	79.1
	SOM	-49.26	27.89	-1.77	0.12072	-115.2	16.7

Key: SOC = soil organic carbon; CPI = carbon pool index; LI = lability index; SOM = soil organic matter. *Values of P-value in bold highlight indicate that the parameters had strong and significant effect on increasing soil management index of the studied soil in respective land use types.*

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4. Discussion

Land use types, soil depths and grassland cover pose high variation in accumulation of soil organic carbon and the overlying carbon management indices. Except for the ranch land use type, which recorded the lowest carbon management indices at both varying soil depths (63.1–91.2), other land use types have good carbon management indices (> 100) over the reference land used in the present study. The low carbon management indices at varying soil depths in ranch land could be attributed to high removal of grassland biomass by the grazed animals, resulting in low organic matter inputs, hence affecting ecosystem management options of soil organic carbon. Available literature affirms that grassland contains 10% of terrestrial biomass, 30% of the global terrestrial organic carbon in soils, and occupy 70% of agricultural land ([28,34–38]. Photosynthesis by plants constitutes carbon inputs whereas their respiration decomposition of organic matter constitutes carbon loss, thereby creating a balance of soil organic carbon stocks in ecosystems [39]. Other studies highlight that organic carbon stored in soil as organic matter is about 20% of global carbon stocks, with its distribution being extended to a soil depth of 1 m [39,40]. Chang et al. [41] found that grazing of animals resulted in variation of soil organic carbon, but the variation was dependent on the grassland types.

The ploughing depth of tractor drawn mouldboard is reported elsewhere to result into variation in soil organic carbon. Reicosky & Archer [42] measured higher CO_2 flux in tillage intensity involving mouldboard plough relative to no tillage practice. Alamouti & Navabzadeh [43] found that soil bulk density, soil organic carbon, soil water infiltration, and crop yields were highly affected by deep tillage. The same parameters were decreased by the increase in ploughing depth [43]. Bilen et al. [44] reported that full-width tillage practice (moldboard plow + disc harrow + leveler) gave 100% surface soil disturbance and resulted in significant CO_2-C fluxes and total porosity. Available literature provides interesting results regarding potential of hand-hoe cultivation in management of soil organic carbon as one of the farming strategies. In corroboration to the findings of the present study, Martinsen et al. [45] found similar variation in soil organic carbon and carbon stocks between conventional and hand-hoe farming on smallholder farms in 40 sites of Eastern and Central provinces in Zambia. According to Martinsen et al. [45], insignificant variation in soil organic carbon between contrasting farming systems could be attributed to its very low net accumulation or inconsistent and significant seasonal changes in sources of their organic matter. Similar to the findings of the present study, average concentrations of organic carbon in hand-hoe and conventional animal drawn tillage were reported to be less than 10 g kg^{-1} in 15 districts of four agro-ecological zones in Zimbabwe, which is a minimum threshold for well managed soils [46]. Eze et al. [47] reported insignificant build-up in soil organic matter in 10–12 years maize-based conservation agriculture system in central and southern Malawi.

Organic carbon is regarded as the measure of carbon in plant and animal remains, which in turn these remains are the soil humus and termed as soil organic matter. On the other hand, soil organic matter plays role in contributing to carbon sequestration, soil structure, retention and turnover of nutrients, moisture conservation and availability, and enhancing pollutants degradation [48]. Throughout literature it has been reported that soil organic carbon is a measureable component of soil organic matter and it plays role in the chemical, physical, and biological systems in soils [48–50]. Monitoring is indispensable as there is a direct relationship between organic carbon and organic matter contents in the soil [49]. The conversion of natural ecosystems to production lands, like for agriculture, is reported to deplete soil organic carbon by 60% and 75% in soils of temperate regions and tropics, respectively [49,51]. The quality of soils is defined as the ability of the soil to function by largely depending on the available soil organic carbon on the topsoil [52,53]. The quality of the soil together with water and air quality constitute three components of environmental quality [54]. Studies have shown that a decrease in soil organic carbon has great impacts on soil quality ([49,54]. According to Johannes et al. [55], soil organic carbon to clay ratio is proportional to the vulnerability of soil structure, but the ratio should be higher than 10% for acceptance of structure vulnerability. Microorganisms can decompose about 90% of organic carbon that enters a soil in organic residues, as well as respiring back carbon into the atmosphere as carbon dioxide (CO_2). According to Deluz et al.

