ESTIMATION OF TREE REMOVALS IN MIOMBO WOODLANDS OF MAINLAND TANZANIA

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EXTENDED ABSTRACT

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 miombo woodlands resources depend on the balance between increment/growth rate and the magnitude of utilization. While many studies have been conducted to evaluate growth rate/increment little has been done to evaluate tree removals in miombo woodlands of mainland Tanzania. Quantification of volume, biomass, and carbon stocks removals is vital in developing effective climate change mitigation strategies, decision making, and promoting sustainable forest management.The overall objective of this study was to assess volume and carbon removals in miombo woodlands of mainland Tanzania as a result of tree cutting. Specifically, the present study intended to: 1), develop biomass and volume models based on stump diameter for assessing forest removals; 2) estimate volume and carbon stocks removals as a result of tree cutting; 3) examine drivers of removals and their influences on aboveground carbon removals in miombo woodlands and 4) estimate volume loss due to extra stump height in miombo woodlands of mainland Tanzania. To this end, two main data sets were used. The first is composed of field data collected from miombo woodlands located in three regions i.e. Manyara, Tabora and Lindi. The data were used for developing individual tree biomass and volume models essential for estimating biomass and volume removals directly from stump diameter (SD). Estimating volume and biomass directly from SD has an advantage of reducing the accumulated errors that could results from estimation of diameter at breast height (DBH) of the removed tree and used the estimated DBH to estimate volume and biomass from available equation that utilize the estimated DBH. The second is stumps data (diameter and height) collected during the implementation of the Tanzania National Forest Resources Monitoring and Assessment (NAFORMA). This data set were requested from Tanzania Forest Services agency (TFS), Tanzania Forestry Research Institute (TAFORI), and Sokoine University of Agriculture through the National Carbon Monitoring Centre (NCMC).This data set were used to respond to the objective two, three and four of this study. All the data were analysed in R software.

Results revealed that, in all the models developed, SD explained over 70% of the variations in belowground biomass (BGB), aboveground biomass (AGB) and volume. By applying the developed models to the NAFORMA stump data, the estimated mean annual volume, AGB and BGB removals in the entire miombo were 1.71±0.54 $m^3ha^{-1}year^{-1}$, 1.23±0.37$tha^{-1}year^{-1}$, and 0.43±0.12 tha^{-1} $year^{-1}$ respectively. The drivers of removals were, timber extraction, fire, shifting cultivation, charcoal, natural death, firewood collection, poles, grazing wild, carving, grazing domestic and mining activities. The estimated removed AGC ranged from 0.0 to 1.273$tCha^{-1}year^{-1}$ with the highest removals accounted by timber and the lowest by mining activities. Since the estimated annual volume removals exceed estimated mean annual increment of 1.6±0.2m^3 $ha^{-1}yr^{-1}$ in miombo woodlands, the removals indicate unsustainability utilization of woodlands resource. This imply that the emission is relatively higher than the sequestration. The results also revealed that removals are more prominent in the following categories; shifting cultivation, production forest, grazing land, general land, village land, Eastern and Southern zones. Furthermore, total annual wood volume, annual volume and carbon per ha lost through extra stump height (ESH) were 3 800 000$m^{-3}year^{-1}$, 0.098 ± 0.034 $m^3ha^{-1}year^{-1}$ and 0.028±0.009 $tCha^{-1}year^{-1}$ respectively.

Based on these findings, it is recommend that, regional developed models should be applied over a wide range of conditions in miombo woodlands of mainland Tanzania

under the threshold of tree diameter sizes used in the modelling. Furthermore, we recommend that the site-specific models should be applied for local inventories in their respective sites. For reducing emissions emanating from removals and by considering national circumstances, all categories of miombo woodlands should be managed although the management (in terms of tree removals) intensity and priorities should consider those categories with unsustainable removals. Similarly, all drivers of removals should be managed and priority should be to those drivers with the highest contribution to removals. Since the estimated annual volume loss through ESH (i.e. 3.8 million m^3year^{-1}) is almost ¼ of the annual volume deficit of 19.5 million m^3year^{-1} reported by NAFORMA, the deficit and further removals could be lowered through proper adherence to appropriate harvesting procedures in the miombo woodlands of Tanzania. Moreover, the use of alternative sources of energy particularly clean energy and planting trees for wood energy must continue to be emphasized. Additionally, it is recommend that stumps data should be used to estimate volume and carbon removed and assess drivers of volume and carbon removals in other vegetation types i.e. mangrove forest, lowland forest, humid montane forest and thickets. This would bring tree removal information at national scale and improve future estimates of Forest Reference Emission Level (FREL).

DECLARATION

I, Bernardol John Manyanda declare to the Senate of Sokoine University of Agriculture that, this thesis is my own original work done and that it has neither been submitted nor being concurrently submitted in any other institution.

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(PhD candidate)

The above declaration is confirmed by:

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Prof. Rogers E. Malimbwi Date

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Prof. Emmanuel F. Nzunda Date

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Dr. Wilson A. Mugasha Date

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DEDICATION

To all people who appreciate the little knowledge added to science.

THESIS STRUCTURE

This thesis consists of six Chapters. Except for Chapter 1 and Chapter 6 that present synopsis of the theme studied, conclusions and recommendations, other Chapters comprise published articles and submitted manuscripts. The content presented in the chapters is either the same as the content submitted to or published in a journal, hence some repetitions have been inevitable. Chapter one includes a discussion of the background information on miombo woodlands, models for assessing volume and biomass removals, extent of removals and increments in miombo woodlands, drivers of removals and implications of extra stump height on wood volume and carbon removals. Additionally, it provides the problem statement, justification and objectives studied. Chapter 2 consists of published paper one. The paper developed biomass and volume models based on stump diameter in miombo woodlands of mainland Tanzania. Although my initial intention for undertaking the study was to find a tool for estimating degradation, the models developed should also be useful for assessing all kind of removals through tree cutting. Chapter three utilizes results from paper 1and forms published paper two. The paper provides the estimates of volume and carbon removals (based on stumps) in the entire miombo woodlands by using equations developed in paper one. Moreover, the paper estimated removals by, species, land use, vegetation, ownership types and Tanzania Forest Services Agency (TFS) zones. Chapter four consists of submitted manuscript one. This manuscript identified the drivers of aboveground carbon removals and estimated the amount of aboveground carbon (AGC) for each drivers identified. Chapter five consists of submitted manuscript two. The manuscript provides estimates of volume and carbon lost through ESH in miombo woodlands. Chapter six presents key contributions of the study and specific recommendations for better conservation and management of miombo woodlands.

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AGB	Aboveground biomass
AGC	Aboveground carbon
AIC	Akaike Information Criterion
BGB	Belowground biomass
BGC	Belowground carbon
C	Carbon
CHAPOSA	Charcoal Potential of Southern Africa
cm	centimeter
CO_2	Carbondioxide
D	diameter at breast height
DBH	Diameter at breast height
DG-ratio	Dry to green weight ratio
E%	Mean Prediction Error percentage
e.g.	For example
EF	Plot expansion Factor
ESH	Extra Stump Height
FAO	Food and Agriculture of the United Nations
Fig.	Figure
FREL	Forest Reference Emission Level
H	Tree height
ha	Hectare
i.e.	That is
IPCC	Intergovernmental Panel on Climate Change
kg	Kilogram

km	Kilometre
lme	linear mixed effects
m	meter
m^3	Cubic centimeter
MAI	Mean Annual increment
Max	Maximum
Min	Minimum
mm	millimeter
MNRT	Ministry of Natural Resources and Tourism
MRV	Measurement, Reporting and Verification
NAFORMA	National Forest Resources Monitoring and Assessment
NFI	National Forest Inventory
NGOs	Non-Governmental Organizations
nlme	Non linear mixed effects
P	Probability value
PFM	Participatory Forest Management
R	R software Development Core Team
R^2	Coefficient of Determination
REDD+	Reduced Emissions from Deforestation and Forest Degradation plus the role of conservation, sustainable management of forest and enhancement of forest carbon stocks
SD	Stump Diameter
SE	Standard Error
SE%	Root Mean Square Error
t	Tone
TFS	Tanzania Forest Services Agency

UNEP	United Nation Environmental Programme
URT	United Republic of Tanzania
WWF	World Wide Fund for Nature
yr	Year

CHAPTER ONE

1.0 General introduction

1.1 Overview of miombo woodlands

Miombo is a vernacular word that has been adopted by ecologists to describe those woodland ecosystems dominated by trees of the genera *Brachystegia*, *Julbernardia* and *Isoberlinia* (L*eguminosae,* sub-family *Caesalpinioideae*) (White, 1983). Miombo woodlands occupy an area of about 2.7 million km^2 in seven African countries namely Angola, Malawi, Mozambique, Tanzania, Zaire, Zambia and Zimbabwe (White, 1983). The coverage represents an important plant diversity center with over 8500 species (White, 1983; Frost, 1996; Burgess *et al.,* 2007; Timberlake and Chidumayo, 2011). Miombo can be divided into dry and wet based on the annual precipitation they receive (White, 1983). The dry and wet miombo woodlands occur in areas receiving annual precipitation of less than 1000 mm and greater than 1000mm respectively.

In Tanzania, miombo woodlands make up about 93% of the 48.1million ha forested land, equivalent to 44.7 million ha (MNRT, 2015; Malimbwi *et al.,* 2018). Although the averages volume is low ($55.1m^3h^{-1}$), miombo woodlands account for about 74% of the growing stocks (3.3 billion m^3) (Malimbwi *et al.,* 2018). The main concentrations of these biomes in the country are found in the western zone (Tabora, Rukwa and Kigoma regions) and the southern zone (Iringa, Lindi, Mtwara and Ruvuma regions). Species diversity differs from place to place in miombo woodlands of mainland Tanzania. Studies have found that tree species composition varies from 99 to 532 (Abdallah, 2001; Mwakalukwa *et al.,* 2014; Nduwayezu *et al.,* 2015; Gonçalves *et al.,* 2017). However, the number of species obtained by different scholars may not be all in that specific site since the number of species captured may be affected by sampling design.

With that higher diversity of species and the large coverage, miombo woodlands offer both direct and indirect benefits. Direct benefits include firewood, charcoal, construction materials, medicines, employment, income and food (Abdallah and Monela, 2007; Gumbo and Clendenning, 2018; Gumbo *et al.*, 2018; Zimba *et al.*, 2018). Indirect benefits encompass soil nutrient inputs through nutrient cycling and through nitrogen fixation and environmental services such as soil and water conservation, biodiversity and carbon sequestration (Munishi and Shear, 2004; Zahabu, 2008; Burgess *et al.*, 2010; Dewees *et al.*, 2010). These benefits are crucial to the millions of people who live in miombo woodlands and many millions of others who are indirectly dependent on the services from these woodlands. Despite this reality, miombo woodlands are under pressure from increasing demands for woodland-based products and services. This has led to deforestation and forest degradation (FAO, 2010; URT, 2018; Hafner *et al.*, 2018). These may have jeopardized the capacity of woodland to function as regulators of the environment. Consequently, increasing flooding, erosion, reduced soil fertility and loss of plant and animal diversity (FAO, 2010). Sustainable provision of goods and services from the miombo woodlands requires effective forest management efforts, which in turn may make a significant contribution to national and global goals for Reduced Emission from Deforestation and forest Degradation “plus”, the role of conservation, sustainable management of forests and enhanced carbon stock (REDD+).

Under the REDD+ mechanism, participating developing countries receive financial incentives for their verified success in reducing carbon emission from forest related activities as well as enhancing the removals of the carbon from the atmosphere (Mauya *et al.*, 2015; Mauya *et al.*, 2019). In order for the REDD+ to work, the following among other things need to be understood; 1) the actual carbon and voume that are being removed in miombo woodlands under business as usual scenario also known as the Reference Emission Level (FREL). 2), the drivers and the extents of their influences on the variations of carbon removals. 3), the amount of volume and carbon loss due to extra stump height (ESH). Assessing removals require availability of biomass/volume-SD models based on SD only. Despite this fact, there has been scarcity of relevant studies in relation to these needs in miombo woodlands of mainland Tanzania.

1.2 Problem statement and justification of the study

1.2.1 Problem statement

Miombo woodlands are important vegetation type, playing a vital role in social, economic, and environmental aspects (Mugasha *et al.,* 2013; Mauya *et al.,* 2014). In Tanzania, Miombo woodlands offer both direct (example; firewood, charcoal, construction and craft materials, medicines, employment, income, fruits, mushrooms, honey, edible insect, and fodder) and indirect benefits (nutrient cycling, soil and water conservation, biodiversity and carbon sequestration). However, the sustainability of goods and services from miombo woodlands depends much on the balance between the magnitude of its utilization (removals) and growth/increments. Although a number of studies have evaluated volume, biomass and carbon increments (Ek, 1994; Grund, 1995; Malimbwi and Mugasha 2001; Malimbwi *et al.*, 2005; Zahabu and Jambia, 2013), only one large-scale study (Treue *et al.,* 2014) has been conducted to provide information on the removals in miombo woodlands under Participatory Forest Management (PFM) in Tanzania. While it is considered difficult to properly estimate the age of the stump of more than five year, Treue *et al.* (2014) estimated volume removals of 4.1 million ha for the past ten years in forest area under PFM in Tanzania. Luoga *et al.* (2002), Chamshama *et al.* (2004), Mongo *et al.* (2014) and Sawe *et al.* (2014) evaluated removals on even smaller scale and provided estimates of volume only. Interestingly the studies estimated volume over a range of years (Luoga *et al.*, 2002; Sawe *et al.*, 2014). Their volume results for Luoga *et.al.* (2002) and Sawe *et al.* (2014) was 7.1 ± 1.2m^3 ha^{-1} and 10.53 ± 3.1 m^3 ha^{-1} respectively. Therefore, efforts to assess large scale removals in miombo woodlands under different management regime is imperative.

Large-scale estimation of volume and carbon removals using stumps in miombo woodlands of mainland Tanzania requires among other, the availability of regional (total area covered by miombo woodlands) volume/biomass- SD models. To date, there is only one biomass/volume – SD allometric equation that was developed from limited sample trees (30 trees) and from only one site in Tanzania (Chamshama, 2004). Therefore, development of volume/biomass – SD allometric models based on adequate sample trees collected from different sites of miombo woodlands in mainland Tanzania is imperative to cover variability in biomass/volume-SD allometry. Moreover, the volume/biomass-SD models would be free from the accumulated errors caused by two steps estimatioms of volume/biomass, i.e. from SD to DBH (applying SD-DBH linear relationships) and then to biomass/volume (applying biomass/volume-DBH relationship models). This has been a common approach of estimating volume of cut trees in the previous studies in miombo woodlands of mainland Tanzania (Mugasha *et al.,* 2013; Masota *et al.*, 2014; Mauya *et al.*, 2014).

The removed trees volume and biomass are caused by combination of drivers, which may vary in extent, severity, origin and frequency. The drivers may either be proximate, such as that caused by logging, grazing, or it may be underlying, such as that caused by population growth, policies (FAO, 2009; Obersteiner *et al.*, 2009; Kissinger *et al.*, 2012).

Low to high carbon removals can be expected in different management categories in which miombo woodlands of Tanzania fall due to varying drivers. Additionally, there is inadequate information on the extent of the contribution of each driver on AGC removals in the entire miombo woodlands of mainland Tanzania. Available studies (Miya *et al.*, 2012; Kessy *et al.*, 2016; Makunga and Misana, 2017) are limited to drivers of forest degradation and did not provides estimates of AGC removals for each driver.

