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Soil Organic Carbon and Emission Factors for Different Land Cover Classes in Tanzania

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ABSTRACT

Quantification of carbon stock and development of country-specific emission factors in relation to the Agriculture, Forestry, and Other Land Use (AFOLU) sector has the potential to improve national greenhouse gas inventory systems. This study was therefore, conducted to quantify soil organic carbon (SOC) and develop emission factors using the national forest inventory data of Tanzania. The results, showed that, the mean SOC for the different land cover subclasses ranged from 31.23 Mg C /ha to 99.8 Mg C /ha. The lowest value being recorded in the bushland thicket and highest value in the forest humid mountains. Spatial interpolation map indicated that, large areas in the central part had low values of SOC, ranging from 0-53Mg C/ha. The SOC for the primary land cover classes were 37.32 Mg C/ha, 43.44 Mg C/ha, 39.68 Mg C/ha for forest, non-non forest and wetlands respectively. Their correspondingly annual emission factors were, 3.56 Mg CO2/ha/yr, 4.14 Mg CO2/ha/yr, and 3.78 Mg CO2/ha/yr, respectively. The values presented in this paper correspond to IPCC tier 2 and can be used for estimation of carbon emission at the national scale for the respective major primary land cover classes.

Key words: Carbon stock – soil – AFOLU – FREL - Emission Factor - Uncertainty

INTRODUCTION

The implementation of global climate change mitigation programmes under the United Nation Framework Convention on Climate Change (UNFCCC) in the tropical countries, had increased the interest on the quantification of terrestrial carbon stock across different land cover classes. Such information is important for computation of greenhouse gas emission as well as for understanding the contribution of different land cover classes in the global carbon cycle (Federici et al. 2008, Mauya *et al*. 2019, Zhen et al. 2022). One of the notable climate change mitigation strategies initiated under the UNFCCC is a programme on reducing emissions from deforestation and forest degradation (REDD+) (Pistorius 2012). This mechanism has been accepted as a low-cost and promising approach for mitigating climate change (Angelsen 2009, 2017), that will also secure many ecological functions of forests, including biodiversity conservation and provision of a number of ecosystem services (Panfil and Harvey 2016).

The success of the REDD+ program, is however anchored on four key elements: (1) a national strategy or action plan; (2) a national Forest Reference Emission Level (FREL) and/or Forest Reference Level (FRL); (3) a robust and transparent national forest monitoring system for Measurement, Reporting and Verification (MRV) of the REDD+ activities; and (4) a system for providing information on how the safeguards are addressed or respected (Herold et al. 2012; Mauya *et al*. 2019). These elements are important for monitoring of REDD+ activities as well as provision of financial incentives. Forest Reference Emission Level (FREL), being one among the four key elements of the REDD+, is defined as the benchmark for carbon emissions against which a country's performance in implementing REDD+ activities can be assessed and credited (Sasaki *et al*. 2016). However, estimation of carbon emission as key variable for setting up FRL, requires information on Activity Data (AD) which refers to the area of forest change (in hectares), e.g., forest converted to grassland or forest converted to cropland; and Emission Factor (EF) which relates to the carbon stock change estimations per unit of activity (in carbon per hectare) (*Eggleston et al*. 2006).

The recommended carbon pools for estimation of total carbon density and emission for FREL development include: those in Above-Ground Biomass (AGB), Below-Ground Biomass (BGB), deadwood, litter and soil organic matter. However, many of the reported FRELs (e.g., Zambia 2016, URT 2017) lack information on soil carbon pools partly because of inadequate data in soil carbon. Soils represent the largest terrestrial organic carbon reservoir (FAO 2018). It is estimated that soils contain about three times more compared to world's vegetation (Scharlemann *et al*. 2014). Lal (2008) and Ontl and Schulte (2012) reported that, about 80% of the total carbon in the terrestrial ecosystem is found in soil. Thus, a quantitative estimation of the forest soil organic carbon (SOC), and the investigation of its governing factors, is crucial for predicting the carbon-climate feedback and updating the carbon budget (Yang *et al*. 2014). Furthermore, the potential consideration of soil carbon credit under the Kyoto Protocol emphasizes the need for a detailed data on SOC stocks (Nketia *et al*. 2009). However, the complexity and dynamics underlying SOC storage and release makes the evaluation of SOC sources and sinks difficulty and still not well understood (Scharlemann *et al*. 2014). In Africa, not much has been done on SOC storage, especially emissions in land-use systems (Yao et al. 2010).

Tanzania, like other tropical countries, submitted her Forest Reference Emission Level (FREL) to the United Nations Framework Convention on Climate Change (UNFCCC) in 2016 for technical assessment. However, the computed total carbon emission did not contain the mineral soil organic carbon pool (URT 2017). This paper presents the SOC and the emission factors for different land cover classes in Tanzania, calculated based on the National Forest Inventory (NFI) data, implemented between 2009 and 2014 through National Forest Resources Monitoring and Assessment (NAFORMA) project. Such information is important for the ongoing REDD+ reporting activities particularly on updating the FREL as well as for conventional objectives related with sustainable forest management.

