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Research Article

Estimates of Volume and Carbon Stock Removals in Miombo Woodlands of Mainland Tanzania

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Miombo woodlands are major vegetation type covering about 93% of the forest land of Mainland Tanzania. It forms an integral part of the rural landscape in Tanzania and plays a crucial role in providing a wide range of goods and services including carbon sequestration. However, the sustainability of forest resources is mostly affected by the magnitude of its utilization. There should be a balance between the forest growth and removals. Nevertheless, the magnitude of removed volume and carbon in the country is not known. Quantification of volume, biomass, and carbon stocks removals is vital in developing effective climate change mitigation strategies, decision making, and promoting sustainable forest management. Based on the National Forest Resources Monitoring and Assessment data (NAFORMA) comprising 7,026 stumps collected from 16,803 circular plots of 10 m and 15 m radii established in Miombo woodlands of Mainland Tanzania, volume and carbon stock removals were estimated with the use of models that utilize stump diameter (SD) as the sole predictor. Results indicate that the annual volumes, aboveground biomass removed, and belowground biomass removed were $1.71 \pm 0.54\,m^3\,ha^{-1}\,year^{-1}$, $1.23 \pm 0.37\,t\,ha^{-1}\,year^{-1}$, and $0.43 \pm 0.12\,t\,ha^{-1}\,year^{-1}$, respectively. In addition, the corresponding aboveground and belowground carbon removed were found to be 0.6 ± 0.18 tC $ha^{-1}\,year^{-1}$ and 0.21 ± 0.05 tC $ha^{-1}\,year^{-1}$ respectively. Since the estimated annual volume removals exceed estimated mean annual increment of $1.6 \pm 0.2\,m^3\,ha^{-1}\,year^{-1}$ in Miombo woodlands, the removals indicate unsustainability that would end up into forest degradation. The results also show that removals are more prominent in the following categories: shifting cultivation, production forest, grazing land, general land, village land, and Eastern and Southern zones. This paper calls for increased appropriate management strategies to ensure sustainability in these land categories and in the entire Miombo woodlands of Mainland Tanzania.

1. Introduction

Miombo woodlands are important vegetation type in the world, playing a vital role in social, economic, and environmental aspects [1]. Miombo woodlands are broadly divided into wet (annual precipitation >1000 mm) and dry (annual precipitation <1000 mm) [2]. In dry Miombo, aboveground woody biomass averages around $55\,t\,ha^{-1}$, whilst in wet Miombo, $90\,t\,ha^{-1}$ is typical [3]. In addition, root biomass can comprise between 20% (in Eastern Tanzania [4]) and 32% (in Zambia [5]) of total woody biomass.

Although Miombo woodlands serve as a reservoir of above and belowground carbon and thereby mitigate the effects of climate change, they are, however, undergoing great change due to deforestation and forest degradation [6]. While deforestation refers to a permanent or long-term conversion of forest to nonforest land [7], forest degradation is defined differently for different purposes. According to IPCC [8], forest degradation involves changes within the forest that negatively affects the structure or function of the stand and/or site, thereby lowering the capacity to supply products and/or services.

The levels of forest removals depend much on management categories that Miombo woodlands fall into. In Tanzania, these categories include ownership, land use, and vegetation types [9]. Under ownership types, Miombo woodlands fall into Central Government, Local Government Authority, Village Government, Private and General Land. While, under land use, they fall into production forest, protection forest, wildlife reserves, shifting cultivation, agriculture, grazing land, built-up areas, and water bodies or swamps [9]. Furthermore, in terms of vegetation types, they are subdivided into closed, open, and scattered woodlands [9]. It is anticipated that these management categories could have different levels of volume, biomass, and carbon stock removals. The reason behind this is different degrees of exposure to biological and anthropogenic processes that act as agents for removals [10]. In addition, the magnitude of harvesting shows that woodlands in public lands are more affected by anthropogenic activities than those in the forest reserves [10].

Monitoring volume, biomass, and carbon removals under different management categories of Miombo woodlands are important because they provide information on forest use that is important in the management decisions to ensure sustainability [11]. Furthermore, it is important to establish baselines for Reduced Emissions from Deforestation and Forest Degradation plus the role of conservation, sustainable management of forest, and enhancement of forest carbon stocks (REDD+) [6, 11]. For baseline establishment, participating countries ought to assess their carbon baseline/reference levels through Measurement, Reporting and Verification (MRV) systems [12–14]. Forest reference emission level (FREL) sets a benchmark for assessing country's performance in implementing REDD+ activities.