During tree removals, it is recommended that trees should be cut closest (usually, 15 cm) to the ground level to avoid wood volume wastage, carbon emissions and abstraction during transportation (URT, 2004; Han and Chad, 2005; Katani *et al.,* 2016). However, experience shows that some trees harvested in miombo woodlands are not cut at 15 cm from ground level. This leave wood volume in the forest due to extra stump height (ESH) that escalate more tree removals and hence carbon emissions if the remained portion rot out and burnt. Based on the literature search, no studies had been encountered quantifying volume and carbon left from ESH in miombo woodlands of mainland Tanzania. This study is therefore intended to fill that gap.

1.2.2 Justification of the study

The findings of this study are intended to contribute to efforts toward sustainable miombo woodlands management. Having biomass/volume – SD allometric equations would facilitate the estimation and monitoring of removals in miombo woodlands in Mainland Tanzania. Volume and carbon stocks removal estimates determined are considered as an essential step in accounting for sustainability of ecosystem goods and services emanating from miombo woodlands. Such estimates are also important in designing management plans for the miombo woodlands that would ensure a sustained potential of this ecosystem's contribution to emission mitigation. Similarly, estimates of the rate of removals in each category would aid in prioritizing mitigation measures so that more efforts are targeted to miombo category with higher removals.

Furthermore, a better understanding of the drivers of removals and their amount of AGB they influence would support management decisions by managers through; 1) prioritizing mitigation intervention i.e. tackling driver in response to the amount of AGC emissions caused. 2) track the impacts of driver on AGC over time. In addition, it is fundamental for better design of REDD+ strategy i.e. REDD+ incentives could be channeled directly to affect the drivers.

Moreover, by having volume and carbon estimates from ESH in miombo woodlands would justify whether or not enforcement of proper tree harvesting is necessary for mitigating climate change. Policies and decision makers can use the findings to check whether harvesting regulations in place are adhered to. Likewise, it would allow knowing which category have higher wood volume and carbon emission from ESH so that relevant management institutions could take targeted measures.

1.3 Research objectives

1.3.1 Overall objective

The overall objective of this study was to assess volume and carbon removals through tree cutting in miombo woodlands of mainland Tanzania.

1.3.2 Specific objectives

Specifically, this study intends to:

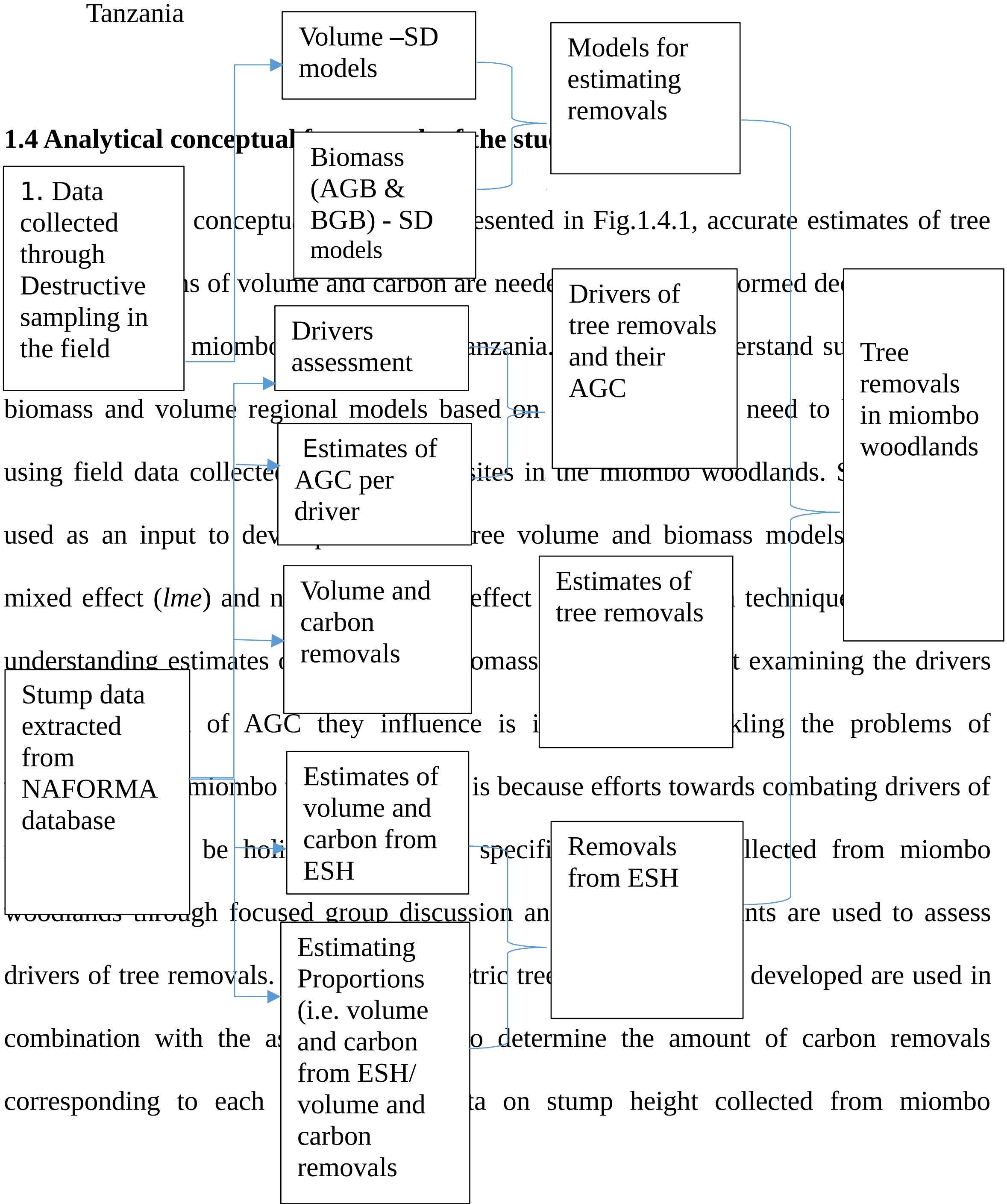
i. develop biomass and volume models based on stump diameter for assessing forest removals in miombo woodlands

ii. estimate volume and carbon stocks removalsin miombo woodlands of mainland Tanzania

iii. examine drivers and their influences on aboveground carbon removals in miombo woodlands of mainland Tanzania

iv. estimate volume loss due to extra stump heightin miombo woodlands of mainland Tanzania

1.4 Analytical conceptual f... the stu...



conceptu... esented in Fig.1.4.1, accurate estimates of tree ...s of volume and carbon are neede... ormed de... miombo ... anzania. ... erstand su... biomass and volume regional models based on ... need to ... using field data collecte... sites in the miombo woodlands. S... used as an input to dev... ree volume and biomass models ... mixed effect (*lme*) and n... effect ... techniqu... understanding estimates ... omass ... t examining the drivers ... of AGC they influence is i... kling the problems of ... miombo ... is because efforts towards combating drivers of ... be holi... specifi... llected from miombo woodlands through focused group discussion an... nts are used to assess drivers of tree removals. ... tric tre... developed are used in combination with the as... o determine the amount of carbon removals corresponding to each ... a on stump height collected from miombo woodlands are also used to provide estimates of volume and carbon removals caused by ESH cut. Volume of ESH is estimated by using fomula applicable to cylinder with circular base while carbon is estimated from biomass by multiplying volume with wood basic density and thereafter with 49% as the conversion factor of biomass to carbon. Moreover, the variables and their relationship, linkages between chapters of the thesis and factors/components investigated is discussed in detail below:

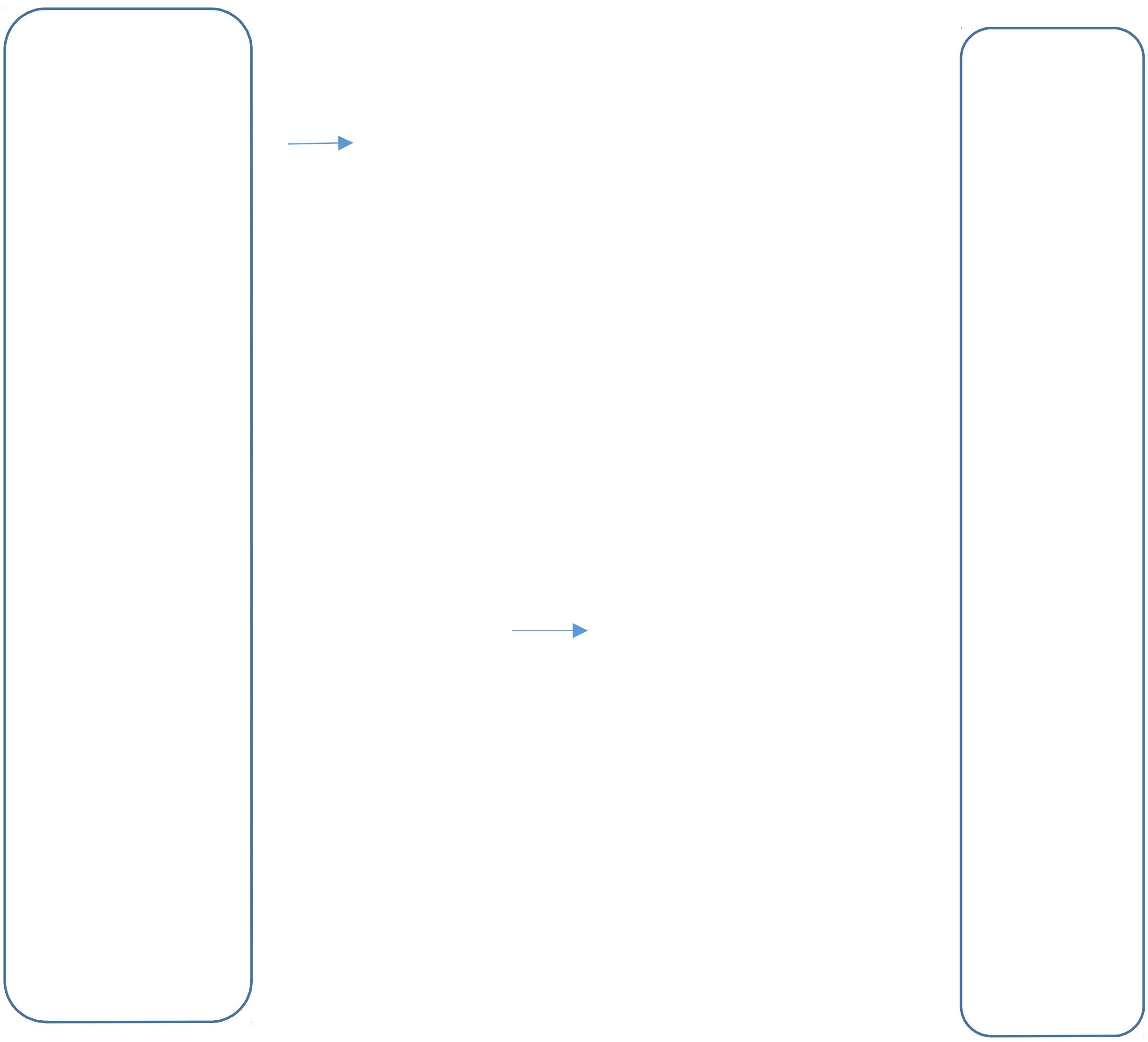


Figure 1.1: Analytical conceptual framework for the study

1.4.1 Models for assessing volume and biomass removals

Standing volume and aboveground biomass (AGB) are the two main parameters of forest stocking that are typically considered within the framework of sustainable forest management and for carbon accounting purposes (Mugasha *et al.,* 2013; Mauya *et al.,* 2014; Malimbwi *et al.,* 2018). Accurate estimation of tree volume and forest biomass is important for forecasting expected yields, in forest management. It is also important in carbon storage assessment in relation to climate change mitigation (Mugasha *et al.,* 2013; Mauya, *et al.,* 2014; Masota *et al.,* 2014; Kachamba *et al.,* 2016; Manyanda *et al.,* 2019; Manyanda *et al.,* 2020). Volume and AGB can be estimated directly by harvesting and weighing trees. However direct measurement is impractical since it is time consuming, costly, and usually destructive in nature. Therefore, the general practice is to estimate standing volume and AGB from easy to measure tree variables like diameter at breast height (DBH) and height, and the use of allometric models (Mauya *et al.,* 2014; Mugasha *et al.,* 2013; Mwakalukwa *et al.,* 2014; Masota *et al.,* 2014; Kachamba *et al.,* 2016; Makero *et al.,* 2016).

In a situation where a tree has been removed and only the stump remains as an indicator of its size, the stump dimensions such as stump diameter (SD) and stump height may be used to predict volume and biomass removed (Luoga *et al.,* 2002; Chamshama *et al.,* 2004; Sawe *et al.,* 2014; Mongo *et al.,* 2014; Treue *et al.,* 2014; Manyanda *et al.,* 2019; Manyanda *et al.,* 2020). Two approaches are practical. First is through estimating DBH by developing equations relating DBH andSD from sample trees measured for SD (Luoga *et al.,* 2002; Corral-Rivas, 2007; Aigibe *et al.,* 2012; Sawe *et al.,* 2014).The estimated DBH is then used to estimate biomass and volume by using appropriate existing allometric equations (e.g Mugasha *et al.,* 2013; Mauya *et al.,* 2014). The weakness of this approach stands on the accumulated errors that occurs from the sequence of regression equations i.e. from the estimation of DBH by using measured SD to the estimation of biomass or volume using the estimated DBH. Second is to estimate biomass and volume removals directly from SD only (Chamshama *et al.,* 2004; Manyanda *et al.,* 2019; Manyanda *et al.,* 2020). This approach solves the problem of errors accumulation from estimated DBH as long as the volume or biomass- SD model is unbiased (Manyanda *et al.,* 2019).

1.4.2 Extent of removals and increments in miombo woodlands

Sustainable management of miombo woodlands resource requires among others the balance between growth rates /increments and removals. In a situation where removals exceed increments, unsustainability occurs and vice versa. Various scholars have estimated the extent of volume and biomass removals in a small scale areas in Tanzanian miombo woodlands. For example, Sawe (2014) reported an average annual volume and total biomass values of 6.63 ± 3.0 m^3 ha^{-1} $year^{-1}$and 4.1±0.9 $tCha^{-1}$ respectively in miombo woodlands in Chunya District Mbeya region Tanzania**.** Luoga *et al*. (2002) reported total volume removals of 7.1 ± 1.18m^3 $ha^{-1}$and 19.62 ± 2.58m^3 ha^{-1} calculated from stumps in reserved miombo woodlands and public owned miombo woodlands respectively in eastern Tanzania miombo woodlands. In addition, the same author reported annual volume removals for all uses of 6.38 ± 2.39m^3 ha^{-1} in public lands that are highly degraded in eastern Tanzania miombo woodlands. Furthermore, Mongo *et al*. (2014) reported volume removals of 1.60 ± 1.60, 1.15 ± 1.13, 2.21 ± 1.87and 1.35 ± 2.09 $m^3ha^{-1}year^{-1}$ in Bereku, Haraa, Riroda and Bubu forest reserves respectively in Babati district Manyara region northern Tanzania. Similarly, Treue *et al.* (2014) reported volume removals that varies from 0.004 $m^3ha^{-1}yr^{-1}$ (SE=0.003) in the remote Kiwele forest, to 6.7 $m^3ha^{-1}yr^{-1}$

(SE=2.010) in Masanganya forest, Tanzania. Most of the removals reported in these studies are unsustainable because increments/growth rates are smaller than removals, and some of them do not show the rate of removal per year.