MATERIALS AND METHODS

Study area

The United Republic of Tanzania is a union of Mainland Tanzania and Zanzibar. It is located between longitude 29° and 41° East and Latitude 1° and 12° South. Mainland Tanzania is endowed with a wide range of natural resources associated with a very diverse climate depending on altitude and latitude. The mean annual rainfall varies from below 500 mm to over 2000 mm per annum. The rainfall for the large part of the country is bimodal with short rains from October-December and long rains from March to May.

Based on the FREL land use land cover (LULC) change analysis for Mainland Tanzania there are four primary land cover classes: (1) forest, (2) non-forest, (3) water and (4) wetlands (Table 1 and Figure 1). Each primary class consists of several land cover sub-classes as stipulated in Table 1.

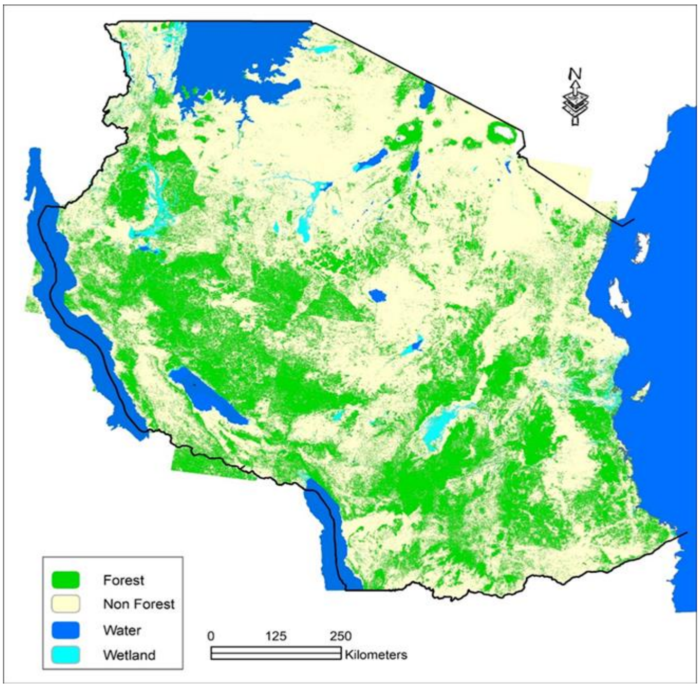

Figure 1. Spatial distribution of the primary land cover classes in Mainland Tanzania as per URT (2017)

Table 1: Classification of land cover types in Mainland Tanzania as per URT (2017)

Land cover sub-class	**Primary class**
Forest: Plantation	Forest
Forest: Mangrove	Forest
Forest: Humid montane	Forest
Forest: Lowland	Forest
Woodland: Closed (>40%)	Forest
Woodland: Open (10-40%)	Forest
Cultivated land (Wooded crops): Mixed tree cropping	Forest
Cultivated land (Wooded crops): Wooded crops	Forest
Woodland (Wooded crops): Scattered cropland (Unspecified) density)	Forest
Bushland: Thicket	Forest
Bushland: Thicket with emergent trees	Forest
Bushland: Dense	Non forest
Bushland: Emergent trees	Non forest
Bushland: Open	Non forest
Bushland: Scattered cultivation	Non forest
Cultivated land: Agro-forestry system	Non forest
Cultivated land: Grain crops	Non forest
Cultivated land: Herbaceous crops	Non forest
Grassland: Bushed	Non forest
Grassland: Open	Non forest
Grassland: Scattered cropland	Non forest
Grassland: Wooded	Non forest
N/A	Non forest
Open land: Bare soil	Non forest
Open land: Rock outcrops	Non forest
Open land: Salt crusts	Non forest
Other areas	Non forest
Water: Inland water	Wetland
Water: Swamp	Wetland

Sampling design

In this study, we used the NAFORMA dataset whose detailed sampling design has been described in Tomppo *et al*. (2014). The distributions of the soil sample plots over Tanzania are shown in Figure 3. Essentially, NAFORMA followed a stratified systematic cluster sampling, where cluster with 6 to 10 plots (Figure 2) depending on the estimated difficulty to access the plots were established. The distances between clusters were ranging from 10 to 45 km, while the distance between plots within the cluster was 250 m. Soil samples were taken from first and last plot in the permanent sample clusters. This means:

- If there were 6 plots in the cluster – soil samples were taken from plot 3 and 8.
- If there were 8 plots in the cluster – soil samples were taken from plot 2 and 9.
- If there were 10 plots in the cluster – soil samples were taken from plot 1 and 10

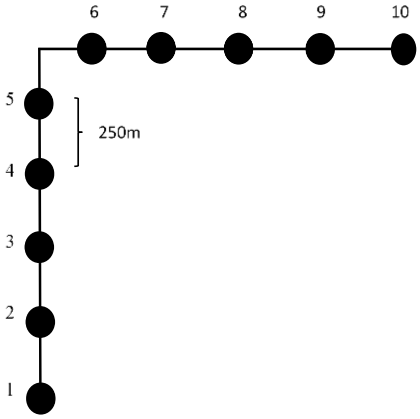

Figure 2: NAFORMA cluster design (black solid circles = plot).