Tanzania has established her FREL [15] which has been approved [16]. FREL has only included two REDD + activities, i.e., deforestation and conservation [15]. Forest degradation was not included due to inadequate national inventory data for establishing baseline and monitoring [15]. Nevertheless, the National Forestry Resources Monitoring and Assessment in Mainland Tanzania (NAFORMA) that was conducted over the period of 2009 to 2014 included assessment of harvesting through stump measurements. The stumps are an indication of removals and can be used to estimate volume, biomass, and carbon removals in different forest management categories. On the other hand, tree stumps can further be used to indicate tree species that are highly removed. Such information is important in forest management where appropriate intervention may be implemented to sustain utilization of specific tree species. Therefore, taking advantage of NAFORMA data, this study aimed at estimating volume, biomass, and carbon stock removals in the entire Miombo woodlands and its subsequent management categories by applying models that utilize only stump diameter (SD) in Mainland Tanzania. The volume and biomass models were developed in Miombo woodlands of Mainland Tanzania covering Miombo-rich regions [11]. Understanding volume, biomass, and carbon stocks removed is an essential step in accounting for ecosystem goods and services. Such estimates are important in designing management plans for the Miombo woodlands that will ensure a sustained potential of this ecosystem's contribution to emission mitigation. Furthermore, understanding the rate of removals in each category will aid in prioritizing mitigation measures so that more efforts are targeted to Miombo category with higher removals.

2. Materials and Methods

2.1. Study Area Description. The study was conducted on entire Miombo woodlands of Mainland Tanzania that covers 44.7 million ha which is equivalent to 93 percent of the total forest area and 73.9 percent of the total growing stocks (Figure 1). Miombo woodlands occur in different administrative regions in Mainland Tanzania that are characterized by both tropical and subtropical climates. They are mainly found in the western zone (Tabora, Rukwa, and Kigoma regions) and the southern zone (Iringa, Lindi, Mtwara, and Ruvuma regions) (Figure 1) where vast areas occur in the village lands [9]. The weather conditions for all regions may be divided into three distinct seasons: a hot dry season from mid-August to the end of October, a hot wet season from November to the beginning of April, and a relatively cool dry season from April to the beginning of August. Furthermore, two rainfall regimes exist. In the southern, southwestern, central, and western parts of the country, including Lindi, Rukwa, and Tabora, the rainy season starts in mid-November and ends in mid-May. In the north and in the northern coastal zones, the rain is distributed over two shorter periods (October–December and March–May) [17].

2.2. Data Collection

2.2.1. Sampling Design. This study was based on sampling design implemented by NAFORMA [9]. NAFORMA sampling design was double sampling for stratification and was designed based on a simulation study described by Tomppo et al. [18]. The first-phase sample consists of dense grid of L-shaped clusters overlaid on the map of Mainland Tanzania at distances of 5 km × 5 km between the clusters. The first-phase clusters that contained 6–10 plots per cluster were assigned to 18 predefined strata based on predicted growing stock, time consumption for cluster measurement, and slope of the terrain. Since each stratum had unique sampling intensity, the second-phase samples were systematically selected from the first-phase sample, based on sampling intensities in each of the 18 strata. Only the clusters selected during the second phase of sampling were measured in the field. The distance between field plots within a cluster was 250 m, while the distance between clusters varied from the shortest possible distance (5 km) to 45 km depending on the second phase selection.

2.2.2. Data Acquisition. In the NAFORMA, concentric circular plots of 15 m radius were used as the sampling units. All stumps with diameter ≥5 cm within plot radius of 15 m were measured for diameter and height using calliper or

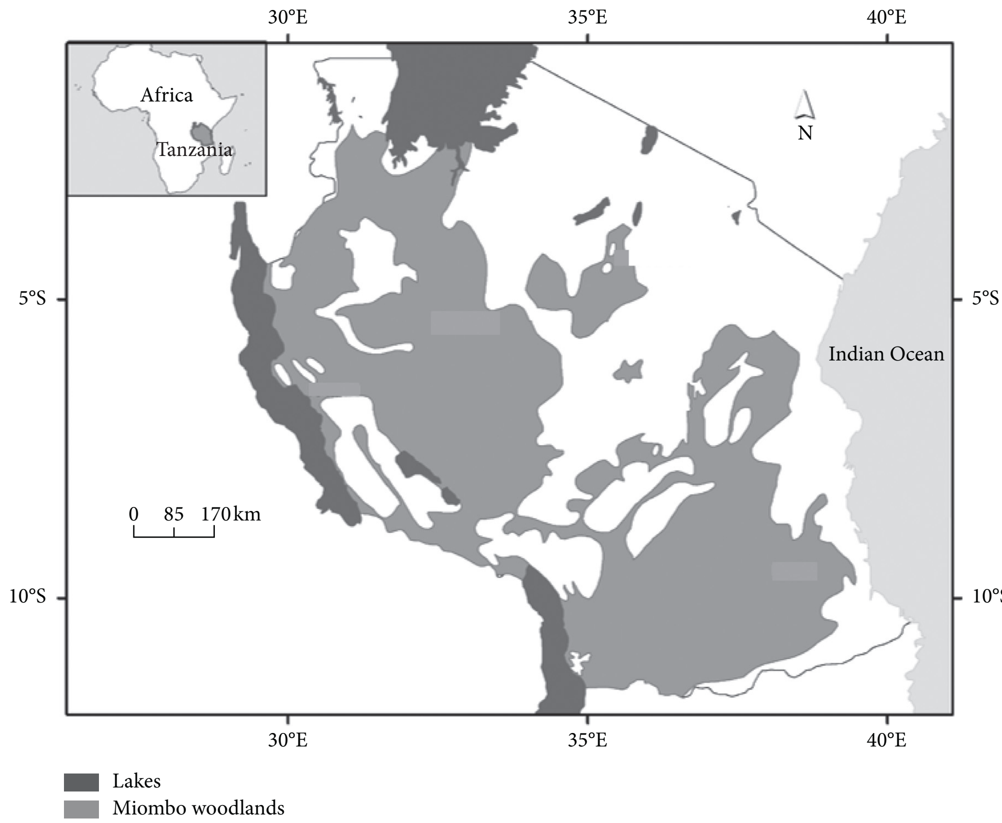

Figure 1: A map of Mainland Tanzania showing Miombo woodlands (modified from [17]).