On the other hand, a number of studies have been conducted in Tanzania and outside Tanzania to bring information on the volume and biomass increments of miombo woodlands. 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±0.2m^3 ha^{-1} yr^{-1} (Ek, 1994; Malimbwi *et al.,* 2005; Treue *et al.,* 2014). Other studies report, the annual volume increment of woodlands to be in the range between 0.57 and 4.35$m^3ha^{-1}year^{-1}$ (Chidumayo, 1988; Grundy, 1995).

Biomass and carbon increment are also reported in the miombo woodlands. Ek (1994) reported a mean annual biomass increments (MAI) of between 0.57 and 2.97 t/ha/year for a period of 13 to 16 years in miombo woodlands in Morogoro, Tanzania. However, this was smaller compared to the MAI of young or exploited miombo woodlands (0.7 to 4.2 t/ha/year) in the same area. In mature miombo woodlands, the biomass increments are between 0.58 and 3 tha^{-1} (Malimbwi and Mugasha, 2001). The increment is vigorously for the young miombo woodlands that may range from 1.2 to 3.4 tha^{-1} (Chidumayo, 2013). The MAI in miombo woodlands depends on species composition, amount of rainfall, and soil factors (Frost, 1996; Chidumayo, 2013). The annual carbon stock increments from miombo woodlands provide insight of the incremental carbon stock in miombo woodlands of Tanzania and elsewhere had been reported. For example (Chidumayo, 1997) observes 0.9 $tCha^{-1}$ $year^{-1}$ over 35-year-old miombo in Zambia, while Stromgaard (1985) reported 0.5tC ha^{-1} $year^{-1}$ for 16 year old miombo in northern Zambia;

Williams *et al.* (2008) also reported 0.75tCha^{-1} year^{-1} over 50-year-old miombo woodlands.

1.4.3 Drivers of removals in the miombo woodlands

Understanding dynamics of estimates of volume and biomass removals requires a thorough understanding of the drivers influencing such dynamics. The drivers of tree removals are multifaceted and cannot be reduced to a few variables; rather they operate at different levels and scales in the human-environment linkages that ultimately cause change to forests (Geist and Lambin, 2011; Kissinger, 2017). They are broadly divided into two categories: proximate and underlying drivers. Proximate or direct drivers are human activities operating at the national, regional and local levels. They include shifting cultivation, livestock grazing, wood extraction through logging and charcoal production, infrastructural development such as roads, uncontrolled fires, livestock grazing in forests and fuelwood collection (Geist and Lambin, 2011; Hosonuma *et al.,* 2012; Kissinger *et al.,* 2012). The amount of carbon removed by these drivers differs in response to scale and time of occurrence.

Underlying or indirect drivers do not directly drive removals and are often distant from their area of impact but influence the proximate drivers (Kissinger, 2017). They can be hard to identify, but are crucial for understanding what drives various actors to harvest the woodlands. Underlying drivers includes a complex interactions of social, economic, political, policies and institutions, demographic factors, cultural and technological developments that in combination create the enabling environment for proximate drivers to unfurl (Geist and Lambin, 2011; Kissinger *et al.,* 2012). Underlying drivers stem from multiple scales: International markets and commodity prices are important global scale underlying drivers (Kissinger *et al.,* 2012; Goll *et al.,* 2014). At national scales, population growth, expansion of infrastructure, demand from domestic markets and problems associated with governance and national policies are critical underlying drivers (Goll *et al.,* 2014). Expansion of infrastructure facilities improves access to forests in remote areas may increase extraction of fuelwood. Other national underlying drivers are poor governance, corruption, low capacity of public forest agencies to enforce regulations, land tenure uncertainties, inadequate natural resource planning and monitoring (Goll *et al.,* 2014). Underlying drivers related to poverty and subsistence activities exert pressure at local scale (Kissinger *et al.,* 2012).

Since drivers of tree removals occur at all levels i.e. global to local level, strategies to address drivers should be available at all levels. Defining what actions can best affect driver at the most appropriate level is an important consideration for policy and decision-makers. Enabling factors such as effective information systems to guide decisions, institutional capacity, transparency and accountability, political will, and consultation with stakeholders underpin any strategy to affect drivers. Any appropriate strategy to affects driver depend much on the knowledge of the amount of tree removals for each driver. The information of amount of tree removals of each driver would disclose the driver to be addressed most.

1.4.4 Implications of extra stump height on volume removals and carbon emissions

One major way of mitigating carbon emission is either conserving the existing carbon pools on land by slowing down deforestation and forest degradation or by adopting improved forest harvesting practices (Lusambo *et al.,* 2016; Katani *et al.,* 2016). For improved harvesting practices, trees are usually cut closest to the ground level (usually at 15 cm) to avoid wood volume wastage, carbon emissions and abstraction during transportation (Grundy, 1996; URT, 2004; Han and Chad, 2005; Katani *et al.*, 2016). Unless there are physical obstructions, wood wastage in stumps is classified as avoidable waste that is subject to a fine if it exceeds the maximum allowable waste in Mainland Tanzania (URT, 2004). For commercial purpose woody materials left i.e. loss on harvesting sites, including extra stump height (ESH) are considered as "under-utilized. This means that more wood volume removals would be required when the wood volume demands are unfulfilled and eventually would cause more carbon emissions if the ESH rot out or burnt. The study by Geijer *et al.* (2012) revealed that cutting trees to the recommended height implies a 0.3 percent decrease in the emissions of greenhouse gases. Potential value loss and underutilization of the available wood resources due to ESH have been cited often (Shaffer and Taumas, 1992; Boston and Dysart, 2000). Despite this, most of the trees harvested in miombo woodlands are cut at ESH which consequently causes more volume and carbon removals. This jeopardizes sustainable availability of miombo woodlands as carbon reservoirs.

On the other hand, ESH enables higher resprouting ability especially for miombo woodlands for which resprouting is important for regeneration. Notable studies (Shackleton, 2000; Mishra *et al.*, 2003; Amri *et al.*, 2010; Ferdinand *et al.*, 2011; Syampungani *et al.*, 2017) have shown that stump height has a strong influence on the coppicing ability of Miombo woodlands that, the shorter the stump height, the less number of coppices and vice versa.

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CHAPTER TWO

Paper One

Biomass and volume models based on stump diameter for assessing degradation in miombo woodlands of mainland Tanzania

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CHAPTER THREE

Paper Two

Estimates of volume and carbon stocks removals in Miombo woodlands of mainland Tanzania

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CHAPTER FOUR

Manuscript one

Drivers of removals and their influence on variation of aboveground carbon emissions in miombo woodlands of mainland Tanzania

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Abstract

Background: Removals of trees caused by both natural and anthropogenic drivers such as logging and fire causes substantial carbon emissions. Better insights into drivers and their variations of aboveground carbon removals is therefore needed. We assessed the drivers of aboveground carbon (AGC) removals and quantified the dynamics of removals-induced carbon emissions due to drivers using the National Forest Resources Assessment and Monitoring (NAFORMA) data sets in R software. Miombo woodlands that is the largest vegetation type covering about 93% of forest land in mainland Tanzania was the case study.

Results: Drivers of AGC removals in miombo woodlands of mainland Tanzania in order of importance were; timber, fire, shifting cultivation, charcoal, natural death, firewood collection, poles, grazing by wildlife animals, carvings, grazing by domestic animals, and mining. The average AGC removals by drivers range from 0.0 - 1.273tCha^{-1}year$^{-1.}$

Conclusions: Increased mitigation efforts in addressing removals by timber, fires, shifting cultivation, charcoal and natural death would be effective in addressing forest degradation in the REDD+ process in Tanzania. Since NAFORMA provides national picture on drivers and their variation on AGC removals, site-specific studies need to be conducted to generate information that would be used for local forest management. This kind of study need to be conducted in other vegetation types like Montane and Mangrove forest in Tanzania.

Key words: Drivers, aboveground carbon, emissions, miombo, removals

4.1 Background

Managing the carbon stocks of the land use sector is currently a key focus for climate change mitigation in developing countries [1, 2, 3]. In terrestrial ecosystems, forests and woodlands play a major role for the mitigation and adaptation to climate change via carbon storage [4, 2]. After oceans, forests are the world's largest storehouses of carbon and they provide ecosystem services that are important to human wellbeing [5]. Tropical forests alone store a quarter of a trillion tons of carbon in above and below ground biomass [6]. Notwithstanding their contribution to the climate change mitigation, Tanzania's forests face enormous challenges including deforestation and forest degradation [7].

Deforestation and forest degradation are amongst the major anthropogenic sources of greenhouse gas emissions (GHG), contributing about 17 per cent globally [8]. Of the total emissions, degradation is responsible for at least one-fifth in the Brazilian Amazon [9], two-thirds in Indonesian forests [10], and almost half in African tropical forests [11]. Forest degradation also leads to forest fragmentation and can contribute to deforestation [12]. While deforestation refers to a permanent or long-term conversion of forest to non-forest land [13, 14], forest degradation is the changes within the forest that negatively affect the structure or function of the stand and/or site, and thereby lower the capacity to supply products and/or services [15, 16].

The changes within the forests involves removals of trees and hence contributing to carbon emissions. The drivers of carbon removals are multifaceted and cannot be reduced to a few variables; rather they operate at different levels and scales in the human-environment linkage [17]. These drivers are divided into two broad categories: proximate and underlying causes. Proximate causes are typically human activities operating at the local level. They include shifting cultivation and cattle ranching, wood extraction through logging or charcoal production, and infrastructural development such as transportation, markets and settlements. On the other hand, underlying causes do not directly cause removals but influence the proximate causes. This category includes a complexity of economic issues, policies and institutions, technological factors, socio-cultural, and demographic factors [11, 17, 18].

Aboveground biomass (AGB) is not static, but rather spatially and temporally highly variable, particularly in the tropics with the same factor likely having different results [19, 20, 21]. This makes its quantification challenging. It is generally assumed that about half of AGB consists of carbon in different vegetation types including miombo woodlands in Tanzania. Miombo woodlands are the largest vegetation types in Tanzania covering about 93% of the forest area of 48.1million ha [22]. As in other tropical forest landscape, complex matrices of low to high AGC removal densities can be expected in entire miombo woodlands in Tanzania and its management categories due to varying drivers. Additionally, which drivers contribute more to the variations of AGC removals in the entire miombo woodlands and its management categories is to a large extent unknown. This has been due to lack of appropriate assessment mechanism. Nevertheless, the Mainland Tanzania National Forest Inventory (NFI) data source which is commonly referred as NAFORMA, have recently become available based on country REDD+ readiness activities that allow assessment of AGC removals and their amount of AGC emissions in miombo woodlands [3]. The objective of the present study was to identify the drivers of AGC removals and assess which of the identified drivers contribute more to the variation of AGC in miombo woodlands of Tanzania mainland. Specifically the study sought to: (1) identify drivers of AGC removals (2) quantify the amount of AGC removals by each driver and, (3) Ranking the identified drivers in order of their contribution to the variations of AGC.

Understanding the drivers of AGC removals and their amount of AGC removed is fundamental for better design of REDD+ strategy. In some cases, REDD+ incentives would be channeled directly to affect drivers. Moreover, a better understanding of drivers of AGC removals are required as part of developing mitigation interventions at sub-national levels to ensure improved land-use change. This kind of understanding is also crucial for subsequent development of management plans in order to tackle each driver in response to the amount of AGC emissions caused.

4.2 Results

4.2.1 Drivers and their corresponding number of stems and aboveground carbon removals

We identified eleven drivers for tree cutting and these were, forest fires, firewood collection, grazing by both wildlife, domesticated animals, carving, poles, shifting cultivation, timber, and mining activities (Table 4.1).

4.2.2 Drivers and their variations on the number of stems and AGC removals

Table 1 also shows the contribution of the drivers in terms of the number of stems and AGC removals per hectare per year for miombo woodlands in Tanzania. Higher number of stems/ha/year were removed by shifting cultivation, followed by charcoal, natural death, firewood collection and poles. In terms of biomass however, we observed higher AGC removals by timber followed by fire, shifting cultivation, charcoal and natural death (Table 4.1).

The contribution of the drivers concerning number of stems and carbon removals were further expressed based on different management categories and subcategories of miombo woodlands. Considering Tanzania Forest Services Agency (TFS) administrative zones, large number of stems were removed by charcoal followed by firewood collection and shifting cultivation whereas grazing was the least in the central zones (Table 2). Onn the other hand, charcoal removed more AGC followed by firewood collection, natural death and shifting cultivation while grazing had the least removals. In the other zones, the drivers seem to change leading positions between charcoal production, timber and fire (Table 4.2).

Considering vegetation types, natural death, timber production and shifting cultivation appear to be leading causes of removals interchangeably in the closed woodlands, open woodlands and Woodlands with scattered cropland for both number of stems and AGB (Table 4.3). Grazing, mining and carvings are among the least contributors to removals in the three vegetation types. Regarding ownership types, higher number of stem removals were observed due to natural death followed by fire, poles and timber in the central government land (Table 4.4). While the least number of stems removals per hectare per year was observed due to carving followed by grazing domestic and charcoal. The highest AGC was removed as timber followed by natural death, fire and charcoal. Carvings, grazing domestic and shifting cultivation accounted for the least AGC removals in this ownership types (Table 4.4). The contribution of the drivers of removal in terms of number of stems and AGC removals appear to be changing leading positions in other ownership types i.e. general land, local government land, private land and village land (Table 4.4).

Table 4.5 indicates drivers and the variations of number of stem and carbon removals in the different land use types. Regarding protection forestland, the highest number of stems removed were due to natural death followed by poles, firewood collection and timber (Table 4.5). In terms of AGC, the highest AGC were removed as timber followed by charcoal, natural death, poles and fire. Grazing by domestic animals, carvings and grazing by wild animals accounted for the least AGC removals in protection forest. In other land use types such as production forest, grazing land, shifting cultivation, water bodies or swamps and wildlife reserves, drivers of removals appear to be changing leading positions in terms of the number of stems and AGC.