[49], soil organic matter is considered to be a result of the difference between inputs and losses. The soil organic matter is influenced by climatic conditions, type of the soil, and land use or management options [49]. Whereas soil organic matter inputs to the soil depend on production of plant biomass from supplemental amendments and by-products from animal production, the losses are due to decomposition of organic matter and soil erosion [49,54]. However, these inputs and losses of soil organic carbon are not well assessed to provide inference of carbon trends in Tanzanian land use types and ordinary land management options on smallholder farms. Therefore, this was an important knowledge gap about clearly addressing dynamics of soil organic carbon in different land use types.

Regression analysis showed that for every single unit increase in soil organic carbon, carbon pool index, and lability index there are increases in carbon management indices by 84.49, 100.52, and 112.67, respectively in tractor cultivated land use type. In this fitted model, lability index outperforms other two parameters in contributing to variability in carbon management index under tractor cultivated land. Soil organic carbon is still to be improved in tractor cultivated land, along with evaluating effects associated with disc depth, which is not covered by the scope of the present study. The trend observed in hand hoe cultivated land, systematically reverses that of tractor cultivated land. Every unit increase in lability index, soil organic carbon, and carbon pool index resulted in increase of carbon management indices by 97.17, 147.65, and 223.28, respectively in hand hoe cultivated land. This finding suggests that carbon pool index displays the highest carbon management index in hand hoe cultivated land. In other words, lability index remains to be a constraint that requires more attention in carbon management index of hand hoe cultivated lands. A similar trend to that hand hoe cultivated land was followed by regression results from ranch land. Every unit increase in lability index, soil organic carbon, and carbon pool index resulted in increase of carbon management indices by 30.95, 82.62, and 170.50, respectively in ranch land use type. This finding shows how carbon pool index is superior to other regressed parameters in increasing carbon management index in ranch land use type. Although similar trends are portrayed by the regressed parameters in the ranch land and hand hoe cultivated land, there is still a disparity in the magnitude of the values, which could be attributed to the transformations of organic carbon in such contrasting land use types. Using soil samples from 30 cm depth topsoil of five major land use types and three slope positions, Buraka et al. [56] found significantly lowest and highest mean of soil organic carbon in bare and bush lands. According to Burakaet al. [56], bare land lost 3.82 times higher soil organic carbon than bush land and 2.68 times more than forest land. Soil organic carbon is also concentrated in lower-slopes. Wang et al. [57] found that soil organic carbon and management indices were well predicted with regression analysis using 290 topsoil samples, and accuracy and the model differed with land use types. Using multiple linear regressions analysis with 210 surface soil samples (0-20 cm), Liuet al. [58] found that soil organic carbon distribution in four different land use types followed a trend forestland > scrubland > grassland > farmland. According to Liuet al. [58], soil organic carbon was importantly influenced by land use types, slope and curvature. Liu et al. [58] also emphasized that multiple regression model accurately performed better than geo-statistics in prediction of soil organic carbon and management indices in contrasting land use types.

Different land use types and resulting changes are globally in carbon dynamics [50,59]. Sharma et al. [60] found that soil organic carbon in a 7% of forest area converted to agricultural land, the latter had 15% changes for the period 10 years. In the same period these changes in agricultural land resulted to 4.88 Mt loss of soil organic carbon while conversion of forest to agricultural land resulted to 3.16 Mt of soil organic carbon [60]. Abebe et al. [61] indicated that soil organic carbon was an important ecological indicator of soil quality which is determined also by the landscape. According to Abebe et al. [62], soil organic carbon is influenced by different types of land use and topographic inclination. Abebe et al. [62] analyzed soil organic carbon in soils with three depths of 0–50 cm, in land use types of grazing land, bushland, plantation, and cropland under topographic positions of upper, middle, and lower altitudes. A study conducted by Abebe et al. [62] found that soil organic carbon varied significantly across topographic, land use types, and agro-ecosystems. Furthermore, soil organic carbon was significantly higher in bushland and grazing lands and lowest in cropland [62]. Low soil organic carbon in cropped land was attributed to poor management options and