measuring tape. However, after May 2011, all measurements of stumps were changed to minimum stump diameter of ≥10 cm within a plot radius of 10 m. They were done in order to improve speed in data collection in the smaller plot and by avoiding measuring smaller trees stumps, which are not resistant to annual fires and thereby cause inefficiency in estimating volume and biomass of trees in Miombo woodlands [19]. We acknowledge that, by increasing SD threshold, some of the small stumps would be left unmeasured and hence underestimation of volume and biomass would occur. However, its inclusion would not mean much since small-diameter stumps have smaller contribution to volume and biomass than larger trees. Furthermore, the decrease of size of the plots from 15 m to 10 m would not matter much because all values would be calibrated at per unit area (ha). The SD was measured outside bark immediately under the cutting point (felling cut). If the bark was damaged or missing, logical additions for bark were done. When a stump was taller than 1.3 m, the diameter was measured at the 1.3 m height (DBH).

The age of a stump since harvesting was recorded. The precise estimation of age of stump as numerical value may be subjective but necessary to determine rate of removals. We used all possible means for estimating the numerical value of stump age. These included the colour and freshness of the exposed wood, the size of the sprouts/coppices, and the presence of fire scorch on exposed wood. In addition, the local people who were involved in the data collection assisted the process of stump age determination. The names of the harvested trees species and SD were recorded. The criteria used for identification of the harvested species were coppice growth and wood and bark characteristics of the stump. Identification of species names (vernacular) and confirmation of stump age were done with the help of local tree identifier experienced in ethnobotany and aspect of wood utilization. Allocation of species botanic names to the vernacular names was done later using appropriate species checklist.

For the purpose of this study, all the plots that were surveyed for stumps measurement in Miombo woodlands were extracted from NAFORMA database. In total, 7,323 stumps from 16,803 plots were extracted.

2.3. Data Analysis. Data cleaning to remove obvious outliers due to measurement or recording errors was done before importation into R software for analysis [20]. After data cleaning, 7,026 stumps from 16,803 plots were left. The minimum and maximum SD were 5 cm and 240 cm, respectively, while the mean was 16.868 cm. Likewise, most of the *SD* (6889 stumps) had a diameter between 5 cm and 50 cm, while stumps of greater than 50 cm diameter were very few (only 137 stumps). All tree stumps with the age records of more than 5 years were dropped from the analysis. This is because it is considered difficult to correctly estimate the age of the stump that was harvested more than five years. In total, 297 tree stumps of this category were not included in the analysis. On the other hand, all stumps that were measured at 1.3 m were omitted from the analysis. In total, 449 stumps of this category were dropped.

2.3.1. Estimating Volume Removals. To estimate volume removals per tree, we used allometric equation developed for Miombo woodlands [11] (Table 1). The estimated individual tree volume was divided by respective estimated age of the stump to obtain rate of volume removals per year. The estimated individual tree volumes per year were summed up and expressed on per plot and per ha basis. Since each stratum had unique sampling intensity, it was necessary to calculate Expansion Factor (EF) for each respective stratum. We avoided using simple mean volume and carbon because the estimated values would ignore the nature of the sampling design upon which the data were collected. The EF describes the area in which a sample plot represents in each stratum. Since first-phase sampling units were distributed proportionally to stratum area, the area of the stratum k (A_k) was calculated as follows:

$$\widehat{A}_k = A * \frac{n_k}{n_1}, \quad (1)$$

where n_k is the number of first-phase plots in stratum k (ha); n_1 is the total number of first-phase plots; and A is the total inventory area (Mainland Tanzania area). Practical sequences of computation are shown below and further described [21]:

$$EF_k = \frac{\widehat{A}_k}{n_k}, \quad (2)$$

where $\hat{A}_k$ is the area of stratum k and n_k is the total number of plots observed in stratum k.

Consider that $n_{t,k}$ number of plots of land cover subclass t falling in stratum k. The area $\hat{A}_{t,k}$ of land cover subclass t in stratum k was computed as follows:

$$\widehat{A}_{tk} = \sum_{t\varepsilon k} n_{tk*}\mathrm{EF}_k, \quad (3)$$

where $n_{t,k}$ is the number of plots of land cover subclass t in stratum k and EF_k is the expansion factor of stratum k.

Area of land cover subclass t in the country is the summation of areas of land cover subclasses t found in each stratum; i.e., $\hat{A}_t = \hat{A}_{t1} + \hat{A}_{t2} + \hat{A}_{t3} + \cdots + \hat{A}_{tk}$, where tk is the land cover subclass t in stratum k.