Table 4.1: Drivers and their corresponding number of stems and AGC removals in mainland Tanzania

Drivers	Stems $ha^{-1}yr^{-1}$	Stem %	AGBt$ha^{-1}yr^{-1}$	AGCtC$ha^{-1}yr^{-1}$	Agb%
Timber	0.780	7.307	0.244	0.119	21.034
Fire	0.845	7.916	0.196	0.096	16.897
Shifting cultivation	2.741	25.677	0.191	0.093	16.466
Charcoal	1.747	16.365	0.182	0.089	15.690
Natural death	1.233	11.550	0.160	0.079	13.793
Firewood collection	1.376	12.890	0.089	0.043	7.672
Poles	1.588	14.876	0.078	0.038	6.724
Grazing wild	0.256	2.398	0.014	0.007	1.207
Carvings	0.050	0.468	0.004	0.002	0.345
Grazing domestic	0.053	0.496	0.002	0.001	0.172
Mining	0.006	0.056	0.000	0.000	0.010

Table 4.2: Drivers and their corresponding number of stems and AGC removals in zones of mainland Tanzania

Zone names	Drivers	Stems/ha/yr	Stem%	Agbt/ha/yr	AgctC/ha/yr	AgctC%
Central	Charcoal	3.687	28.472	0.187	0.092	49.202
	Firewood collection	3.653	28.213	0.055	0.027	14.429
	Timber	1.334	10.303	0.046	0.023	12.215
	Shifting cultivation	1.808	13.961	0.042	0.020	10.969
	Natural death	0.693	5.351	0.027	0.013	7.131
	Fire	0.870	6.722	0.018	0.009	4.662
	Poles	0.820	6.332	0.003	0.001	0.787
	Grazing domestic	0.019	0.148	0.001	0.001	0.380
	Grazing wild	0.065	0.498	0.001	0.000	0.225
	Total	12.949	100	0.380	0.186	100
Eastern	Timber	5.812	12.466	0.746	0.366	30.732
	Charcoal	11.014	23.625	0.655	0.321	26.979
	Natural death	7.904	16.954	0.405	0.198	16.670
	Shifting cultivation	5.151	11.050	0.189	0.092	7.772
	Firewood collection	8.157	17.497	0.178	0.087	7.337
	Poles	5.137	11.019	0.097	0.048	4.004
	Fire	1.022	2.193	0.079	0.039	3.258
	Grazing wild	2.201	4.722	0.069	0.034	2.844
	Carvings	0.199	0.426	0.010	0.005	0.396
	Grazing domestic	0.023	0.048	0.000	0.000	0.008
	Total	46.62	100	2.428	1.19	100
Lake	Fire	0.515	6.604	0.089	0.044	33.115
	Poles	2.303	29.520	0.049	0.024	18.096
	Firewood collection	2.555	32.755	0.042	0.021	15.674
	Timber	0.379	4.862	0.035	0.017	13.031
	Charcoal	0.663	8.495	0.023	0.011	8.555
	Natural death	0.782	10.023	0.023	0.011	8.720
	Shifting cultivation	0.417	5.347	0.005	0.003	1.901
	Grazing wild	0.187	2.394	0.002	0.001	0.909
	Total	7.801	100	0.268	0.132	100
Northern	Charcoal	8.040	21.454	0.331	0.162	22.579
	Shifting cultivation	13.459	35.915	0.324	0.159	22.145
	Timber	1.257	3.355	0.301	0.147	20.525
	Poles	6.117	16.325	0.209	0.102	14.248
	Natural death	4.459	11.898	0.166	0.081	11.301
	Firewood collection	2.881	7.688	0.103	0.05	7.006
	Fire	1.092	2.915	0.030	0.015	2.072
	Grazing wild	0.168	0.449	0.002	0.001	0.124
	Total	37.473	100	1.466	0.717	100
Southern highlands	Natural death	2.397	25.501	0.332	0.163	59.949
	Poles	3.026	32.200	0.08	0.039	14.403
	Timber	0.649	6.908	0.075	0.037	13.576
	Firewood collection	2.294	24.407	0.052	0.026	9.44
	Shifting cultivation	0.621	6.61	0.008	0.004	1.401
	Grazing domestic	0.091	0.964	0.004	0.002	0.731
	Charcoal	0.258	2.741	0.002	0.001	0.421
	Grazing wild	0.063	0.67	0.000	0.000	0.079
	Total	9.399	100	0.553	0.272	100
Southern	Fire	4.143	14.368	0.586	0.287	36.115
	Timber	2.149	7.455	0.304	0.149	18.729
	Shifting cultivation	7.009	24.309	0.293	0.144	18.049
	Natural death	7.122	24.7	0.183	0.09	11.257
	Poles	4.477	15.528	0.112	0.055	6.923
	Charcoal	0.885	3.07	0.064	0.031	3.916
	Firewood collection	1.54	5.342	0.048	0.024	2.961
	Grazing wild	0.884	3.067	0.019	0.01	1.199
	Carvings	0.311	1.078	0.011	0.006	0.702
	Grazing domestic	0.233	0.809	0.002	0.001	0.121
	Mining	0.079	0.273	0.000	0.000	0.028
	Total	28.832	100	1.622	0.797	100
Western	Timber	1.782	11.582	0.163	0.08	27.946
	Shifting cultivation	5.317	34.564	0.127	0.062	21.766
	Natural death	1.592	10.348	0.073	0.036	12.584
	Firewood collection	1.866	12.128	0.065	0.032	11.195
	Charcoal	1.364	8.866	0.059	0.029	10.053
	Fire	0.922	5.993	0.059	0.029	10.169
	Poles	2.419	15.726	0.031	0.015	5.366
	Grazing domestic	0.025	0.163	0.005	0.002	0.794
	Grazing wild	0.097	0.632	0.001	0.000	0.128
	Total	15.384	100	0.583	0.285	100

Table 4.3: Drivers and their corresponding number of stems and AGC removals in miombo woodlands vegetation subtypes of mainland Tanzania

Vegetation types	Drivers	Stems/ha/yr	Stems %	Agbt/ha/yr	AgctC/ha/yr	Agct/ha/yr %
Closed woodlands (crown cover >40%)	Natural death	2.07	30.122	0.251	0.123	28.341
	Timber	0.847	12.325	0.250	0.122	28.111
	Shifting cultivation	0.782	11.380	0.183	0.090	20.737
	Fire	0.642	9.342	0.063	0.031	7.143
	Poles	1.041	15.148	0.044	0.022	5.069
	Firewood collection	0.675	9.822	0.040	0.020	4.628
	Charcoal	0.414	6.024	0.040	0.020	4.608
	Grazing wild	0.338	4.919	0.010	0.005	1.152
	Carvings	0.027	0.393	0.001	0.001	0.230
	Grazing domestic	0.036	0.524	0.001	0.000	0.000
	Total	**6.872**	**100**	**0.883**	**0.434**	**100**
Open woodlands (Crown cover between 10-40%)	Timber	11.005	52.522	0.262	0.128	21.053
	Fire	0.903	4.310	0.246	0.121	19.901
	Charcoal	1.454	6.939	0.193	0.095	15.625
	Natural death	1.686	8.047	0.167	0.082	13.487
	Shifting cultivation	2.448	11.683	0.158	0.078	12.829
	Firewood collection	1.55	7.398	0.101	0.049	8.059
	Poles	1.538	7.340	0.086	0.042	6.908
	Grazing wild	0.245	1.169	0.017	0.008	1.316
	Carvings	0.055	0.262	0.005	0.003	0.493
	Grazing domestic	0.061	0.291	0.003	0.002	0.329
	Mining	0.008	0.038	0.000	0.000	0.000
	Total	**20.953**	**100**	**1.238**	**0.608**	**100**
Woodlands with scattered cropland	Shifting cultivation	16.587	59.963	0.735	0.36	48.257
	Charcoal	1.751	6.330	0.241	0.118	15.818
	Timber	0.382	1.381	0.18	0.088	11.796
	Firewood collection	2.032	7.346	0.127	0.062	8.311
	Poles	4.994	18.054	0.121	0.059	7.909
	Natural death	0.858	3.102	0.073	0.036	4.826
	Fire	0.912	3.297	0.039	0.019	2.547
	Pole	0.063	0.228	0.006	0.003	0.402
	Carvings	0.083	0.300	0.001	0.001	0.134
	Total	**27.662**	**100**	**1.523**	**0.746**	**100**

Table 4.4: Drivers and their corresponding number of stems and AGC removals in ownership types of miombo woodlands in mainland Tanzania

Ownership types	Drivers	Stems/ha/yr	Stems %	Agbt/ha/yr	AgctC/ha/yr	AgctC %
Central Government	Timber	0.507	10.511	0.114	0.056	26.306
	Natural death	1.503	31.143	0.103	0.050	23.651
	Fire	0.695	14.409	0.079	0.039	18.124
	Charcoal	0.284	5.888	0.037	0.018	8.604
	Grazing wild	0.561	11.617	0.037	0.018	8.467
	Firewood collection	0.331	6.851	0.026	0.013	6.040
	Poles	0.551	11.406	0.020	0.010	4.652
	Shifting cultivation	0.372	7.704	0.016	0.008	3.792
	Carvings	0.011	0.218	0.001	0.000	0.232
	Grazing domestic	0.012	0.254	0.001	0.000	0.132
	Total	**4.827**	**100**	**0.434**	**0.213**	**100**
Local Government	Natural death	1.684	23.388	0.310	0.152	33.885
	Charcoal	1.738	24.134	0.217	0.106	23.743
	Timber	0.988	13.719	0.210	0.103	23.032
	Firewood collection	2.315	32.141	0.140	0.068	15.288
	Fire	0.225	3.128	0.031	0.015	3.446
	Shifting cultivation	0.118	1.634	0.004	0.002	0.471
	Poles	0.106	1.476	0.001	0.000	0.080
	Grazing domestic	0.019	0.269	0.000	0.000	0.054
	Grazing wild	0.008	0.111	0.000	0.000	0.002
	Total	**7.201**	**100**	**0.914**	**0.448**	**100**
Village land	Fire	1.000	7.911	0.315	0.154	22.305
	Timber	0.841	6.654	0.278	0.136	19.694
	Natural death	2.000	15.815	0.227	0.111	16.082
	Charcoal	1.363	10.779	0.177	0.087	12.550
	Shifting cultivation	3.038	24.024	0.160	0.079	11.366
	Poles	2.337	18.479	0.122	0.060	8.678
	Firewood collection	1.755	13.882	0.115	0.056	8.156
	Grazing wild	0.170	1.347	0.008	0.004	0.564
	Carvings	0.066	0.522	0.004	0.002	0.300
	Grazing domestic	0.063	0.499	0.004	0.002	0.288
	Mining	0.011	0.087	0.000	0.000	0.017
	Total	**12.645**	**100**	**1.411**	**0.691**	**100**
Private Land	Shifting cultivation	11.128	59.113	1.102	0.540	60.139
	Charcoal	2.466	13.101	0.355	0.174	19.388
	Timber	0.625	3.320	0.135	0.066	7.344
	Firewood collection	1.913	10.160	0.116	0.057	6.348
	Poles	1.991	10.577	0.059	0.029	3.216
	Natural death	0.374	1.987	0.046	0.023	2.517
	Fire	0.278	1.478	0.016	0.008	0.872
	Pole	0.033	0.175	0.003	0.001	0.167
	Grazing wild	0.016	0.088	0.000	0.000	0.009
	Total	**18.825**	**100**	**1.832**	**0.898**	**100**
General land	Timber	1.577	13.068	0.807	0.395	48.146
	Natural death	2.719	22.537	0.247	0.121	14.754
	Charcoal	2.163	17.925	0.226	0.111	13.470
	Fire	1.911	15.838	0.155	0.076	9.268
	Shifting cultivation	1.308	10.839	0.086	0.042	5.127
	Poles	0.854	7.080	0.085	0.042	5.059
	Carvings	0.256	2.124	0.034	0.017	2.056
	Firewood collection	0.721	5.976	0.027	0.013	1.586
	Grazing wild	0.260	2.153	0.006	0.003	0.344
	Grazing domestic	0.297	2.461	0.003	0.002	0.191
	Total	**12.065**	**100**	**1.675**	**0.821**	**100**
Unknown	Firewood collection	1.051	68.394	0.010	0.005	69.823
	Natural death	0.486	31.606	0.004	0.002	30.177
	Total	**1.536**	**100**	**0.014**	**0.007**	**100**

Table 4.5: Drivers and their corresponding number of stems and biomass removals in land use types of miombo woodlands in mainland Tanzania

Ownership types	Drivers	Stems/ha/yr	Stems %	Agbt/ha/yr	AgctC/ ha/yr	AgctC %
Production forest	Fire	1.144	10.794	0.390	0.191	27.325
	Timber	1.086	10.247	0.380	0.186	26.609
	Charcoal	1.426	13.455	0.203	0.099	14.163
	Natural death	2.294	21.646	0.167	0.082	11.731
	Poles	1.968	18.570	0.108	0.053	7.582
	Firewood collection	1.582	14.927	0.106	0.052	7.439
	Shifting cultivation	0.668	6.303	0.048	0.024	3.433
	Grazing wild	0.230	2.170	0.010	0.005	0.715
	Carvings	0.097	0.915	0.010	0.005	0.715
	Grazing domestic	0.089	0.840	0.005	0.002	0.286
	Mining	0.014	0.132	0.000	0.000	0.000
	Total	**10.598**	**100**	**1.427**	**0.699**	**100**
Protection forest	Natural death	3.749	40.325	0.176	0.086	44.792
	Timber	0.936	10.068	0.090	0.044	22.917
	Fire	1.754	18.866	0.069	0.029	15.104
	Grazing wild	1.567	16.855	0.045	0.022	11.458
	Poles	0.457	4.916	0.010	0.005	2.604
	Firewood collection	0.671	7.217	0.008	0.004	2.083
	Charcoal	0.083	0.893	0.004	0.002	1.042
	Grazing domestic	0.061	0.656	0.001	0.000	0.000
	Shifting cultivation	0.019	0.204	0.00	0.000	0.000
	Total	**9.297**	**100**	**0.403**	**0.192**	**100**
Wildlife reserve	Natural death	1.985	40.776	0.213	0.104	41.935
	Timber	0.364	7.477	0.121	0.059	23.790
	Fire	0.903	18.550	0.079	0.039	15.726
	Grazing wild	0.932	19.145	0.06	0.029	11.694
	Poles	0.184	3.780	0.014	0.007	2.823
	Firewood collection	0.367	7.539	0.01o	0.005	2.016
	Charcoal	0.069	1.417	0.005	0.003	1.210
	Grazing domestic	0.052	1.068	0.001	0.001	0.403
	Shifting cultivation	0.012	0.247	0.000	0.001	0.403
	Total	**4.868**	**100**	**0.503**	**0.248**	**100**
Shifting cultivation	Shifting cultivation	21.885	64.141	1.664	0.815	64.376
	Timber	0.985	2.887	0.31	0.152	12.006
	Charcoal	2.368	6.940	0.187	0.092	7.267
	Firewood collection	2.463	7.219	0.15	0.073	5.766
	Poles	4.52	13.247	0.134	0.066	5.213
	Natural death	0.952	2.790	0.094	0.046	3.633
	Fire	0.87	2.550	0.044	0.022	1.738
	Carvings	0.077	0.226	0.001	0	0.000
	Total	**34.12**	**100**	**2.584**	**1.266**	**100**