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extensive biomass removal. The dynamics of soil organic carbon in surface layers (0–10 cm) of some ferrasols from Oumé, mid-west Côte d'Ivoire decreased from natural forest to mixed crop systems [63]. Seifu et al. [64] found significant differences in soil organic carbon as affected by land use types and slope/elevation with the highest soil organic carbon recorded at the lower elevation.

5. Conclusions

This study examined carbon footprint as an indicator of soil health at spatiotemporal scales with different land use types and varying soil depths in Morogoro region of Tanzania, representing eastern agro-ecological zone. Land use types and soil depths showed significant effects on the studied parameters. However, there were no significant interaction effects between land use types and soil depths on the measured parameters, but the highest values were recorded in tractor cultivated land, which were statistically comparable with bare (reference) land. The studied parameters were higher in 0–15 cm than 15–30 cm soil depths. Hand hoe cultivated land at 0–15 cm recorded significantly high CMI. Regression analysis showed interesting results on the contribution of regressed parameters in increasing CMI. Similar trends observed in CMI but with disparity magnitudes for ranch land and hand hoe cultivated land types in regressed parameters provide useful insight in transformations of organic carbon in contrasting land use types. Similar trends, but high disparity in magnitudes of regressed parameters on predicting carbon management indices portray research gap that has not been attended. Therefore, much research remains to be conducted in diverse land use types and soil depths to ascertain critical options for carbon stock management and sequester carbon along the context of environmental vulnerability to climate change.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

Table A1. Plot size and soil sampling plan in each land use type.

20 m	S8 S10	S8 S10	S8 S10
	S7	S7	S7
	S3 S9	S3 S9	S3 S9
	S1	S1	S1
	S6 S5	S6 S5	S6 S5
	S2 S4	S2 S4	S2 S4
	50 m	50 m	50 m
	Replication 1	**Replication 2**	**Replication 3**

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Appendix B

Table A2. Data collected and arrangement.