Data collection

On the border of each soil sampling, plot, four mini pits were located in the four cardinal directions. At each vertical mini pit wall, starting from the top, a volumetric soil sample was collected from three depths, 0–10, 10–20 and 20–30 cm. Soil samples from the respective depths were bulked into one per plot.

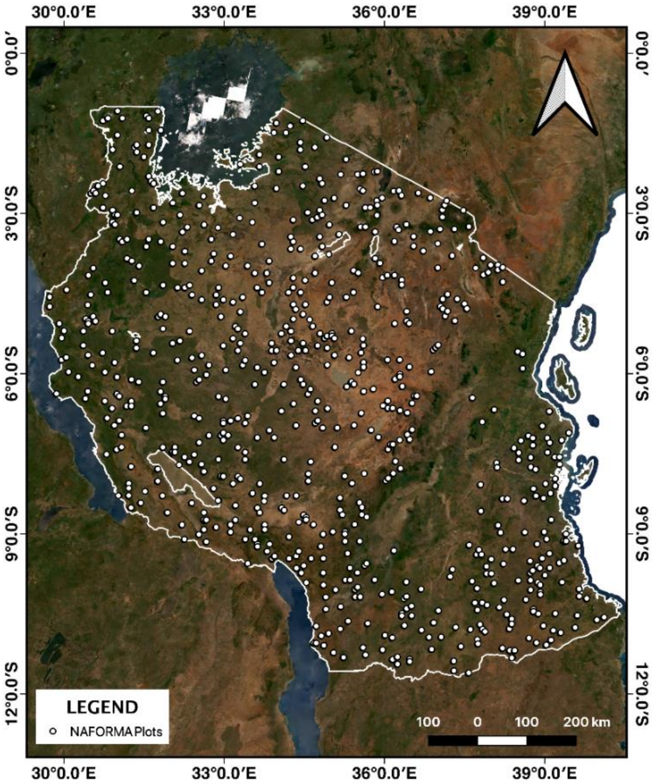

Figure 3. Distribution of soil sample plots over Tanzania

Data analysis

Soil organic Carbon content

Soils were analyzed for carbon content according to Walkley and Black (1934) and bulk density (Moreira *et al.* 2012) and then converted to Mg C hectare−1 for each of the plot, which were then aggregated to vegetation sub-class by computing their respective average values for all plots in the respective sub-classes. The soil organic carbon (SOC) values of each primary land cover class were estimated as area weighted mean of the land cover sub-classes estimates, which were weighted by their corresponding areas using equation 1. Details on the area's computations following the NAFORMA design are given in Mauya *et al.* (2019)

$$Y_M = \frac{\sum_{k=1}^{n} Y_k \times \hat{A}_k}{\sum_{i=1}^{n} \hat{A}_k} \qquad (1)$$

Where: Ym is the weighted estimate of SOC in Mg C per hectare in a primary land cover class M, A_k is the area of land cover sub-class k, Y_k is SOC per ha of the land cover sub-class and *n* is the number of land cover sub-classes in the primary land cover class.

Mapping and interpolation of SOC

To get an overview of the spatial distributions of the SOC of the respective plots over Tanzania, we overlaid the plots on the map of Tanzania. Furthermore, a spatial interpolation map was generated to show the distribution of the SOC in both sampled and un-sampled sites using the interp package in R software.

SOC emission factor

The Intergovernmental Panel on Climate Change (IPCC) refers to three general tiers for estimating emissions/removals of GHGs. The Tiers represent different levels of methodological complexity: Tier 1 is the basic method, Tier 2 uses country-specific data, and Tier 3 is the most demanding in terms of complexity and data requirements. Nations are encouraged to use higher tiers for the measurement of significant C sinks / emission sources. In this study, we used Tier 2 for estimation of emission factor given that we had country-specific information on SOC, which was then used for deriving country-specific reference soil C stocks. Therefore, soil emission factor (EFsoil), for each primary land cover class was computed following the steps outlined in the IPCC (2006) guidelines. The procedure estimates the changes in soil carbon stocks (i.e., emission factor) based on the use of soil factors that account for how the soil is tilled, the method of management, and inputs in the post deforestation land use. In the first step: Change in soil carbon stock (ΔSOC in t C ha $^{-1}$) was estimated using equation 2:

$$\boldsymbol{\Delta SOC = C_{soil} - (C_{soil} * F_{LU} * F_{MG} * F_{I})} \quad (2)$$

Where:

ΔSOC = Change in soil carbon stock, t C ha $^{-1}$

$\mathbf{C_{soil}}$ = Carbon stock in soil organic matter (to 30cm), t C ha $^{-1}$

$\mathbf{F_{LU}}$ = Stock change factor for land-use systems for a particular land-use, dimensionless (IPCC AFOLU GL)

$\mathbf{F_{MG}}$ = Stock change factor for management regime, dimensionless

$\mathbf{F_{I}}$ = Stock change factor for input of organic matter, dimensionless

In this study default value for $\mathbf{F_{LU}}$ = 0.48, $\mathbf{F_{MG}}$= 1, $\mathbf{F_{I}}$ = 1.