Ownership types	Drivers	Stems/ha/yr	Stems %	Agbt/ha/yr	AgctC/ha/yr	AgctC %
Agriculture	Shifting cultivation	12.914	52.100	0.884	0.433	49.373
	Firewood collection	4.776	19.268	0.411	0.201	22.919
	Charcoal	2.107	8.500	0.217	0.107	12.201
	Fire	0.807	3.256	0.093	0.046	5.245
	Timber	0.405	1.634	0.072	0.035	3.991
	Poles	2.669	10.768	0.065	0.032	3.649
	Natural death	0.962	3.881	0.036	0.018	2.052
	Pole	0.068	0.274	0.006	0.003	0.342
	Grazing domestic	0.034	0.137	0.002	0.001	0.114
	Grazing wild	0.045	0.182	0.001	0.001	0.114
	Total	**24.787**	**100.000**	**1.787**	**0.877**	**100.000**
Grazing land	Grazing domestic	1.83	18.096	0.606	0.297	44.196
	Charcoal	2.339	23.129	0.41	0.201	29.911
	Shifting cultivation	2.754	27.232	0.101	0.049	7.292
	Poles	1.405	13.893	0.08	0.039	5.804
	Firewood collection	1.281	12.667	0.078	0.038	5.655
	Fire	0.297	2.937	0.055	0.027	4.018
	Timber	0.153	1.513	0.037	0.018	2.679
	Carvings	0.017	0.168	0.003	0.001	0.149
	Natural death	0.022	0.218	0.002	0.001	0.149
	Grazing wild	0.015	0.148	0.001	0.001	0.149
	Total	**10.113**	**100.000**	**1.373**	**0.672**	**100.000**
Built up area	Firewood collection	7.798	100	0.319	0.156	100
	Total	**7.798**	**100**	**0.319**	**0.156**	**100**
Water body/swamp	Timber	12.758	66.667	2.599	1.273	95.994
	Poles	6.379	33.333	0.108	0.053	4.006
	Total	**19.137**	**100**	**2.707**	**1.327**	**100**
Other land	Fire	1.371	27.861	0.085	0.042	35.878
	Poles	0.415	8.435	0.045	0.022	19.128
	Firewood collection	0.605	12.289	0.041	0.02	17.176
	Natural death	1.102	22.398	0.033	0.016	13.793
	Charcoal	1.105	22.464	0.031	0.015	13.159
	Grazing wild	0.138	2.808	0.001	0.001	0.558
	Shifting cultivation	0.184	3.744	0.001	0.001	0.309
	Total	**4.92**	**100**	**0.238**	**0.116**	**100**

4.3 Discussion

The overall objective of this paper was to identify the drivers of AGC removals and to quantify the contributions of each driver to the variation of AGC removals and hence carbon emissions in miombo woodlands in Tanzania using NAFORMA data set. In this study, drivers and their corresponding estimates of AGC and number of stems removals have been reported. The carbon stored in the aboveground biomass (AGB) pool is typically the largest among the Intergovernmental Panel for Climate Change (IPCC) carbon pools for REDD+ reporting purposes. It is understood that while removals by shifting cultivation fire, firewood collection and charcoal, results immediately into carbon emissions, it is not the case with removals for timber, carvings and poles which may end up in construction and furniture whose emissions may be delayed. Nonetheless, timber in the form of furniture, carvings or construction is more in the process of contributing to emissions although delayed. Due to the uncertainty of time taken for timber to act as stored carbon, all removals are assumed to eventually contribute to emissions.

Several drivers contributed number of stems and AGC removals in mainland Tanzania. These drivers included charcoal, wildfire, firewood collection, grazing by both wildlife and domesticated animals, carving, poles, shifting cultivation, timber, and mining activities. Since drivers of AGC removals are similar to drivers of forest degradation in miombo woodlands, comparison across studies were based on studies conducted to determine forest degradation drivers. The result found in the present study is comparable to results found in miombo woodland in Masito forest in western Tanzania and Liwale district southern Tanzania [23, 24, 25]. These studies documented only six drivers responsible for forest degradation. Sites specific and the methodologies applied on these studies explains fewer documentation of drivers. On the other hand, [26] documented ten drivers for forest degradation in Philippines that agrees with results from the present study. The methodology employed, particularly on the sampling procedures could explain the similarity.

In terms of the contribution of drivers on the number of stems and AGC removals nationally, removals by shifting cultivation, natural death, poles and charcoal production account for the highest number of stem removals. The reason could be attributed by high demand of charcoal in the country for cooking energy in which small diameter trees are involved. Tanzania’s annual consumption of charcoal is 1 658 000 tons [27]. About 85% of the total urban population depends on charcoal for household cooking and energy for small and medium enterprises [28]. Additionally, more than 40% of the tree removals can be attributed to charcoal use alone in Tanzania [29]. Higher removals by shifting cultivation is probably due to intensification of shifting cultivation in Tanzania. Shifting cultivation in Tanzania occupies 7.6% of the total country land area and 33% of area classified as woodlands in Tanzania [22]. Other scholars [30, 31] asserted that shifting cultivation contribute more to forest degradation due rising demand for agricultural products, dietary changes, agricultural trade and adjustment. Firewood collection and poles on the other hand, rank third and fourth in taking large amount of stems in the woodlands. This is probably because; firewood is the main source of energy rural areas [32]. The same author noted that, lack of alternative and affordable sources of energy dependence of communities on forests. Construction purposes both in the rural and urban areas probably account for higher removals of trees as poles. Furthermore, climate change impacts like diseases eruptions and severe drought naturally kills trees. These effects have recently increased tremendously. Mining and grazing by domesticated animals appeared as the least drivers responsible for stems removals. This is because of the smallest area subjected into mining and carvings activities.

In terms of AGC removals, timber and fire accounts for the highest AGC removals. This may be explained by the large trees removals that comprises of the largest biomass. According to [33], large trees tend to account for a large proportion of the AGB in mature forests; often between 30 and 40% of the AGB can be found in trees with diameters greater than 70 cm. Elsewhere in miombo, [34] found that most miombo had been heavily disturbed because of local benefits attached to them like dry-season fodder for large livestock populations, fuelwood for domestic use and rural industry and construction materials for farm structures and homes for millions. Higher AGC removals in miombo woodlands due to fire is because of its roles as the management tools. When fire is frequently and uncontrolled, it could kill trees and eventually cause carbon emissions.

Considering administrative zones, charcoal and timber account for higher AGC removals in the Eastern zone. Conversely, charcoal and firewood collection account for higher number of stem removals in this zone. This is due to the highest charcoal and timber consumption that may be linked to the closeness to Dar es Salaam city. Dar es Salaam, Tanzania's largest city, accounts for more than 50% of all charcoal consumed in the country [35]. Moreover, higher timber consumption in this zone could be attributed to high demand of timber for furniture and infrastructure development particularly houses in the Dar es Salaam city. Dar es Salaam is the primary destination of timber and timber products (including all round and sawn timber) and accounting for 87% of timber felled in southeast Tanzania [36]. Other important domestic markets of timber and wood products from the zone are Zanzibar, Mafia and Arusha [25]. Shifting cultivation and charcoal account for the largest number of stems and AGC removals in the northern zone probably due to intensification of shifting cultivation. In the lake zone, fire, firewood collection and pole account for the large stems and AGC removals probably due to heavily dependence trees for cooking energy and constructions purposes. Furthermore, presence of dry litter that foster fire occurrence explains the removals due to fire in this zone. The regular fires in the miombo region can, if too frequent or intense, cause mortality of large and small trees and prevent regeneration [37]. Likewise, long-term plot-scale experiments had shown that under annual burning miombo woodland is converted to grassland [38, 37], and that in the absence of fire, miombo starts to form closed canopy forest [37].

Regarding vegetation types, shifting cultivation, charcoal, timber poles, and firewood collection accounted for the highest AGC and number of stems removals in the woodland with scattered woodland. Shifting cultivation in Tanzania is practiced by more than 70% of the population. Other scholar [25] found that shifting cultivation is common and practiced for all annual crops grown in Tanzania. The most cited reasons for shifting their plots are; invasion of weeds and evading wild animals. On the other hand, natural death, timber and shifting cultivation accounts for the largest AGC removals in the closed woodland. Natural death is more prominent in this vegetation probably because protection forest and wildlife area comprises most of this vegetation where by no harvesting is allowed. Regarding timber, most of the timber is removed illegally.

In terms of ownership types, fire, timber charcoal and natural death account for higher number of stems removals in all the categories of ownership. This may be attributed to population growth and inadequate presence of alternative sources of energy for cooking and construction purpose that ultimately forces people to heavily depend on charcoal and timber. Irrespective of the fact that, forest under general land is almost open access in which free movement of people take products [39], its contribution to the total removals is low as opposed to private and village land. On the other hand, shifting cultivation accounts for the highest AGC removals probably because is the dorminant driver that characterize the regime.

Considering land use types that miombo woodlands falls, it was revealed that shifting cultivation and charcoal account for the highest number of stem removals in grazing and shifting cultivation land. This is because large numbers of stems are removed during land preparation in the shifting cultivation. Likewise, charcoal making and firewood collection characterize the land. Furthermore, natural death, poles, charcoal and firewood collection causes more stems cut in the production forest, protection forest and wildlife reserves land. This is much explained by the nature of the ownership types and the large dependence of charcoal and firewood for cooking energy while poles for construction purposes. In contrast, AGC removals that ultimately ends up into carbon emissions are driven by charcoal, natural death, shifting cultivation, poles, timber, fire and firewood collection in all land use types. This may be attributed by population growth that demand more products from the woodlands and climate change impacts that naturally kills trees through eruption of diseases and drought. Moreover, economic growth based on the export of primary commodities and an increasing demand for timber and agricultural products in a globalizing economy are critical reasons behind carbon emissions.

4.4 Conclusions

AGC removals in miombo woodlands of Mainland Tanzania are caused by a range of drivers that lead to varying levels of carbon emissions. The results revealed that charcoal, timber, shifting cultivation, fire, firewood collections, poles and natural death are the prominent main drivers of AGC removals in mainland Tanzania. Interestingly, results also revealed that although charcoal, shifting cultivation and fuelwood removals more stems per hectare and hence jeopardizes future carbon sink its share to carbon removals is minimal as compared to timber and natural death that account for higher AGC removals. For the purpose of reducing emissions emanating from AGC removals and by considering national circumstances, all drivers should be managed although the management intensity and priorities should consider the significance contribution of AGC emissions by timber, fire, charcoal, shifting cultivation, and natural death in the entire miombo woodlands and its subsequently categories. This would contribute to creation of considerable carbon sink as well as ensure persistent potential for the miombo woodlands to store carbon thus contributing to the REDD+ process in Tanzania. Moreover, this kind of study need to be conducted in other vegetation types like Montane and Mangrove forest in Tanzania. On the other hand, since NAFORMA provide national picture on drivers and their variation on AGC removals, we recommend site specific studies be conducted to bring information that would be used to devise appropriate strategies to deal with drivers in their order of contribution to AGC removals in the local settings. Additionally tree planting for timber and energy should be encouraged as mitigating measure.

4.5 Methods

4.5.1 Study Area Description

The study involved the entire miombo woodlands of mainland Tanzania that covers about 44.7 million ha (Fig. 4.1).Vast areas of miombo woodlands falls under the village lands ownership, which lack proper management institution [40]. Depending on altitude and latitude, mainland Tanzania is characterised by both tropical and subtropical climates. The mean annual rainfall varies from below 500 to over 2000 mm per annum. The rainfall for the large part of the country is bimodal with short rains from October to December and long rains from March to May. The weather conditions of the country may be divided into 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 mid-August.

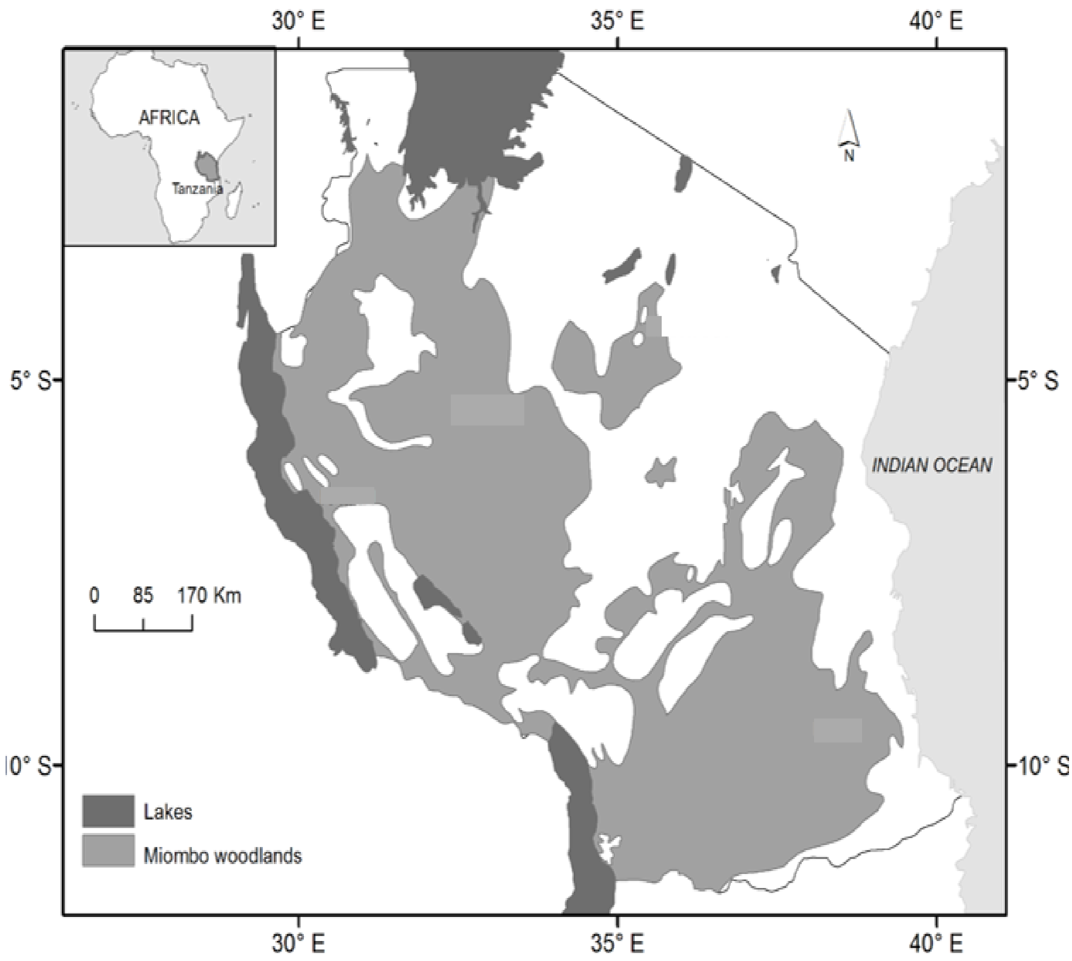

Figure 4.1: A map of Mainland Tanzania showing miombo woodlands (modified from [41])

4.5.2 Data collection

4.5.2.1 Sampling design

The data used for the assessment of drivers and their influence on variation of AGC removals presented in this paper were collected by NAFORMA [22]. Systematic double sampling for stratification with optimal allocation of individual plots in cluster was sampling design of the NAFORMA (Fig. 4.2). The design was chosen after sampling simulations to reduce uncertainty of estimates under given budget constraints. The detail of the planning of this design and other uncertainties are given in [42, 22, 2, 3]

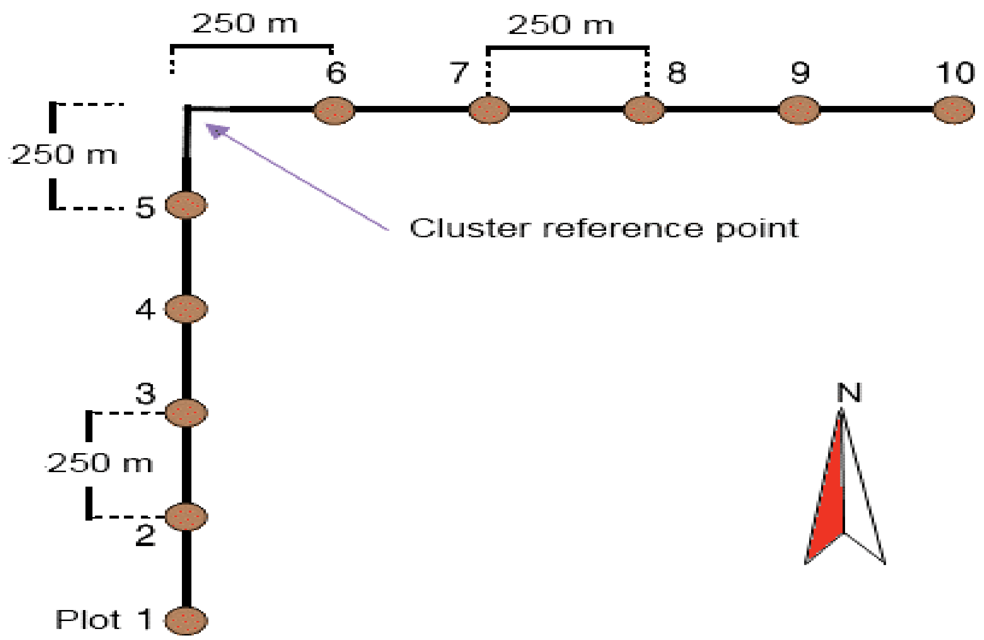

Figure 4.2: Cluster design

Source: [22]

4.5.2.2 Data acquisition

All stumps with diameter ≥ 5 cm within the circular plot radius of 15 m were measured for diameter and height using calliper or measuring tape. In addition, age, name and end uses to which the removed trees were put into were identified. The details on how age of the stumps and end uses of the removed trees were decided are given in [43, 3]. For the purpose of the present study, all plots that were surveyed for stumps measurement were extracted from NAFORMA database.