Plot-level values were multiplied by respective plot EF values corresponding to each stratum. The estimated individual plot values were summed up and expressed on a per ha basis. Moreover, the volume removals were then expressed based on land use types, i.e., production forest, protection forest, wildlife reserve, agricultural, shifting cultivation, grazing land, built-up area, water bodies or swamps, and other lands. Furthermore, they were calculated according to vegetation types (closed woodlands (crown cover >40%), open woodlands (crown cover between 10 and 40%), and woodlands with scattered cropland). They were also calculated based on ownership types (central government land, local government land, village land, private land, general land, and not known), regional division, and tree species. On the other hand, we tested for significance to explore if there were differences in mean volume between the different categories. We conducted two-way analysis of variance (ANOVA). Analysis of mean volume across categories was then done using Duncan's multiple range test for ratio to pinpoint which means of categories are different.

2.3.2. Biomass Removal Estimation. We estimated both AGB and BGB removals per tree using allometric equations developed for Miombo woodlands in Mainland Tanzania [11] that utilize SD as the explanatory variable (Table 1). Although BGB is not removed from the woodlands, it is assumed that when the tree is cut, the stump and roots will eventually rot and decompose to release carbon. The estimated individual tree AGB and BGB were divided by respective estimated age of the stump to obtain rate of AGB and BGB removals per year. Plot-level estimates were calculated and expressed on a per ha basis. Biomass removals by woodlands types, land use types, ownership types, zones, regions, and tree species were determined using similar procedure as that used to quantify volume removals. On the other hand, we tested for significance to explore if there were differences in mean biomass between the different categories. We conducted two-way analysis of variance (ANOVA) by applying Duncan's multiple range test for ratio to pinpoint which mean biomasses are different among categories.

2.3.3. Carbon Stock Removal Estimation. Carbon stocks are widely estimated from forest biomass estimates [22]. Many authors assume the carbon concentration of tree to be between 45% and 50% of the dry biomass [22–25]. In this study, we estimated tree carbon concentration by multiplying AGB and BGB by 49% [25]. Then, we estimated plot-level by summing all the trees carbon in the respective plot. The carbon removals by zones, regions, tree species, vegetation, land use, and ownership types were estimated in a way as same as that for volume and biomass removals.

3. Results

3.1. Removals by Vegetation, Land Use, and Ownership Types. Table 2 presents volume, biomass, and carbon removals based on vegetation, land use, and ownership categories of Miombo woodlands. Highest-volume removals per hectare per year were observed in woodlands with scattered cropland followed by open woodlands while closed woodlands were the least (Table 2). In addition, findings showed higher-volume removals in shifting cultivation land as expected followed by agricultural land, production forest land, and grazing land (Table 2). Moreover, we observed higher-volume removals per hectare in private land followed by general land and village land. The least-volume removals were found in central government land followed by local government land (Table 2). Interestingly, none of the categories (Table 2) had volume values that were statistically significantly different ($p < 0.05$).

Table 1: Prediction models used for volume and biomass removal estimation.

Parameter estimates	Model names	Models	R^2	MPE %
Volume	Manyanda et al. [11]	$Y = 0.000032 \times SD^{2.7992}$	0.709	−10.5
Aboveground biomass	Manyanda et al. [11]	$Y = 0.03785 \times SD^{2.6700}$	0.92	−7.9
Belowground biomass	Manyanda et al. [11]	$Y = 0.1056 \times SD^{2.1035}$	0.86	−12.2

Table 2: Volume, biomass, and carbon removals by vegetation, land use, and ownership types.