However, in order to estimate the annual ΔSOC we divided by 20 years which is the default period for changes in soil carbon stock. This implies that, over a 20 years period of time a new steady state for a given land use is reached.

In the second step total EF and annual EF for each land cover class were calculated using equations 3&4 below:

$$\text{Total EFsoil} \left({}^{t\,CO_2}/_{ha}\right) = \Delta SOC \times {}^{44}/_{12} \qquad (3)$$

$$\text{Annual EFsoil} \left({}^{t\,CO_2}/_{ha}/_{yr}\right) = {}^{\Delta SOC}/_{20} \times {}^{44}/_{12} \qquad (4)$$

RESULTS

The descriptive statistics of the SOC of the different land cover subclasses are presented in Table 2. The results showed that the mean SOC for the different land cover subclasses ranged from 31.23 Mg C /ha to 99.8 Mg C /ha. The lowest value being recorded in the bushland thicket and highest value in the forest humid montane. The box plots in Figure 4, shows further that the SOC varies among the land cover subclasses. The largest variation is observed on the forest humid mountains as well as in the forest plantation.

Table 2. Soil organic carbon for different land cover subclasses

Land cover- sub- class	N	Mean SOC (Mg C/ ha)
Bushland dense	31	44.05 ± 14.42
Bushland open	58	35.31 ± 11.35
Bushland scattered	20	36.91 ± 24.04
Bushland thicket	19	31.23 ± 19.60
Cultivated wooded	39	40.89 ± 18
Cultivated land	134	38.09 ± 8.05
Cultivated land agroforestry	21	54.67 ± 17.12
Cultivated land herbaceous	78	39.04 ± 10.25
Forest humid montane	17	99.80 ± 20.5
Forest lowland	42	36.82 ± 13.95
Forest plantation	12	81.94 ± 35.2
Grassland bushed	9	35.17 ± 37.72
Grassland open	46	45.22 ± 13.88
Grassland scattered	13	48.84 ± 27.95
Grassland wooded	54	41.25 ± 9.35
Other areas	20	39.39 ± 23.53
Water wetland	18	39.68 ± 25.53
Woodland closed	129	35.19 ± 8.35
Woodland open	550	35.16 ± 3.85
Woodland scattered	46	42.68 ± 14.02