4.5.2.3 Data extraction

The whole NAFORMA data set was imported to R software. By using “sqldf” R package which runs Structured Query Language (SQL) statements on R data frames, all stump data from miombo woodlands were extracted. Finally, data cleaning i.e. removal of noisy data and outliers was done. For the purpose of this study, we extracted from NAFORMA database all the plots that were surveyed for stumps measurement in miombo woodlands. In total, we extracted A total 7 323 stumps from 16 803 plots from NAFORMA database.

4.5.3 Data analysis

4.5.3.1 Analysis of drivers of aboveground carbon removals

To obtain the drivers of AGC removals, the identified trees with their corresponding drivers for their removals were listed. The drivers were sorted alphabetically in order to identify total number of drivers responsible for removals in miombo woodlands. Those drivers that were similar like removals due to firewood collection for domestic and industrial use were regarded as firewood collection.

4.5.3.2 Drivers and their influence on aboveground carbon removals

We included multiple drivers identified (11 drivers) in the analysis, so that the interrelationships between the drivers and AGB removed could be accounted. To define the influence of each driver on AGC removals, AGB removed per tree was estimated using allometric equation that estimates tree biomass from the remaining stump [7]. The estimated individual tree AGB removal in its corresponding driver was divided by age of the stump to get the rate of AGB removals per year. AGB removals per year per tree was summed up and expressed on per plot basis. Since each stratum had unique sampling intensity, it was necessary to calculate expansion factors (*EF*) for each respective stratum since simple mean of AGB 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. The details on how the *EF* factor was calculated are shown in [2, 3]. Consequently, AGB plot level values were multiplied by respective *EF* value corresponding to each stratum. The AGB plot level values were expressed on per hectare (ha). To obtain the influence of each driver on AGC removals, AGB removals per ha values were multiplied by 0.49 as the conversion factor of AGB to AGC [44]. Finally, the AGC and their corresponding drivers were summarized in terms of Zones, miombo vegetation subtypes, Land use and Ownership types.

4.6 Abbreviations

AGC: Aboveground carbon; NAFORMA: National Forest Resources Assessment and Monitoring; GHG: Greenhouse Gas Emissions; AGB: Aboveground biomass; NFI: National Forest Inventory; REDD+: Reduced Emissions from deforestation and forest degradation "plus," the role of conservation, sustainable management of forests, and enhanced carbon stock; TFS: Tanzania Forest Services Agency; IPCC: Intergovernmental Panel for Climate Change.

4.7 Declarations

4.7.1 Ethics approval and consent to participate

Not applicable

4.7.2 Consent for publication

Not applicable

4.7.3 Funding

No financial support was provided regarding the preparation of this manuscript.

4.7.4 Availability of data and materials

All authors declare that the datasets used in this study are available upon request from the Tanzania Forest Service, Ministry of Natural Resources and Tourism Tanzania.

4.7.5 Competing interests

The authors declare that they have no competing interests.

4.8 Authors' contributions

BJM has been involved in designing the study, drafting the manuscript, data analysis and write up: WAM performed analysis and revised the manuscript: EFN and REM made substantial contributions to conception and revising the manuscript. REM, EFN, WAM have given final approval of the version to be published. All authors read and approved the final manuscript.

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CHAPTER FIVE

Manuscript two

Stump height: A potential escalator of wood volume and carbon removals in miombo woodlands of mainland Tanzania

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Abstract

Interest in climate change mitigation and adaptation through the Reduced Emissions from Deforestation and Forest Degradation plus the role of conservation, sustainable management of forest and enhancement of forest carbon stocks (REDD+) has led to either retaining the forest unharvested or an increased need for proper tree volume harvesting. However, experience shows that significant number of trees harvested are not cut at the specified stump height from the ground (usually at 15cm) which ends up into leaving parts of wood volume unharvested. It is anticipated however that, leaving higher height tree stumps would escalate wood volume removals and hence carbon emissions. Better insights on the extent of wood volume of extra stump height (ESH) in miombo woodlands covering about 93% of total forest area in mainland Tanzania is apparently needed. Quantifying wood volume from ESH is vital in evaluating effectiveness of available harvesting act and regulations enforcement. Moreover, it is vital in reviewing harvesting regulations, improving harvesting practices and thereby mitigating climate change. Based on a sample of 5 264 stumps from 16 219 circular plots of 10 m and 15 m radii, collected in Miombo woodlands in Mainland Tanzania, total volume per year and volume per hectare per year loss of ESH was estimated by using equation applicable to cylinder with circular base in R software**.** Result revealed that, total wood volume per year, annual volume and carbon per hectare lost through ESH were 3 800 000 $m^{-3}year^{-1}$, 0.098 ± 0.034$m^3ha^{-1}year^{-1}$ and 0.028±0.009 $tCha^{-1}year^{-1}$ respectively. Results further revealed that volume loss of ESH was higher in eastern zone, village land, private, and shifting cultivation. Since the estimated annual volume loss from ESH is almost ¼ of the annual volume deficit of 19.5 million m^3year^{-1}, the deficit and further removals could be lowered through strictly adhering to appropriate harvesting procedures in the miombo woodlands of Tanzania.

Key words: Volume loss, extra stump height, miombo, tree removals, carbon removal

5.1 Introduction

The significance of forests, particularly tropical forests, in the global carbon cycle has led to the consideration and recognition of forest-based climate change mitigation measures in the international climate negotiations, agreements and policy frameworks (Lusambo *et al.,* 2016; Manyanda *et al.,* 2019; Mauya *et al.,* 2019, Manyanda *et al.,* 2020). REDD+ that essentially involves implementation of a variety of policy approaches and incentive plans to the activities related with reduction in deforestation and forest degradation, as well as forest conservation, sustainable management of forests and the enhancement of forest carbon stocks in the tropical forests is among of the recognized efforts (Mauya *et al.,* 2019). One major way of mitigating carbon emission is emission avoidance or conserving the existing carbon pools on land by slowing down deforestation or by adopting improved forest harvesting practices (Lusambo, 2016; Katani *et al.,* 2016). For improved harvesting practices, trees are usually cut closest to the ground level (usually at 15cm) to avoid wood volume wastage, carbon emissions and abstraction during transportation (Han and Chad, 2005; URT, 2004; Katani *et al.*, 2016). Unless there are physical obstructions, wood wastage in stumps is classified as avoidable waste that is subject to a fine if it exceeds the maximum allowable waste in Mainland Tanzania (URT, 2004). Woody materials left i.e. loss on harvesting sites, including extra stump height (ESH) are considered as "under-utilized. Nevertheless, experience shows that during wood harvesting, a significant number of trees are not cut at the specified stump height (Kozak and Stephen, 1992). This means that more wood volume removals will be needed if the wood volume demands does not square with supply and eventually would cause more carbon emissions. The study by Geijer *et al.* (2012) revealed that cutting trees to the recommended height implies a 0.3 percent decrease in the emissions of greenhouse gases. Furthermore, potential value loss and underutilization of the available wood resources due to ESH have been cited often to emphasize the importance of leaving low stumps for better utilization of wood (Shaffer and Taumas, 1992; Boston and Dysart, 2000; Hall and Han, 2004).

Mainland Tanzania, unlike many other developing countries, has a wealth of up to-date National Forest Inventory (NFI) data that can support estimation of annual wood volume loss from ESH. Mainland Tanzania’s NFI was implemented between 2009 and 2014 through National Forest Resources Monitoring and Assessment (NAFORMA) Project. Of the 48.1 million ha total forest area in mainland Tanzania, miombo woodlands occupy about 93% (MNRT, 2015). Manyanda *et al.* (2020) reported that miombo management categories have different levels of volume and carbon removals due to tenure rights and different exposure to anthropogenic drivers. To date there are no study that provide estimates of wood volume and carbon of ESH in the management categories where miombo woodlands of mainland Tanzania i.e. Tanzania Forest Services Agency (TFS) zones, administrative regions, species, vegetation, land use and ownership types. The objective of the present study was to provide estimates of the wood volume and carbon of ESH in the categories of miombo woodlands. Specifically the study aimed at; 1) estimating wood volume and carbon emission from ESH and 2) assessing the implication of wood volume and carbon emission of ESH to volume and carbon removals respectively by TFS Zones, administrative regions, species, vegetation, land use and ownership types of miombo woodlands. This would allow checking whether harvesting regulations in place are adhered to. Likewise, it would allow knowing which category have higher wood volume and carbon emission of ESH so that targeted measures could be taken. Efforts would be targeted to enhance proper trees harvesting through relevant institutions such as TFS and Non-Governmental Organizations (NGOs) involved in forest management.

5.2 Materials and methods

5.2.1 Study area description

The study involves the entire miombo woodlands of mainland Tanzania that covers a total area of 44.73 million ha (Fig.1). The main concentrations of miombo woodlands are found in the western zone (Tabora, Rukwa and Kigoma regions) and the southern zone (Iringa, Lindi, Mtwara and Ruvuma regions) (Fig. 1). Vast areas of miombo woodlands fall under the village lands ownership, most of which lack proper management

(Malimbwi *et al.*, 2018). The village land in turn is in different administrative regions in mainland Tanzania, characterised by both tropical and subtropical climates. The weather conditions for all regions may be divided into 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 mid-August. Moreover, 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 zone, the rain is distributed over two shorter periods (October–December and March–May).

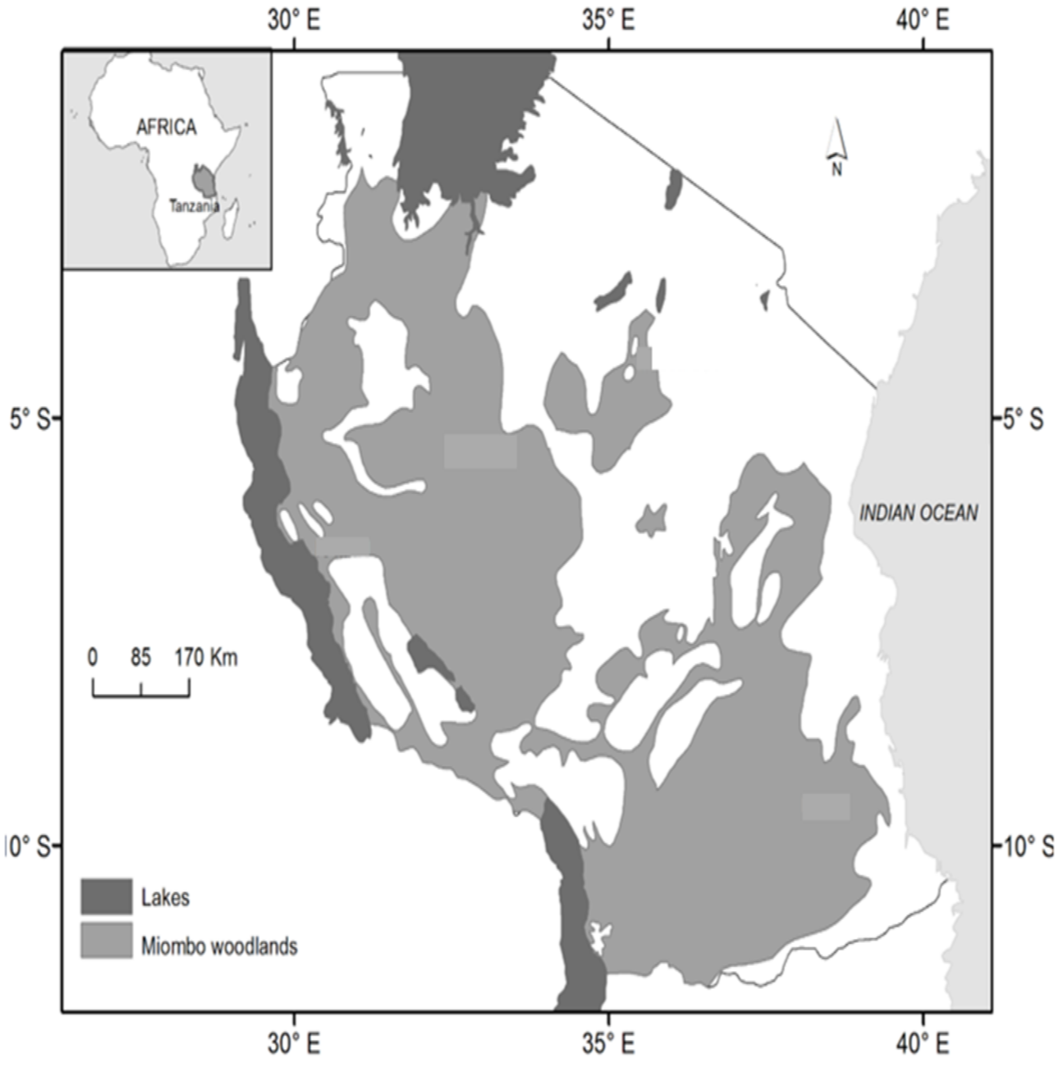

Figure 5.1: A map of mainland Tanzania showing miombo woodlands

Source: Mauya *et al*. (2014)

5.3 Data collection

The study is based on data collected under NAFORMA. Data for this study was extracted from NAFORMA database located at Sokoine University of Agriculture, Morogoro Tanzania.

5.4 Data extraction

The whole NAFORMA data set was imported to R software. By using “sqldf” R package which runs Structured Query Language (SQL) statements on R data frames, all stump data from miombo woodlands were extracted. Finally, data cleaning i.e. removal of noisy data and outliers was done. For the purpose of this study, we extracted from NAFORMA database all the plots that were surveyed for stumps measurement in miombo woodlands. In total, we extracted 5 264 stumps from 16 219 plots from NAFORMA database.