Miombo management categories	Miombo management categories subdivision	Volume (m^3 ha^{-1} $year^{-1}$)	Biomass (t ha^{-1} $year^{-1}$)		Carbon (tC ha^{-1} $year^{-1}$)	
			AGB	BGB	AGC	BGC
Vegetation types	Closed woodlands (crown cover >40%)	1.3 ± 0.38^{a}	0.95 ± 0.27^{a}	0.33 ± 0.08^{a}	0.46 ± 0.13	0.16 ± 0.04
	Open woodlands (crown cover between 10 and 40%)	1.8 ± 0.39^{a}	1.28 ± 0.25^{a}	0.44 ± 0.07^{a}	0.63 ± 0.12	0.22 ± 0.03
	Woodlands with scattered cropland	1.91 ± 0.79^{a}	1.47 ± 0.60^{a}	0.66 ± 0.27^{a}	0.72 ± 0.30	0.33 ± 0.13
Land use	Production forest	2.06 ± 0.63^{abc}	1.45 ± 0.41^{abc}	0.48 ± 0.11^{ab}	0.71 ± 0.20	0.23 ± 0.10
	Protection forest	1.15 ± 0.40^{abc}	0.85 ± 0.28^{abc}	0.32 ± 0.09^{ab}	0.41 ± 0.14	0.16 ± 0.07
	Wildlife reserve	0.54 ± 0.17^{bc}	0.4 ± 0.12^{bc}	0.15 ± 0.04^{b}	0.2 ± 0.06	0.07 ± 0.03
	Shifting cultivation	3.63 ± 1.09^{ab}	2.71 ± 0.08^{ab}	1.08 ± 0.30^{a}	1.33 ± 0.39	0.53 ± 0.19
	Agriculture	2.54 ± 1.44^{abc}	1.93 ± 1.08^{abc}	0.8 ± 0.44^{ab}	0.94 ± 0.53	0.39 ± 0.26
	Grazing land	2.02 ± 1.39^{a}	1.37 ± 0.87^{a}	0.4 ± 0.18^{ab}	0.67 ± 0.43	0.19 ± 0.21
	Built-up areas	0.4 ± 0.39^{bc}	0.32 ± 0.30^{bc}	0.16 ± 0.14^{b}	0.16 ± 0.15	0.08 ± 0.07
	Water body/swamp	1.26 ± 0.93^{abc}	0.97 ± 0.78^{abc}	0.41 ± 0.39^{ab}	0.48 ± 0.35	0.2 ± 0.11
	Other lands	0.29 ± 0.18^{c}	0.23 ± 0.11^{c}	0.1 ± 0.09^{b}	0.11 ± 0.06	0.05 ± 0.21
Ownership type	Central government land	0.75 ± 0.25^{a}	0.55 ± 0.18^{b}	0.21 ± 0.06^{a}	0.27 ± 0.09	0.13 ± 0.03
	Local government land	1.26 ± 0.50^{a}	0.93 ± 0.36^{ab}	0.35 ± 0.13^{a}	0.46 ± 0.18	0.22 ± 0.06
	Village land	2.05 ± 0.54^{a}	1.45 ± 0.35^{ab}	0.49 ± 0.09^{a}	0.71 ± 0.17	0.35 ± 0.05
	Private land	2.67 ± 0.99^{a}	1.95 ± 0.68^{a}	0.72 ± 0.20^{a}	0.96 ± 0.34	0.47 ± 0.10
	General land	2.3 ± 1.29^{a}	1.68 ± 0.93^{ab}	0.59 ± 0.32^{a}	0.82 ± 0.46	0.4 ± 0.16
	Not know	0.77 ± 0.22^{a}	0.59 ± 0.17^{b}	0.25 ± 0.05^{a}	0.29 ± 0.04	0.14 ± 0.01

Note: volume and/or biomass with the same superscript letters in the category are not significantly different ($p < 0.05$).

3.2. Removals by Administrative Zones and Regions. Regarding administrative zones, we observed higher volume removals in the eastern zone followed by the southern zone (Table 3). Conversely, the zone with least-volume removals was the lake zone followed by central zones (Table 3). Interestingly, none of the zones (Table 3) had volume values that were statistically significantly different ($p < 0.05$). Considering administrative regions, the highest volume removals were experienced in Dar es Salaam and Pwani regions, followed by Tanga, Lindi, Mtwara, Morogoro, and Iringa regions, while the regions with the lowest removals were Mara and Arusha followed by Manyara (Table 4).

3.3. Removals by Tree Species. Tree species which were highly removed in terms of volume were *Terminalia sambesiaca*, *Pterocarpus angolensis*, *Brachystegia* sp., *Protea rubrobracteata*, *Julbernardia globiflora*, *Brachystegia microphylla*, *Brachystegia spiciformis*, *Dalbergia melanoxylon*, *Brachystegia boehmii*, and *Afzelia quanzensis* (Table 5).

In terms of biomass and carbon stock removals, the patterns observed in terms of species, vegetation, land use and ownership types, regions, and zones are the same as for volume removals (Tables 2–5).

4. Discussion

This study utilized NAFORMA field data collected over a period between 2009 and 2014. The NAFORMA was the first ground-based national forest inventory that was conducted across Mainland Tanzania. The data were collected from more than 30,000 sample plots, and they provided a baseline data to allow informed decisions to promote sustainable management of the national forest resources. For the purpose of the present study where it aimed at assessing removals from Miombo woodlands, only stump data from Miombo woodlands among other land cover types were used. Appropriate allometric equations developed locally which use SD as the explanatory variable were applied to estimate volume, AGB, BGB, and carbon stock removals.

4.1. Volume, Biomass, and Carbon Stock Removals. Tree removals represented an average volume of 1.71 ± 0.54 m^3 ha^{-1} $year^{-1}$ over the whole country. Study conducted by Treue et al. [26] in Miombo woodlands under participatory forest management (PFM) in Tanzania represented an average volume removal of 1.55 ± 0.53 m^3 ha^{-1} $year^{-1}$. Likewise, Mongo et al. [27] reported volume removals of 1.60 ± 1.60, 1.15 ± 1.13, 2.21 ± 1.87, and 1.35 ± 2.09 m^3 ha^{-1}

Table 3: Volume, biomass, and carbon removals in Miombo woodlands by zones in Mainland Tanzania.