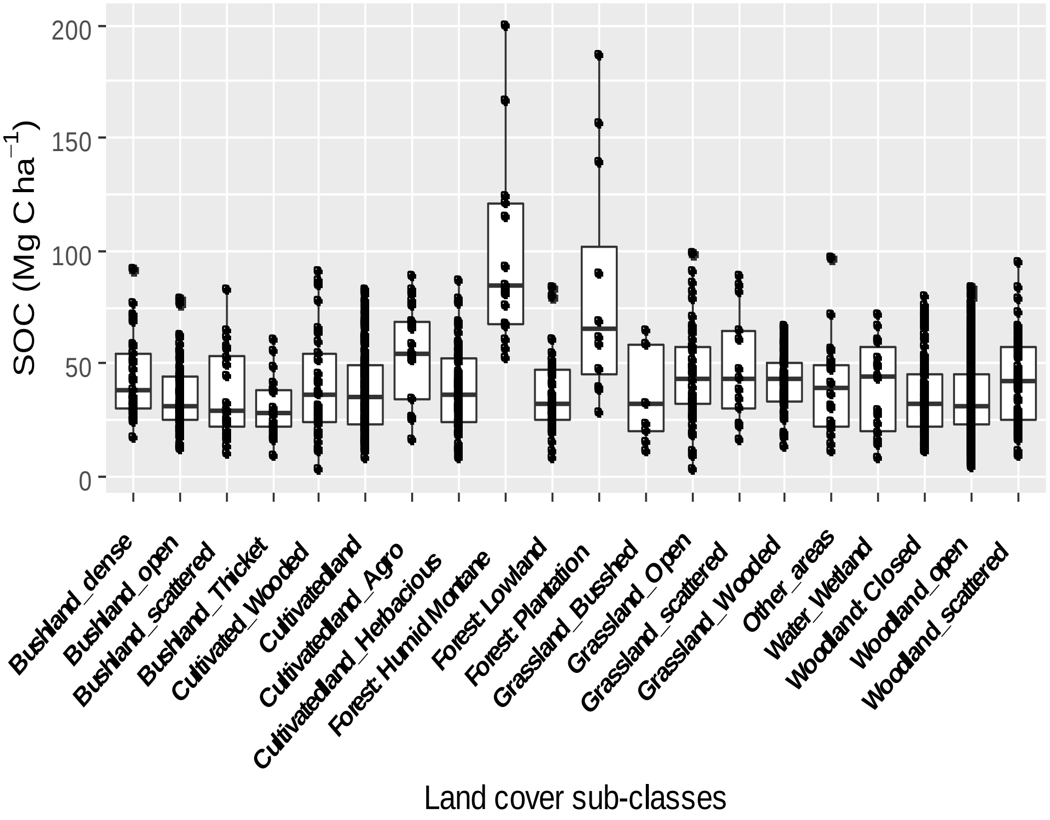

Figure 4. Box plots for the distribution of SOC for each of the land cover sub-class. The high dots represent maximum value, the solid middle bar is the median value and lower dot is lower value

Aggregation of the land cover subclasses, into land cover classes in Table 3, indicated that, forest plantation had higher average weighted SOC as compared to other land cover classes. The map of the spatial distribution of SOC based on the field plot data show patterns in the distribution of the SOC (Figure 5(a)). Large areas in the central part of the country had low values of SOC ranging from 0-53 Mg C /ha. The areas with higher SOC are quite limited and are mainly found in the mountainous areas of northern as well as southern highlands of Tanzania. Similar trends were observed in soil carbon map of Tanzania developed using nearest neighbor interpolation method (Figure (5b)).

Table 3. Soil organic carbon for different NAFORMA land cover classes

Land cover class	N	SOC (Mg C/ ha)
Closed woodland	129	35.19 ± 8.35
Forest plantation	12	81.94 ± 35.42
Montane and Lowland	59	59.77 ± 16.35
Non-forest	523	43.44 ± 14.88
Open woodland	550	35.16 ± 3.85
Thicket	19	31.23 ± 19.60
Wetland	18	39.68 ± 25.53
Wooded	46	42.68 ± 14.02

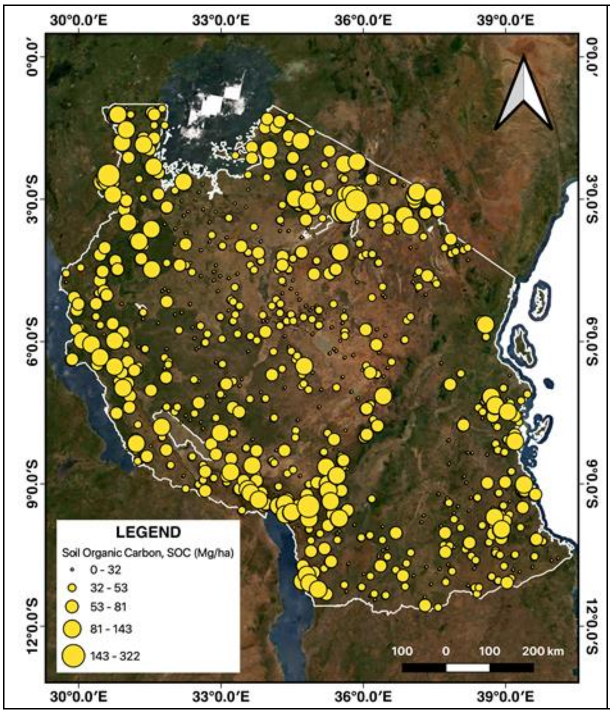

Figure 5(a). SOC for the field sample plots

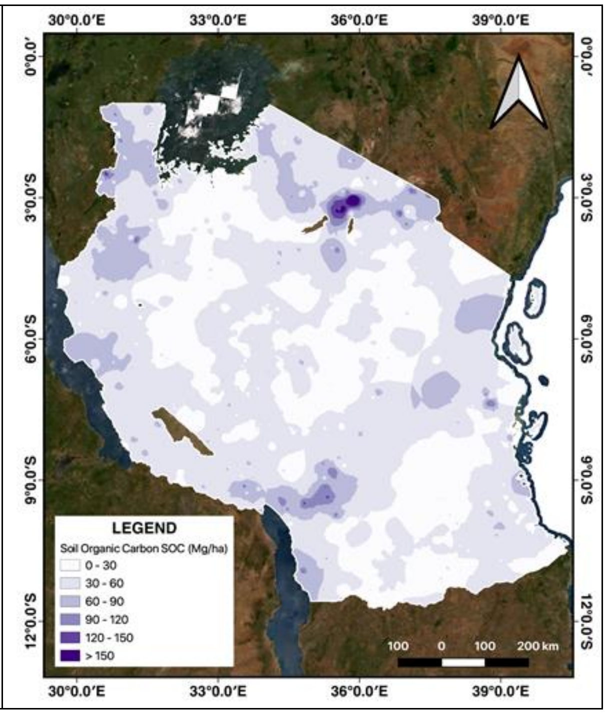

Figure 5(b). Spatial interpolation of SOC

Table 4. Soil organic carbon and emission factors for primary land cover classes

Primary land cover class	N	Mean SOC (Mg C/ha)	Total emission factor (Mg CO_2/ha)	Annual emission factor (Mg CO_2/ha/yr)
Forest	817	37.32 ± 2.82	71.16 ± 5.38	3.56 ± 0.27
Non-forest	523	43.44 ± 6.53	82.83 ± 12.45	4.14 ± 0.62
Wetland	18	39.68 ± 10.13	75.66 ± 19.31	3.78 ± 0.97