Land Use Type	Depth (cm)	Repl.	OC (%)	L-Treatment	L-Reference	Ref. Land Use	Carbon Pool Index (CPI)	LI	CMI	OM (%)
Tractor	0-15	1	4.2	0.10	0.09	3.3	1.27	1.11	141.41	7.2
Tractor	15-30	1	3.1	0.08	0.07	2.7	1.15	1.14	131.22	5.3
Tractor	0-15	2	3.1	0.08	0.11	4.2	0.74	0.73	53.68	5.3
Tractor	15-30	2	2.5	0.06	0.06	2.3	1.09	1.00	108.70	4.3
Tractor	0-15	3	4.1	0.10	0.11	3.9	1.05	0.91	95.57	7.1
Tractor	15-30	3	3.8	0.09	0.08	2.8	1.36	1.13	152.68	6.6
Tractor	0-15	4	3.7	0.09	0.10	3.7	1.00	0.90	90.00	6.4
Tractor	15-30	4	3.6	0.09	0.07	2.6	1.38	1.29	178.02	6.2
Tractor	0-15	5	3.1	0.08	0.11	4	0.78	0.73	56.36	5.3
Tractor	15-30	5	2.7	0.07	0.06	2.3	1.17	1.17	136.96	4.7
Tractor	0-15	6	3.7	0.09	0.07	2.6	1.42	1.29	182.97	6.4
Tractor	15-30	6	3.1	0.08	0.06	2.2	1.41	1.33	187.88	5.3
Hand hoe	0-15	1	2.6	0.10	0.09	3.3	0.79	1.11	87.54	4.5
Hand hoe	15-30	1	1.9	0.09	0.07	2.7	0.70	1.29	90.48	3.3
Hand hoe	0-15	2	2.5	0.12	0.11	4.2	0.60	1.09	64.94	4.3
Hand hoe	15-30	2	1.8	0.10	0.06	2.3	0.78	1.67	130.43	3.1
Hand hoe	0-15	3	2.1	0.13	0.11	3.9	0.54	1.18	63.64	3.6
Hand hoe	15-30	3	1.5	0.11	0.08	2.8	0.54	1.38	73.66	2.6
Hand hoe	0-15	4	2	0.16	0.10	3.7	0.54	1.60	86.49	3.4
Hand hoe	15-30	4	1.9	0.18	0.07	2.6	0.73	2.57	187.91	3.3
Hand hoe	0-15	5	2.8	0.33	0.11	4	0.70	3.00	210.00	4.8
Hand hoe	15-30	5	1.7	0.29	0.06	2.3	0.74	4.83	357.25	2.9
Hand hoe	0-15	6	2.8	0.68	0.07	2.6	1.08	9.71	1046.15	4.8
Hand hoe	15-30	6	1.3	0.05	0.06	2.2	0.59	0.83	49.24	2.2
Ranch	0-15	1	2.6	0.10	0.09	3.3	0.79	1.11	87.54	4.5
Ranch	15-30	1	2.1	0.08	0.07	2.7	0.78	1.14	88.89	3.6
Ranch	0-15	2	3.1	0.11	0.11	4.2	0.74	1.00	73.81	5.3
Ranch	15-30	2	1.3	0.05	0.06	2.3	0.57	0.83	47.10	2.2
Ranch	0-15	3	2.7	0.10	0.11	3.9	0.69	0.91	62.94	4.7
Ranch	15-30	3	1.8	0.07	0.08	2.8	0.64	0.88	56.25	3.1
Ranch	0-15	4	3.6	0.13	0.10	3.7	0.97	1.30	126.49	6.2
Ranch	15-30	4	1.4	0.05	0.07	2.6	0.54	0.71	38.46	2.4
Ranch	0-15	5	2.9	0.11	0.11	4	0.73	1.00	72.50	5
Ranch	15-30	5	1.3	0.05	0.06	2.3	0.57	0.83	47.10	2.2
Ranch	0-15	6	2.5	0.09	0.07	2.6	0.96	1.29	123.63	4.3
Ranch	15-30	6	1.9	0.07	0.06	2.2	0.86	1.17	100.76	3.3
Bare (Reference)	0-15	1	3.3	0.09	0.09	3.3	1.00	1.00	100.00	5.7
Bare (Reference)	15-30	1	2.7	0.07	0.07	2.7	1.00	1.00	100.00	4.7
Bare (Reference)	0-15	2	4.2	0.11	0.11	4.2	1.00	1.00	100.00	7.2
Bare (Reference)	15-30	2	2.3	0.06	0.06	2.3	1.00	1.00	100.00	4
Bare (Reference)	0-15	3	3.9	0.11	0.11	3.9	1.00	1.00	100.00	6.7
Bare (Reference)	15-30	3	2.8	0.08	0.08	2.8	1.00	1.00	100.00	4.8
Bare (Reference)	0-15	4	3.7	0.10	0.10	3.7	1.00	1.00	100.00	6.4
Bare (Reference)	15-30	4	2.6	0.07	0.07	2.6	1.00	1.00	100.00	4.5
Bare (Reference)	0-15	5	4	0.11	0.11	4	1.00	1.00	100.00	6.9
Bare (Reference)	15-30	5	2.3	0.06	0.06	2.3	1.00	1.00	100.00	4
Bare (Reference)	0-15	6	2.6	0.07	0.07	2.6	1.00	1.00	100.00	4.5

Bare (Reference)	15-30	6	2.2	0.06	0.06	2.2	1.00	1.00	100.00	3.8

Key: *LI = lability index; CMI = carbon management index.*

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