Zone name	Volume (m^3 ha^{-1} $year^{-1}$)	Biomass (t ha^{-1} $year^{-1}$)		Carbon (tC ha^{-1} $year^{-1}$)	
		AGB	BGB	AGC	BGC
Eastern	3.69 ± 1.21^a	2.71 ± 0.85^a	0.98 ± 0.27^a	1.33 ± 0.42	0.48 ± 0.13
Southern	2.53 ± 0.85^b	1.75 ± 0.52^b	0.56 ± 0.11^b	0.86 ± 0.26	0.27 ± 0.05
Northern	2.08 ± 0.95^b	1.56 ± 0.69^b	0.61 ± 0.25^b	0.76 ± 0.34	0.3 ± 0.12
Southern highland	0.91 ± 0.37^b	0.62 ± 0.28^b	0.19 ± 0.11^b	0.31 ± 0.14	0.09 ± 0.05
Western	0.94 ± 0.84^b	0.71 ± 0.52^b	0.3 ± 0.10^b	0.35 ± 0.25	0.15 ± 0.05
Central	0.47 ± 0.18^b	0.36 ± 0.14^b	0.16 ± 0.06^b	0.18 ± 0.07	0.08 ± 0.03
Lake	0.38 ± 0.27^b	0.29 ± 0.21^b	0.13 ± 0.09^b	0.14 ± 0.10	0.06 ± 0.01

Note: volume and/or biomass with the same superscript letter are not statistically significantly different and vice versa is also true ($p < 0.05$).

Table 4: Volume, biomass, and carbon removals in Miombo woodlands by regions in Mainland Tanzania.

Region name	Volume (m^3 ha^{-1} $year^{-1}$)	Biomass (t ha^{-1} $year^{-1}$)		Carbon (tC ha^{-1} $year^{-1}$)	
		AGB	BGB	AGC	BGC
Dar es Salaam	6.72 ± 2.41	5.32 ± 1.82	2.61 ± 0.73	2.61 ± 0.92	1.28 ± 0.28
Pwani	6.6 ± 3.41	4.8 ± 2.38	1.67 ± 0.37	2.35 ± 1.16	0.82 ± 0.18
Tanga	4.59 ± 2.25	3.43 ± 1.64	1.3 ± 0.30	1.68 ± 0.08	0.66 ± 0.15
Lindi	3.98 ± 1.76	2.67 ± 1.06	0.74 ± 0.10	1.31 ± 0.52	0.36 ± 0.05
Mtwara	2.49 ± 1.32	1.87 ± 0.98	0.75 ± 0.19	0.92 ± 0.48	0.37 ± 0.09
Morogoro	2.46 ± 0.78	1.82 ± 0.57	0.68 ± 0.11	0.89 ± 0.28	0.33 ± 0.05
Iringa	1.55 ± 0.06	0.99 ± 0.21	0.22 ± 0.01	0.48 ± 0.02	0.11 ± 0.05
Tabora	1.54 ± 0.77	1.17 ± 0.57	0.48 ± 0.12	0.57 ± 0.28	0.24 ± 0.06
Kigoma	1.19 ± 0.21	0.91 ± 0.09	0.39 ± 0.02	0.45 ± 0.04	0.19 ± 0.01
Ruvuma	1.18 ± 0.46	0.87 ± 0.33	0.35 ± 0.06	0.43 ± 0.16	0.17 ± 0.03
Mwanza	0.99 ± 0.05	0.77 ± 0.01	0.35 ± 0.02	0.38 ± 0.01	0.17 ± 0.01
Singida	0.73 ± 0.34	0.56 ± 0.26	0.24 ± 0.06	0.27 ± 0.13	0.12 ± 0.03
Shinyanga	0.63 ± 0.08	0.47 ± 0.02	0.18 ± 0.09	0.23 ± 0.01	0.09 ± 0.05
Mbeya	0.52 ± 0.32	0.4 ± 0.24	0.17 ± 0.05	0.19 ± 0.12	0.08 ± 0.02
Dodoma	0.46 ± 0.36	0.36 ± 0.28	0.17 ± 0.07	0.18 ± 0.14	0.09 ± 0.03
Rukwa	0.43 ± 0.24	0.32 ± 0.17	0.13 ± 0.03	0.16 ± 0.09	0.06 ± 0.02
Kagera	0.35 ± 0.29	0.27 ± 0.22	0.12 ± 0.05	0.13 ± 0.11	0.06 ± 0.02
Manyara	0.1 ± 0.09	0.08 ± 0.07	0.04 ± 0.02	0.04 ± 0.03	0.02 ± 0.01
Arusha	0.09 ± 0.01	0.07 ± 0.02	0.03 ± 0.02	0.03 ± 0.01	0.01 ± 0.01
Mara	0.09 ± 0.02	0.07 ± 0.03	0.04 ± 0.02	0.03 ± 0.01	0.02 ± 0.01

$year^{-1}$ in Bereku, Haraa, Riroda, and Bubu forest reserves, respectively, in Babati district, Manyara region, and northern Tanzania. These reported findings are slightly lower than the current study because they were carried out in reserved forests with some sort of protection, while NAFORMA data, in addition to protected area, represents large forest area which remains unprotected and therefore vulnerable to tree cutting. Since limited studies have been conducted on the volume removals per ha per year in Miombo woodlands in Tanzania, comparison across studies was also based on studies that were conducted to determine growth rate. The estimated volume increments of Tanzanian Miombo woodlands are estimated to range from 0.8 to 3.3 m^3 ha^{-1} yr^{-1} with a mean of 1.6 ± 0.2 m^3 ha^{-1} yr^{-1} [26, 28]. Other studies report the annual volume increment of woodlands to be in the range between 0.57 and 4.35 m^3 ha^{-1} $year^{-1}$ [29–31]. In the Miombo woodland categories where volume removal exceeds increment rates, the removals are deemed unsustainable and the woodlands may consequently be depleted over time.