SOC and Emission Factor for Primary land cover classes

The land cover classes presented in Table 3, were further aggregated into three key primary land cover classes (Table 4). The classes were, forest, non-forest and wetland. The results showed that the SOC for the non-forest category was relatively higher as compared to forest and wetlands. The uncertainties, for the SOC for the wetland class was relatively higher as compared to the other classes. The annual emission factors for the three classes are also presented in Table 4.

DISCUSSION

The overall objective of this paper was to compute SOC and emission factors for different land cover classes of Mainland Tanzania, using NAFORMA data. The results indicated that, the values of SOC from different land cover sub-classes (Table 2) are in-line with other studies reported in Africa and elsewhere. For example, Henry *et al.* (2019) indicated that SOC across Africa ranges from 23.7 to 46.0 Mg C ha^{-1}, which essentially is within the ranges of most land cover subclasses in this study. However, there was slightly unique variations in SOC among the land cover subclasses. For example, among the land cover sub-classes, forest humid mountains and forest plantation resulted into higher average SOC as compared to other land cover sub-classes. Similar observations had been reported by Amanuel *et al.* (2018), Guan *et al.* (2019), who concluded that, natural forests and plantations had higher average SOC as compared to other land cover classes. This may be attributed by the differences in vegetation types as well as climate, management factors and topographical features (Prichard *et al.* 2000; Guo and Gifford 2002, Deng *et al.* 2013), associated with specific land cover subclasses. For example, many studies (e.g., Mao *et al.* 2015; Kuruppuarachchi *et al.* 2016, Alidoust *et al.* 2018), have suggested that climatic factors, especially temperature and precipitation, are the most important determinants of SOC distribution at large scales. In this study, most of the tropical humid mountain forests, as well as plantation forests, are located in lower temperature zones, this may contribute to higher SOC accumulation as compared to other land cover classes. Furthermore, higher tree carbon content attributed by the presence of large trees in the tropical humid mountains along with higher litter falls input rates, may promote higher SOC stocks, and sequestration rates in tropical humid mountains as compared to other cover classes (Liao *et al.* 2012). A study by Meliyo *et al.* (2016), in the Western Usambara Mountains in Tanzania found that, soil organic carbon increased with elevation, in correlation with marked differences in vegetation types and climate. Shen-Xuan *et al.* (2015) found same trend in a study conducted in China.

Interpolation of the SOC over the entire Tanzania indicated a pattern, where large areas in central parts of Tanzania including the regions surrounding the capital city of Tanzania (i.e., Dodoma) and the areas close to Lake Victoria basins (Figure 5b), had low SOC as compared to the northern part and mountainous areas of Tanzania. The reasons for this pattern is associated with the climatic conditions, where most of the areas in the central part are characterized by semi- arid climatic conditions, which are essentially characterized by high temperatures and less rainfall, which results into considerable decline in water availability associated with high evapotranspiration. Such conditions lead to low biomass production and SOC. These areas are also dominated by communities practicing uncontrolled pastoralism and agro-pastoralism. Overgrazing and soil compaction from the livestock is common leading to land degradation. Rainfall seasons are short and rains fall in a few storms resulting to soil erosion due to overland flow on bare and compacted soils. Top soils which normally contains higher amount of soil organic matter compared to subsurface soils, are thus very thin or missing in some parts due to rampant sheet, rill and inter-rill erosions.

In order to report SOC in line with the primary land cover classes reported in the FREL, the mean average weighted SOC was computed for forest, non-forest, and wetlands. The wetlands class resulted into higher average weighted mean of SOC irrespective of having few observations as compared to other classes. This is in line with the others studies which concluded that, wetlands occupy a substantial portion of SOC irrespective of its small coverages (Stern *et al.* 2007, Mitsch *et al.* 2008, Uhran *et al.* 2021). The balance, between carbon input, (organic matter production) and output (decomposition, methanogenesis, etc.), and the resulting storage of SOC, in the wetland depends on several factors such as the topography and landscape position of the wetland, the hydrologic regime, the type of plants present, the temperature (and therefore climate) and moisture of the soil, the pH and salinity, and the morphology of the wetland (Collins and Kuehl 2001). This long list of factors indicates that, SOC accumulation in wetlands is a delicate process influenced by many variables. This calls for the need for more research on quantification of SOC in the wetlands using denser sample plots. To further align, with the FREL reporting, the emission factors for the primary land cover classes were finally computed. The values obtained for the key primary land cover classes were in line with the default values for drained organic soils in managed forests, reported in IPCC (2006), chapter 3, Table 3.2.15. For example, for the forest primary land cover class the emission factor obtained from this study was 3.55 ± 0.26 Mg $C0_2$/ha/year, while for the IPCC is 0.82-3.82 Mg $C0_2$/ha/year. This indicates that, the emission factors developed in this study can be used across tropical ecosystems for estimating carbon emission from soil.