5.5 Sampling design, plot shape and size by NAFORMA

NAFORMA sampling design followed a double sampling for stratified systematic cluster sampling described by Tomppo *et al.* (2010). The first-phase sample consisted of dense grid of L-shaped clusters overlaid on the map of Tanzania mainland at distances of 5 km x 5 km between the clusters. The first-phase clusters were assigned to 18 pre-defined strata based on predicted growing stock, time consumption for cluster measurements and slope of the terrain. Since each stratum had unique sampling intensity, the second-phase samples that were only measured in the field were systematically selected from the first phase sample, based on sampling intensities in each of the 18 strata. A total of 32 660, field plots were established across all land cover types in Tanzania mainland (Figure 2). The details on the distance between clusters, number of plots in a cluster, plot designs and uncertainty in the sampling design are explained in Tompo *et al.* (2014), Tompo *et al.* (2010), and Mauya *et al.* (2019) and Manyanda *et al*. (2020).

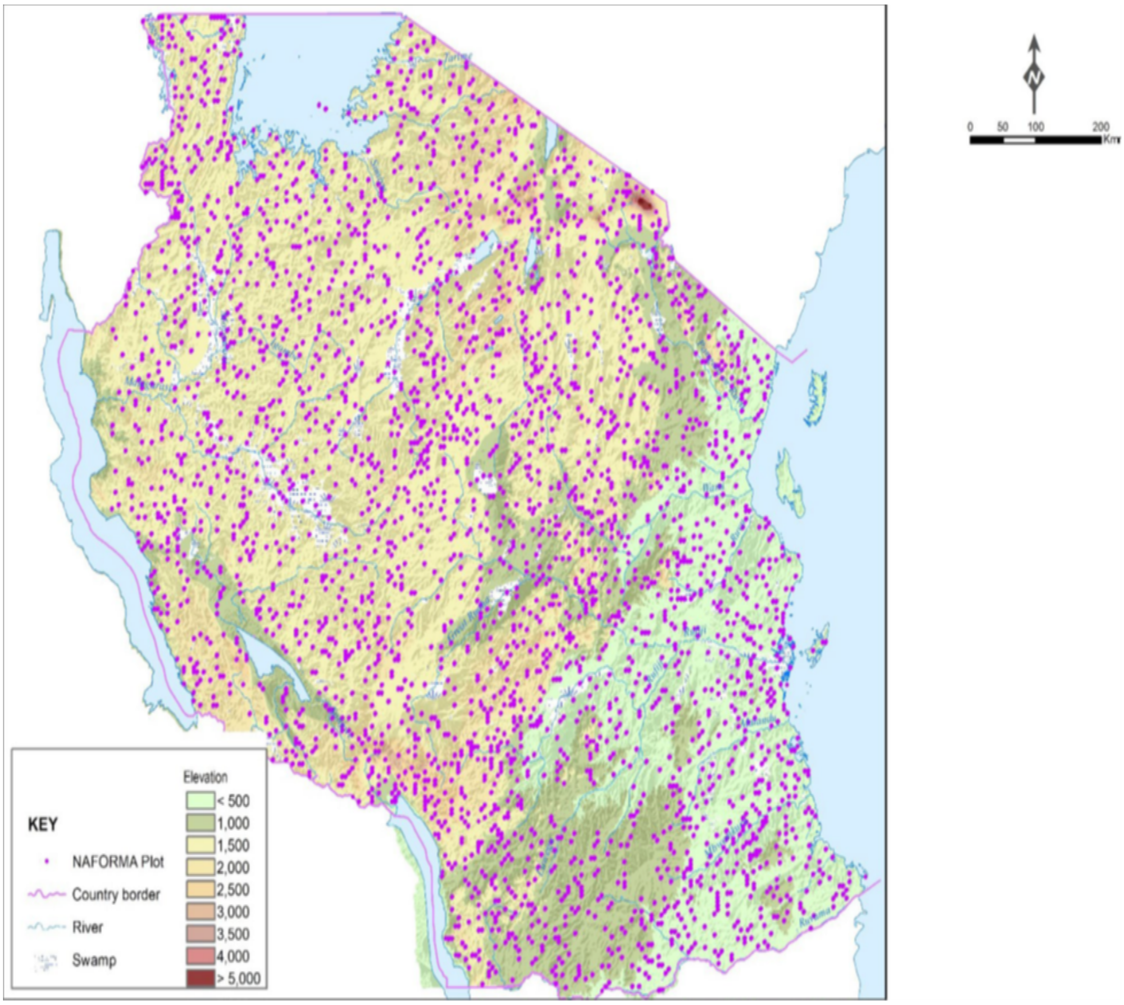

Figure 5.2: Distribution of sample plots in Mainland Tanzania

(Source Mauya *et al.*, 2019)

5.6 Data acquisition by NAFORMA

In the NAFORMA, all stumps with diameter ≥ 5 cm within plot radius of 15 m were measured for diameter and height using calliper or measuring tape from 2010 to May 2011. However, after May 2011, all measurements of stumps were changed to minimum stump diameter of ≥10 cm within a plot radius of 10 m.

This was done in order firstly to improve speed in data collection in the smaller plot and secondly to avoid measuring smaller tree stumps, which are not resistant to annual fires and thereby causes inefficiency in estimating volume and biomass removed through trees cutting in miombo woodlands (Kielland-Lund1 990b). We acknowledge that by increasing stump diameter threshold, some of the small stumps would be left unmeasured and hence underestimation of volume and biomass removed. However, such volume and biomass would not be much since small diameter trees have less contribution to stand volume and biomass than larger ones. The decrease of plot size from 15 m to 10 m would not affect estimates because all stand values are calibrated at per hectare basis. The stump diameter (SD) was measured outside bark immediately under the cutting point. If the bark was damaged or missing, logical compensation for bark thickness were done. When a stump was taller than 1.3 m, the diameter was measured at the 1.3 m height (*DBH*). Stump height was measured by measuring tape from the level of the ground. The age of a stump since harvesting was recorded as numerical value. The precise estimation of age of stump as numerical value may be subjective but necessary to determine rate of volume and carbon due to ESH, 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. Further details on how stumps were measured can be obtained in URT (2010).

5.7 Data analysis

5.7.1 Estimating annual wood volume and carbon loss from extra stump height

Stump height data was evaluated for outliers before carrying out statistical analysis in R software. Then, volume loss per ESH was estimated using formula applicable for calculating volume of cylinder with circular base (Equation 1 and 2) as follows;

$$V = \pi D^2 Hi \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(1)$$

Where V = is the wood volume of ESH, D = is the measured top diameter of the stump and Hi= is the height of the ESH of individual stump obtained by equation 2 as follows;

$$Hi = h_{md} - h_{rd} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(2)$$

Where; h_{md} is the measured total height of the stump and h_{rd} is the recommended height of the stump.

However, the wood volume calculated in this way is slightly underestimated, since the diameter at the recommended height is often bigger than that above due to tapering. The precision of wood volume calculations would be improved if there were taper functions to enable volume calculations of a tree at any height.

Moreover, carbon emission was calculated from biomass. Biomass of the ESH were computed by multiplying wood volume of ESH and wood basic density (Equation 3). Species-specific wood density values from the global wood density database were used. Where wood density was missing, average wood basic density of 0.58 g/cm^3 (Malimbwi *et al.* 2000) was used. Then tree carbon was obtained by multiplying biomass by 49% as a conversion factor for biomass to carbon (MacDicken, 1997).

$$B = W_{bd} * V \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots 3$$

Where; B= biomass of ESH, W_{bd} is the wood basic density and V is the wood volume of ESH

The estimated wood volume and carbon of the ESH was divided by estimated stump age to get the rate of volume and carbon loss per year. Wood volumes and carbon of the ESH per year was summed up and expressed on per plot basis. Since each stratum had unique sampling intensity, plot expansion factors (EF) in each stratum were calculated. EF is the area represented by each plot in a stratum. The sequence on the calculation of EF can be observed in Manyanda *et al.* (2020) and Mauya *et al.* (2019). The plot level wood volume and carbon values were multiplied by EF values corresponding to each stratum. The plot level volume and carbon values were then expressed at per hectare basis. Finally, the wood volume and carbon of ESH was then expressed according to zones, regions, species land use, vegetation and ownership types.

On the other hand, statistical significance test was employed to explore if there were differences in mean volume and carbon from ESH between the 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.

5.7.2 Assessing the proportions of wood volume and carbon emission of extra stump height to volume and carbon removals

Volume and biomass removals per tree, was calculated by using Equation 4 and 5 respectively. These are allometric equations developed for miombo woodlands in mainland Tanzania (Manyanda *et al.,* 2019). The estimated individual tree volume and carbon was divided by respective estimated age of the stump to obtain rate of volume and carbon removals per year. The estimated individual tree volume and carbon per year were summed up and expressed at per plot and per ha basis. Similar procedures as those used in calculating wood volume of ESH were used to incorporate EF in the calculation of final volume and carbon removals. Details on how volume and carbon removals were calculated with the incorporation of EF in the entire miombo woodlands and its categories can be obtained in Manyanda *et al.* (2020).

$$Y = 0.000032 \times SD^{2.7992} \quad \text{……} \quad (4)$$

$$Y = 0.03785 \times SD^{2.6700} \quad \text{……} \quad (5)$$

Where; Y is either volume or biomass of tree and SD in the stump diameter

On the other hand, implication was estimated as the proportion (in percentage) of the ESH volume or carbon over removed volume or carbon respectively.

5.8 Results

5.8.1 Wood volume and carbon of extra stump height and their proportion to volume and carbon removals by zones, regions, species, vegetation, land use and ownership types

Table 5.1 shows annual wood volume and carbon of ESH, volume and carbon removals and proportions by ownership types, land use types and zones. In terms of ownership types, we observed higher wood volume of ESH per year in village land followed by private, central government and general land. Local government land revealed the lowest total wood volume of ESH per year (Table 5.1). Similarly, we found higher wood volume of ESH per hectare per year in private land, followed by general land, not known land, village land, local government land while the least was from the central government land

(Table 5.1). Carbon loss from ESH followed similar trends as for wood volume per hectare per year. Moreover, wood volume and carbon of ESH implied 6% and 5% respectively more removals in the private land while in the other categories it implied 5% and 4% for wood removals and carbon removals respectively.

Considering land use types, we observed higher total wood volume of ESH per year in the production forest land followed by shifting cultivation, protection forest, wildlife reserves, grazing land while the least was from water bodies/swamps. Higher wood volume and carbon of ESH per hectare per year was found in the shifting cultivation land, followed by production forest, protection forest and grazing land (Table 5.1). This implied 7%, 5%, 5%, and 3% more wood volume removals in the shifting cultivation land, production forest, protection forest and grazing respectively. Furthermore, the carbon loss of ESH implied 5%, 4%, 4% and 2% as the proportion of more carbon removals in the shifting cultivation land, production forest, protection forest and grazing land respectively (Table 5.1).

Regarding administrative zones, we observed higher total wood volume of ESH per year in the southern zone followed by eastern, western, northern, southern highland, central zones while the least was in the lake zone. Conversely, wood volume and carbon of ESH per hectare per year was higher in the eastern zone followed by Northern, Southern, Western, Central, Southern highland zones while the lowest was recorded in in the Lake zone (Table 5.1). Table 1 further indicate the proportions of volume and carbon of ESH to volume and carbon removals.

In terms of regions, wood volume and carbon of ESH per hectare per year was higher in the regions of Dar es Salaam, Pwani, Tanga, Mtwara, Lindi, Morogoro, Tabora, Ruvuma, Singida and kigoma while Mara, Manyara and Arusha had smallest (Table 5.2).

For vegetation types, the highest value of annual wood volume loss of ESH was recorded in open woodlands while the smallest value was in woodlands with scattered cropland (Table 5.3). Conversely, the wood volume and carbon of ESH per hectare per year was higher in the woodlands with scattered cropland while the smallest was in the closed woodlands (Table 5.3). Table 4 indicates the thirty species with the highest proportion of ESH volume and carbon. *Brachystegia sp, Julbernardia globiflora, Pterocarpus angolensis, Terminalia sambesiaca and Isoberlinia sp* revealed the higher volume and carbon per hectare per year from ESH while *Combretum collinum, Bridelia melanthesoides* and *Spirostachys africana* had the least volume per hectare per year.

The ESH volume and carbon by zones, ownership and land use types, vegetation subtypes and species in miombo woodlands has also been expressed in percentages and equivalent carbon loss (Table 5.1, 5.2, 5.3 and 5.4).

Table 5.1: Wood volume and carbon of extra stump height and its proportion to wood volume and carbon removals by ownership, land use and Zones in miombo woodlands in mainland in Tanzania

Miombo management categories	Miombo management categories subdivision	Area (Ha)	Total volume of ESH (m^3year^{-1})	Volume of ESH ($m^3ha^{-1}year^{-1}$)	Volume removals ($m^3ha^{-1}year^{-1}$)	Carbon removals ($tCha^{-1} year^{-1}$)	Carbon lossof ESH ($tCha^{-1}year^{-1}$)	Proportion of volume/carbon of ESH to volume/carbon removed (%)
Ownership types	Village land	24 330 049.5	2 242 389.8	0.092 ± 0.019[a]	2.00±0.55	0.71±0.17	0.03±0.02a	5(4)
	Private land	2 987 394.5	551 385.5	0.185 ± 0.057[a]	3.05±1.36	0.96±0.34	0.05±0.03a	6(5)
	Central government	12 973 229.1	513 546.8	0.040 ± 0.013[ab]	0.75±0.25	0.27±0.09	0.01±0.01ab	5(4)
	General land	2 524 053.8	281 521.9	0.112 ± 0.057[a]	2.22±1.27	0.82±0.46	0.03±0.02a	5(4)
	Local government	3 539 359.2	236 183.5	0.067 ± 0.027[ab]	1.26±0.50	0.46±0.18	0.02±0.01ab	5(4)
	Not known	114 885.4	11 620.7	0.101 ± 0.194[a]	0.86±0.22	0.29±0.04	0.03±0.02a	12(10)
Land use types	Production forest	19 818 693.3	1 944 809.3	0.098 ± 0.023[a]	2.06±0.63	0.71±0.20	0.028±0.007[ab]	5(4)
	Shifting cultivation	3 447 023.4	873 995.3	0.254 ± 0.075[a]	3.63±1.09	1.33±0.39	0.072±0.021[a]	7(5)
	Protection forest	7 989 689.4	467 640.0	0.059 ± 0.018[ab]	1.15±0.40	0.41±0.14	0.017±0.005[ab]	5(4)
	Wildlife reserve	10 619 467.9	260 047.5	0.024 ± 0.007[ab]	0.54±0.17	0.2±0.06	0.007±0.002[c]	4(3)
	Grazing land	4 148 271.1	242 373.3	0.058 ± 0.019[ab]	2.02±1.39	0.67±0.43	0.017±0.006[ab]	3(2)
	Water body/ swamp	31 442.9	12 212.4	0.022 ± 0.014[ab]	3.53±2.93	0.48±0.35	0.11±0.154[a]	1(23)
	Other land	514 786.5	8 253.9	0.016 ± 0.013[ab]	0.29±0.18	0.11±0.06	0.005±0.004[c]	6(4)
Zone names	Southern	12 660 736.6	1 543 984.3	0.122±0.026[a]	2.55±0.87	0.86±0.26	0.035±0.007[a]	5(4)
	Eastern	5 935 011.4	994 408.9	0.168±0.049[a]	3.63±1.19	1.33±0.42	0.048±0.014[a]	5(4)
	Western	10 412 145.1	541 584.8	0.052±0.021[b]	0.80±0.31	0.35±0.25	0.015±0.006[b]	7(4)
	Northern	2 728 754.9	338 489.0	0.124±0.062[a]	2.08±0.98	0.76±0.34	0.035±0.018[a]	6(5)
	Southern highland	7 764 001.4	192 881.2	0.025±0.013[b]	0.90±0.86	0.31±0.14	0.007±0.004[b]	3(2)
	Central	4 634 449.3	178 753.1	0.039±0.015[b]	0.50±0.19	0.18±0.07	0.011±0.004[b]	8(6)
	Lake	2 226 563.1	38 681.7	0.017±0.014[b]	0.36±0.28	0.14±0.10	0.005±0.004[b]	5(4)

Note: 1. Proportion with and without bracket are for carbon and volume of ESH to annual removals respectively.