Volume removals were further presented according to zones, regions, vegetation, land use, and ownership types. Regarding land use types, much of the volume removals were found to be in the shifting cultivation lands followed by agricultural lands, production forestlands, and grazing lands. The highest removals in these woodland categories were expected since in the shifting cultivation and agricultural lands, farmers clear-fell the trees in favour of agricultural crops. On the other hand, since production forests are set for timber and charcoal production, these activities explain why this category has high volume removals. For the grazing land, domesticated and wild animals are the main drivers of removals in which grasses and shrubs are grazed out. This leads to exposure of trees that are easily cut for timber, charcoal, poles, and firewood. Moreover, elephant grazing can also reduce tree populations significantly [32, 33]. The last 50 years have witnessed an intensification of these land use activities driven by increasing human and livestock populations, as well as the human-induced concentration of wildlife herbivores into small conservation areas [34–37].

Regarding vegetation of Miombo woodlands subdivision, there was higher volume removals in the woodlands with scattered croplands because in this subdivision farmers

Table 5: Thirty species with highest volume, biomass, and carbon removals in Miombo woodlands in Mainland Tanzania.

Species scientific name	Volume (m^3 ha^{-1} $year^{-1}$)	Biomass (t ha^{-1} $year^{-1}$)		Carbon (tC ha^{-1} $year^{-1}$)	
		AGB	BGB	AGC	BGC
Terminalia sambesiaca	0.205	0.120	0.015	0.059	0.008
Pterocarpus angolensis	0.102	0.075	0.027	0.037	0.013
Brachystegia sp.	0.099	0.072	0.025	0.035	0.012
Protea rubrobracteata	0.074	0.045	0.007	0.022	0.003
Julbernardia globiflora	0.069	0.052	0.021	0.025	0.010
Brachystegia microphylla	0.058	0.041	0.012	0.020	0.006
Brachystegia spiciformis	0.058	0.044	0.018	0.022	0.009
Dalbergia melanoxylon	0.050	0.035	0.011	0.017	0.005
Brachystegia boehmii	0.042	0.032	0.013	0.015	0.006
Afzelia quanzensis	0.035	0.025	0.007	0.012	0.003
Albizia sp.	0.033	0.022	0.006	0.011	0.003
Pericopsis angolensis	0.032	0.024	0.009	0.012	0.004
Xeroderris stuhlmannii	0.030	0.022	0.007	0.011	0.003
Pteleopsis myrtifolia	0.030	0.022	0.008	0.011	0.004
Albizia versicolor	0.025	0.018	0.006	0.009	0.003
Burkea africana	0.023	0.018	0.007	0.009	0.004
Pseudolachnostylis maprouneifolia	0.023	0.017	0.006	0.008	0.003
Brachystegia bussei	0.023	0.018	0.007	0.009	0.004
Diplorhynchus condylocarpon	0.023	0.018	0.009	0.009	0.005
Isoberlinia sp.	0.022	0.017	0.007	0.008	0.003
Combretum zeyheri	0.022	0.017	0.007	0.008	0.004
Acacia nigrescens	0.022	0.016	0.006	0.008	0.003
Acacia sp.	0.021	0.016	0.007	0.008	0.003
Diplorhynchus mossambicensis	0.016	0.012	0.004	0.006	0.002
Bridelia melanthesoides	0.015	0.010	0.003	0.005	0.001
Combretum collinum	0.014	0.010	0.004	0.005	0.002
Albizia gummifera	0.013	0.009	0.003	0.004	0.001
Combretum molle	0.013	0.010	0.005	0.005	0.002
Pterocarpus tinctorius	0.012	0.009	0.003	0.004	0.002
Brachystegia longifolia	0.011	0.009	0.004	0.004	0.002

clear-fell trees in favour of agricultural crops similar to shifting cultivation. Furthermore, open woodland was the second to woodlands with scattered croplands mainly because of the exposure of trees to activities such as tree cut for timber, firewood, and charcoal. Closed woodlands had the lowest removals mainly because most of the woodlands fall under protection ownership types and are found far away from human settlements.

For ownership types, higher-volume removals were documented in private lands followed by general lands and village lands. Under private tenure regime, individuals or groups with user rights of occupancy exclude others from forest resource use [38]. The highest volume removals documented in this regime are because the majority of private owners have rights to extract all resources in their own forests in spite of the forest policy of Tanzania restricting extraction of forest resources without legal permits from the government for conservation purposes. In the general lands, the main reason for this situation is that forests are rather under an open access regime in which people are free to extract forest products from the woodlands [39, 40]. In contrast, the higher volume removals in village land were probably contributed by allowed harvesting coupled by lack of management plans. This is because out of 1,821 village forest lands involved in participatory forest management (PFM), only 531 village forests have approved management plans [41]. Tanzania forest Act No. 14 of 2002 [42] recognizes communities, through their village councils as the sole managers of village land forest reserves. Evidence from communities that reserved their own forests in the mid-1990s clearly showed that forests were being restored, unregulated activities were being reduced, and encroachment was declining [41]. Forests also continued to provide local subsistence benefits and opportunities for regulated commercial harvesting [41].