Uncertainty estimates are an essential element of a complete inventory of greenhouse gas emissions and removals. They should be derived for both the national level and the trend estimate, as well as for the component parts such as emission factors, activity data and other estimation parameters for each category. In this study, we presented analysis of uncertainty, which are within the bound of our expectations as well as within the IPCCC reported ranges. There is high uncertainty in wetland, given the high variability of SOC in this category but also may be attributed by small number of field plots on this category as compared to forest and non-forest categories. However, generally the values of uncertainties for the three classes are within the reasonable ranges. As such, they can be used for accounting the uncertainty for carbon emission factors elsewhere but also for computing overall uncertainty of carbon emission in construction of FREL for REDD+.

CONCLUSION

To conclude, our study has quantified the SOC for different land cover subclasses as well for primary land cover classes. Among the land cover subclasses, forest humid mountains and forest plantations had higher amount of SOC as compared to other land cover subclasses. The values of the SOC are within the ranges of other studies reported in Africa. Aggregation of the land cover subclasses to primary land cover classes indicated that there is higher uncertainty in SOC for the wetland class as compared to other classes. Given the relatively fewer samples for this class, our study recommends further intensifications of the samples in future, if the estimates had to be used for the scales less than a nation. The emission factors, developed for all the primary land cover classes were within the IPCC ranges, implying that, they can be used for greenhouse gas accounting particularly for mineral SOC pool, which was not included in the previous Tanzania FREL report of 2017. The values can further be used in similar soil conditions across Africa for reporting greenhouse gas emissions from the AFOLU sector.

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REFERENCES

Alidoust, E., Afyuni, M., Hajabbasi, M.A. & Mosaddeghi, M.R. 2018. Soil carbon sequestration potential as affected by soil physical and climatic factors under different land uses in a semiarid region. Catena 171, 62-71.

Amanuel, W., Yimer, F. & Karltun, E. 2018. Soil organic carbon variation in relation to land use changes: the case of Birr watershed, upper Blue Nile River Basin, Ethiopia. Journal of Ecology and Environment 42, 1-11.

Angelsen, A. 2009. Realising REDD+: National strategy and policy options. Cifor.

Angelsen, A. 2017. REDD+ as result-based aid: General lessons and bilateral agreements of Norway. Review of Development Economics 21, 237-264.

Collins, M.E. & Kuehl, R. 2001. Organic matter accumulation and organic soils. Wetland soils, genesis, hydrology, landscapes, and classification. Lewis Pub., Boca Raton, FL, 137-162.

Deng, L., Wang, K.-B., Chen, M.-L., Shangguan, Z.-P. & Sweeney, S. 2013. Soil organic carbon storage capacity positively related to forest succession on the Loess Plateau, China. Catena 110, 1-7.

Eggleston, H., Buendia, L., Miwa, K., Ngara, T. & Tanabe, K. 2006. 2006 IPCC guidelines for national greenhouse gas inventories.

FAO, 2018. Global Soil Organic Carbon Map (GSOCmap) Version 1.5. Global Soil Organic Carbon Map (GSOCmap) Technical Report.

Federici, S., Vitullo, M., Tulipano, S., De Lauretis, R. & Seufert, G. 2008. An approach to estimate carbon stocks change in forest carbon pools under the UNFCCC: the Italian case. iForest-Biogeosciences and Forestry 1, 86.

Guan, J.-H., Deng, L., Zhang, J.-G., He, Q.-Y., Shi, W.-Y., Li, G. & Du, S. 2019. Soil organic carbon density and its driving factors in forest ecosystems across a northwestern province in China. Geoderma 352, 1-12.

Guo, L.B. & Gifford, R.M. 2002. Soil carbon stocks and land use change: a meta analysis. Global change biology 8, 345-360.

Henry, M., Valentini, R. & Bernoux, M. 2019. Soil carbon stocks in ecoregions of Africa, Biogeosciences Discuss., 6, 797–823. In.

Herold, M., Verchot, L., Angelsen, A., Maniatis, D. & Bauch, S. 2012. A step-wise framework for setting REDD+ forest reference emission levels and forest reference levels. CIFOR brief 52, 1-8.

Kuruppuarachchi, K., Seneviratne, G. & Madurapperuma, B.D. 2016. Carbon sequestration in tropical forest stands: its control by plant, soil and climatic factors. Open Journal of Forestry 6, 59-71.

Lal, R. 2008. Carbon sequestration. Philosophical Transactions of the Royal Society B: Biological Sciences 363, 815-830.

Liao, C., Luo, Y., Fang, C., Chen, J. & Li, B. 2012. The effects of plantation practice on soil properties based on the comparison between natural and planted forests: a meta-analysis. In. Wiley Online Library, pp. 318-327.

Mao, D., Wang, Z., Li, L., Miao, Z., Ma, W., Song, C., Ren, C. & Jia, M. 2015. Soil organic carbon in the Sanjiang Plain of China: storage, distribution and controlling factors. Biogeosciences 12, 1635-1645.

Mauya, E.W., Mugasha, W.A., Njana, M.A., Zahabu, E. & Malimbwi, R. 2019. Carbon stocks for different land cover types in Mainland Tanzania. Carbon balance and management 14, 4.

Meliyo, J.L., Msanya, B., Kimaro, D.N., Massawe, B.H.J., Hieronimo, P., Mulungu, L., Deckers, J. & Gulinck, H. 2016. Variability of soil organic carbon with landforms and land use in the Usambara Mountains of Tanzania.

Mitsch, W.J., Tejada, J., Nahlik, A., Kohlmann, B., Bernal, B. & Hernández, C.E. 2008. Tropical wetlands for climate change research, water quality management and conservation education on a university campus in Costa Rica. Ecological Engineering 34, 276-288.

MNRT, 2015. National Forest Resources Monitoring and Assessment of Tanzania Mainland (NAFORMA). Main Results., 106.

Moreira, F.M., Huising, E.J. & Bignell, D.E. 2012. A handbook of tropical soil biology: sampling and characterization of below-ground biodiversity. Routledge.

Nketia, K., Tutu, P. & Asare, A. 2009. The Forest Dialogue-TFD, Implementing REDD+ in Ghana: contextualization and some challenges. A background Paper for REDD+ Readiness Field Dialogue in Ghana.

Ontl, T. & Schulte, L. 2012. Soil carbon storage, Nature Education Knowledge, 3 (10), 35. In.

Panfil, S.N., & Harvey, C.A. 2016. REDD+ and biodiversity conservation: A review of the biodiversity goals, monitoring methods, and impacts of 80 REDD+ projects. Conservation Letters 9, 143-150.

Pistorius, T. 2012. From RED to REDD+: the evolution of a forest-based mitigation approach for developing countries. Current Opinion in Environmental Sustainability 4, 638-645.

Prichard, S.J., Peterson, D.L. & Hammer, R.D. 2000. Carbon distribution in subalpine forests and meadows of the Olympic Mountains, Washington. Soil Science Society of America Journal 64, 1834-1845.

Sasaki, N., Chheng, K., Mizoue, N., Abe, I. & Lowe, A.J. 2016. Forest reference emission level and carbon sequestration in Cambodia. Global ecology and conservation 7, 82-96.

Scharlemann, J.P., Tanner, E.V., Hiederer, R. & Kapos, V. 2014. Global soil carbon: understanding and managing the largest terrestrial carbon pool. Carbon Management 5, 81-91.

Stern, J., Wang, Y., Gu, B. & Newman, J. 2007. Distribution and turnover of carbon in natural and constructed wetlands in the Florida Everglades. Applied Geochemistry 22, 1936-1948.

Tomppo, E., Malimbwi, R., Katila, M., Mäkisara, K., Henttonen, H.M., Chamuya, N., Zahabu, E., & Otieno, J. 2014. A sampling design for a large area forest inventory: case Tanzania. Canadian Journal of Forest Research 44, 931-948.

Uhran, B., Windham-Myers, L., Bliss, N., Nahlik, A.M., Sundquist, E.T. & Stagg, C.L. 2021. Improved wetland soil organic carbon stocks of the conterminous US through data harmonization. Frontiers in Soil Science, 16.

URT, 2017. Tanzani's forest reference emission level submission to the UNFCCC.

Walkley, A. & Black, I.A. 1934. An examination of the Degtjareff method for determining soil organic matter, and a proposed modification of the chromic acid titration method. Soil science 37, 29-38.

Yang, Y., Li, P., Ding, J., Zhao, X., Ma, W., Ji, C.&Fang, J. 2014. Increased topsoil carbon stock across China's forests. Global Change Biology 20, 2687-2696.

Yao, M.K., Angui, P.K., Konaté, S., Tondoh, J.E., Tano, Y., Abbadie, L. & Benest, D. 2010. Effects of land use types on soil organic carbon and nitrogen dynamics in Mid-West Cote d’Ivoire. European Journal of Scientific Research 40, 211-222.

Zambia, R. 2016. Zambia’s Forest Reference Emissions Level Submission to the UNFCCC. In, Paris: United Nations Framework Convention on Climate Change.

Zhen, Z., Yang, L., Ma, Y., Wei, Q., Jin, H.I. & Zhao, Y. 2022. Upscaling aboveground biomass of larch (Larix olgensis Henry) plantations from field to satellite measurements: a comparison of individual tree-based and area-based approaches. GIScience & Remote Sensing 59, 722-743.