The findings of this study clearly indicate that there are higher volume removals in village land perhaps because it is expected that trees should be harvested from these forests. On the other hand, the least-volume removals were found to be in central government land followed by local government land. Forest policy and act that enable the use of management plans explain this. This also implies that there is somewhat effective law enforcement in both central and local government forests compared to forests under other regimes. Most of central government forests are for protection purposes unlike village forests that are for production purposes. In practice, no tree cutting is allowed in protection forests. However, a forest inventory carried out in 11 most forested districts in Tanzania showed that encroachment and tree cutting are common even in protected forests [43]. In the future, harvesting pressure is likely to increase in the central and local government reserves following resource depletion in private, general, and village land.

In terms of zones, woodlands located in the eastern zone had noticeable higher removals (4.59–6.7 m^3 ha^{-1} $year^{-1}$) compared to other zones. This is in line with the results of 6.7 m^3 ha^{-1} $year^{-1}$ reported by Treue et al. [26] in Dar es Salaam and Pwani regions. Higher charcoal demand in Dar es Salaam city could account for the highest removals. Charcoal consumption grew between 1990 and 2000 by about 80% in Dar es Salaam city in Tanzania [44]. Moreover, Msuya et al. [45] estimated the amount of charcoal consumed in Dar es Salaam to be 1,904 t/day^{-1} or 694,960 t/$year^{-1}$.

The ten mostly harvested tree species in Miombo woodlands of Tanzania are *Terminalia sambesiaca*, *Pterocarpus angolensis*, *Brachystegia* sp., *Protea rubrobracteata*, *Julbernardia globiflora*, *Brachystegia microphylla*, *Brachystegia spiciformis*, *Dalbergia melanoxylon*, *Brachystegia boehmii*, and *Afzelia quanzensis.* This is probably due to the commercial values attached to them in terms of timber and charcoal.

For AGB and BGB, tree removals represented an average of 1.23 ± 0.37 t ha^{-1} $year^{-1}$ and 0.43 ± 0.12 t ha^{-1} $year^{-1}$ of AGB and BGB, respectively. A study conducted by Zahabu [40] recorded aboveground biomass removals of 1 t ha^{-1} $year^{-1}$ for the Miombo woodlands at Kitulangalo in eastern Tanzania that are similar to the results from this study. On the other hand, the biomass increments are between 0.58 and 3 t ha^{-1} $year^{-1}$ in mature Miombo woodlands [44, 46]. The increment is higher in young Miombo woodlands which may range from 1.2 to 3.4 t ha^{-1} $year^{-1}$ [44]. Considering the mean annual AGB increment (MAI-AGB), removals exceeding increment rate in the woodland categories studied indicate unsustainability.

In terms of carbon stock removals, we estimated total average aboveground carbon (AGC) and belowground carbon (BGC) removals of 0.60 ± 0.18 tC ha^{-1} $year^{-1}$ and 0.21 ± 0.05 tC ha^{-1} $year^{-1}$, respectively. However, the mean annual AGC increment (MAI-AGC) in Miombo woodlands of Tanzania ranges between 0.111 and 0.404 tC ha^{-1} $year^{-1}$ [47]. In addition, 0.9, 0.75, and 0.58 tC ha^{-1} $year^{-1}$ increments were found in Miombo woodlands in Zambia, Mozambique, and South Central Africa, respectively [5, 48, 49]. The differences in carbon densities might be attributed to varying degree of exposure to drivers of forest degradation, difference in age of the tree species, and the type of Miombo woodlands involved [50]. Considering the MAI-AGC in Miombo woodlands in Tanzania, it is very clear that removals exceed increments that could end up into woodlands depletion over time.

Moreover, since biomass and carbon stocks were expressed according to zones, regions, species, land use, ownership, and vegetation types, much of the AGB, AGC, BGB, and BGC removals followed similar trends as for volume removals and thus the same explanations applied to volume removal patterns held.

5. Conclusion

This study reported annual volume, biomass, and carbon stock removals per ha that consequently result into carbon dioxide (CO_2) emissions in Tanzania. Volume and carbon removals in all the categories of Miombo woodlands of Mainland Tanzania are unsustainable except in the closed woodland, protection forest, wildlife reserves, swamps, central government land, local government land, southern highland zone, western zone, central zone, and lake zone. For reducing emissions emanating from removals and by considering national circumstances, all categories of Miombo woodlands should be managed although the management intensity and priorities should consider those categories with unsustainable removals. In addition, we recommend the use of stumps data collected by NAFORMA to estimate removals in other vegetation types like mangrove forest, lowland forest, humid montane forest, and thickets. This would bring information on the national status of removals, thereby understanding inferred forest degradation and hence improving future FREL.

Data Availability

The data are available at the database of the Ministry of Natural Resources and Tourism, Tanzania.

Conflicts of Interest

The authors declare that they have no conflicts of interest regarding the publication of this paper.

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