2. Volume and/or carbon of ESH with the same superscript letters in the category are not significantly different ($p < 0.05$).

Table 5.2: Volume and carbon of extra stump height and its proportion to wood volume and carbon removals by regions in miombo woodlands of mainland Tanzania

Region name	Total area (ha)	Total volume of ESH (m^3year^{-1})	Volume of ESH($m^3ha^{-1}year^{-1}$)	Volume removals ($m^3ha^{-1}year^{-1}$)	Carbon removals ($tCha^{-1}year^{-1}$)	Carbon loss from ESH ($tCha^{-1}year^{-1}$)	Proportion of volume/carbon of ESH to volume/carbon removed (%)
Dar es Salaam	18894.56	7105.96	0.376±0.237[a]	6.72±2.41	2.61±0.92	0.107±0.001[a]	6(4)
Pwani	1707204	475735.6	0.279±0.130[a]	6.44±3.41	2.35±1.16	0.079±0.037[a]	4(3)
Tanga	1235077	336028.5	0.272±0.147[a]	4.51±2.30	1.68±0.08	0.077±0.042[a]	6(5)
Mtwara	937563.9	145405.1	0.155±0.084[a]	2.54±1.35	0.92±0.48	0.044±0.024[a]	6(5)
Lindi	5906731	904936.3	0.153±0.044[a]	3.85±1.79	1.31±0.52	0.044±0.013[a]	4(3)
Morogoro	4233808	508891.6	0.120±0.038[a]	2.43±0.78	0.89±0.28	0.034±0.011[a]	5(4)
Tabora	3113899	284471.4	0.091±0.052[a]	1.44±0.80	0.57±0.28	0.026±0.015[a]	6(5)
Ruvuma	5904562	490452.3	0.083±0.029[a]	1.18±0.48	0.43±0.16	0.024±0.008[a]	7(6)
Singida	2052842	122110.4	0.059±0.027[b]	0.78±0.37	0.27±0.13	0.017±0.008[b]	8(6)
Kigoma	2081282	112430	0.054±0.045[b]	0.75±0.58	0.45±0.04	0.015±0.013[b]	7(3)
Dodoma	1028610	45560.42	0.044±0.039[b]	0.51±0.43	0.18±0.14	0.013±0.011[b]	9(7)
Mwanza	130216.3	5639.83	0.043±0.087[b]	0.86±0.04	0.38±0.01	0.012±0.002[b]	5(3)
Shinyanga	1012533	30177.99	0.030±0.032[b]	0.59±0.07	0.23±0.01	0.008±0.003[bc]	5(3)
Rukwa	4217038	117010.3	0.028±0.017[bc]	0.40±0.24	0.16±0.09	0.008±0.005[bc]	7(5)
Mbeya	4970101	130852.8	0.026±0.017[bc]	0.48±0.30	0.19±0.12	0.007±0.005[bc]	5(4)
Iringa	2793900	62028.48	0.022±0.020[bc]	1.63±0.07	0.48±0.02	0.006±0.004[bc]	1(1)
Kagera	1943610	31224.22	0.016±0.015[bc]	0.35±0.30	0.13±0.11	0.005±0.004[bc]	5(4)
Mara	152737.1	1817.69	0.012±0.003[bc]	0.09±0.02	0.03±0.01	0.003±0.001[c]	13(10)
Manyara	1555365	10360.83	0.007±0.006[c]	0.10±0.09	0.04±0.03	0.002±0.002[c]	7(5)
Arusha	1150964	2460.55	0.002±0.001[c]	0.09±0.01	0.03±0.01	0.001±0.001[c]	2(3)

Note: 1. Proportion with and without bracket are for carbon and volume of ESH to annual removals respectively.

2. Volume and/or carbon with the same superscript letters in the region are not significantly different ($p < 0.05$).

Table 5.3: Total wood volume, carbon of extra stump height and its proportion to removals by vegetation types of miombo woodlands in mainland in Tanzania

Miombo woodlands sub vegetation types	Area(ha)	Total volume (m^3year^{-1})	Volume loss from ESH ($m^3ha^{-1}year^{-1}$)	Volume removals ($m^3ha^{-1}year^{-1}$)	Carbon removals ($tCha^{-1}year^{-1}$)	Carbon loss from ESH ($tCha^{-1}year^{-1}$)	Proportion of volume/carbon of ESH to volume/carbon removals (%)
Woodland with scattered cropland	1 631 460.1	235 301.7	0.144 ± 0.070[a]	1.99±0.97	0.72±0.30	0.041±0.020[a]	7(6)
Open woodland (crown cover between 10-40%)	33 745 163.9	2 842 172.3	0.084 ± 0.014[a]	1.74±0.39	0.63±0.12	0.024±0.004[a]	5(4)
Closed woodland (crown cover >40%)	11 139 239.0	729 694.1	0.066 ± 0.018[a]	1.35±0.38	0.46±0.13	0.019±0.005a	5(4)

Note 1. Proportions with and without bracket are for carbon and volume of ESH to annual removals respectively.
2. Volume and/or carbon of ESH with the same superscript letters in the sub vegetation types are not significantly different ($p < 0.05$).

Table 5.4: Thirty species with highest volume and carbon of extra stump height and its proportion to wood volume and carbon removals in miombo woodlands of mainland Tanzania

Species name	Volume of ESH (m^3year^{-1})	Volume of ESH (m^3ha^{-1} $year^{-1}$)	Volume removals (m^3ha^{-1} $year^{-1}$)	Carbon removals ($tCha^{-1}$ $year^{-1}$)	Carbon loss from ESH ($tCha^{-1}$ $year^{-1}$)	Proportion of volume/carbon of ESH to volume/carbon removed (%)
Brachystegia sp.	252174.2	0.005653[a]	0.085	0.035	0.0016[a]	7(5)
Julbernardia globiflora	214839.1	0.004807[a]	0.071	0.025	0.0014[a]	7(6)
Pterocarpus angolensis	187342.1	0.004187[a]	0.103	0.037	0.0012[a]	4(3)
Terminalia sambesiaca	183647.5	0.004132[a]	0.214	0.059	0.0012[a]	2(2)
Brachystegia spiciformis	161224.9	0.003611[a]	0.058	0.022	0.001[a]	6(5)
Brachystegia boehmii	139535.3	0.003125[a]	0.043	0.015	0.0009[a]	7(6)
Brachystegia microphylla	116494.1	0.002618[a]	0.061	0.02	0.0007[a]	4(4)
Diplorhynchus condylocarpon	105631.2	0.002358[a]	0.022	0.009	0.0007[a]	11(8)
Pericopsis angolensis	88071.6	0.001973[ab]	0.031	0.012	0.0006[ab]	6(5)
Xeroderris stuhlmannii	82146.4	0.001845[ab]	0.031	0.011	0.0005[ab]	6(5)
Dalbergia melanoxylon	76607.4	0.001717[ab]	0.051	0.017	0.0005[ab]	3(3)
Pteleopsis myrtifolia	73448.5	0.001648[ab]	0.031	0.011	0.0005[ab]	5(5)
Burkea africana	73415.2	0.001646[ab]	0.022	0.009	0.0005[ab]	7(6)
Afzelia quanzensis	68289.7	0.001535[ab]	0.037	0.012	0.0004[b]	4(3)
Brachystegia bussei	67158.7	0.001508[ab]	0.023	0.009	0.0004[b]	7(4)
Pseudolachnostylis maprouneifolia	59978.4	0.001345[b]	0.023	0.008	0.0004[b]	6(5)
Combretum molle	56393.7	0.001262[b]	0.013	0.005	0.0004[b]	10(8)
Albizia versicolor	54964	0.001236[b]	0.026	0.009	0.0004[b]	5(4)
Markhamia obtusifolia	47398.7	0.001064[b]	0.021	0.003	0.0003[b]	5(10)
Acacia sp.	45954	0.001032[b]	0.018	0.008	0.0003[b]	6(4)
Combretum zeyheri	44532.8	0.000998[b]	0.023	0.008	0.0003[b]	4(4)
Acacia nigrescens	43167.1	0.00097[b]	0.013	0.008	0.0003[b]	7(4)
Albizia sp.	42103.5	0.000947[b]	0.034	0.011	0.0003[b]	3(3)
Diplorhynchus mossambicensis	40604.9	0.000912[b]	0.017	0.006	0.0003[b]	5(5)
Brachystegia longifolia	39817.8	0.000895[b]	0.012	0.004	0.0003[b]	7(8)
Pterocarpus tinctorius	36347.6	0.000817[b]	0.013	0.004	0.0002[b]	6(5)
Isoberlinia sp.	33336	0.00075[b]	0.013	0.008	0.0002[b]	6(3)
Combretum collinum	32072.5	0.00072[b]	0.012	0.005	0.0002[b]	6(4)
Bridelia melanthesoides	31702	0.000713[b]	0.015	0.005	0.0002[b]	5(4)
Spirostachys africana	29178.2	0.000656[b]	0.0646	0.003	0.0002[b]	1(7)

Note: 1. Proportion with and without bracket are for carbon and volume of ESH to annual removals respectively.
2. Volume and/or carbon of ESH with the same superscript letters for species names are not significantly different ($p < 0.05$).

5.9 Discussion

Wood harvesting at ESH escalate substantial volume and carbon removals. We applied formula applicable for the calculation of volume of cylinder with circular base and average basic density to provide an understanding of estimates of wood volume and carbon loss due to ESH in different zones, regions, species, vegetation subtypes, ownership and land use types in which miombo woodlands fall in Mainland Tanzania using NAFORMA data sets. We used indirect method that integrate volume and basic density to provide estimates of carbon loss from ESH since no models that estimates carbon of ESH are available. According to Njana (2017), the use of indirect methods may results into large uncertainties of carbon estimates compared to the use of tree allometric models. The wood volumes and carbon from ESH has also been expressed at annual rates per hectare in each category. Their percentages and carbon equivalent have also been estimated in order to get an insight of which item in the category is contributing most to wood loss due to ESH.

Total tree annual wood volume, wood volume and carbon loss per hectare per year from ESH revealed 3 800 000m^3year^{-1}, 0.098 ± 0.034 $m^3ha^{-1}year^{-1}$ and 0.028±0.009$tCha^{-1}year^{-1}$ respectively. These annual rates of wood removals through ESH are 6% of the total annual volume and carbon removals of 1.71±0.54 $m^3ha^{-1}year^{-1}$ and 0.60±0.18 $tCha^{-1}$ $year^{-1}$ respectively (Manyanda *et al.* 2020). This suggests that if the wood demand i.e. removals is insufficient, 6% more volume would be removed more to suffice the volume demand. On top of that, the total wood volume of Tanzania mainland is estimated at 3.3 billion m^3, in which 97% of the total volume are from trees of natural origin including miombo woodlands (MNRT, 2015). The total annual supply (growth) of wood at national level on the other hand is estimated at 83.7 million m^3 and only about half of this, i.e. about 42.8

million m^3 is available for harvesting at a sustainable basis (MNRT, 2015). Likewise, the annual demand (consumption) of wood in Tanzania is estimated at 62.3 million m^3 while the sustainable supply is about 42.8 million m^3, this indicates 19.5 million m^3 annual deficit. This suggests that quarter of the deficit could be lowered if trees were harvested properly at 15 cm from the ground.

Considering vegetation subtypes of miombo woodlands, the highest volume and carbon loss per hectare per year from ESH in the woodland with scattered cropland could be explained by the nature of the activities taking place in the category. The category is heavily affected by agricultural activities in which tree harvesting does not abide to the harvesting regulations thus implying more volume and carbon removals. Other scholars (Nduwayezu, *et al.*, 2015; Chiteculo and Surovy, 2018), found that open miombo are heavily degraded due to activities related to its land use for pastoral agriculture, cutting of live wood resources for building poles and fencing materials, and unsustainable fuel wood harvesting. Likewise, the least proportion of volume and carbon lost from ESH in relations to volume and carbon removals in the closed woodlands was because most of the protected forest are for conservation purposes in which law enforcement efforts are higher (MNRT, 2015). The proportion of volume and carbon loss of ESH from these regimes were in any case illegal.

In terms of ownership types, higher volume and carbon per hectare per year from ESH revealed in private owned land was probably due to unawareness to follow harvesting regulations stipulated by the government and the nature of the regime. This is because harvesting in the private land is largely governed by the private landowner. This ends up into harvesting trees at higher stump height than recommended and escalate more volume removals due to extra tree cut. Similarly, higher volume and carbon from ESH in the general land is attributed by the fact that the forest under this regime is unmanaged (Lusambo *et al.*, 2016). Likewise, the forest under this regime is regarded as open access or business as usual forest, i.e., access is free and unregulated, possibly because rights are only nominal and unenforced (Lusambo *et al.,* 2016). This ultimately escalate more removals by 5%. In contrast, small volume and carbon from ESH in the central and local government land was probably attributed to laws and regulations enforcement efforts that are implemented by the Government officials.

In terms of land use types, shifting cultivations had relatively higher volume and carbon loss from ESH. This may be attributed by the nature of the land use and unawareness of the harvesting regulations. In the course of land preparation, farmers normally cut trees at any height of a stump, which ends up into leaving higher volume and carbon from ESH in the woodlands. This argument is supported by Chansa (2018) who revealed that when trees are cleared for subsistence agriculture, they are either stumped or cut at breast or waist height. In the present study, cutting of trees at ESH implied 7% and 5% of volume and carbon removals respectively.

Furthermore, higher volume loss in the production forest was to the large extent contributed to inefficiency in the laws and regulations enforcement. This is evidenced further by Milledge *et al.* (2007) who state that inefficiency in laws and regulations enforcements characterize most of the illegal harvesting in the government owned forests. Moreover, wildlife reserve and protection forest reserves had small volume loss because harvesting in the regime is not allowed and those harvesting revealed were from illegal practices.

Regarding zones and regions, Eastern zone which comprises of Dar es salaam, Pwani, Morogoro and Tanga had the highest volume and carbon from ESH because most of the harvesting in this zone ends up into cooking energy (i.e. charcoal, firewood) and timber (Manyanda *et al.*, 2020b in press). When people are harvesting trees for charcoal and firewood, they normally cut trees at any height. This could end into leaving more wood volume in the woodlands. Likewise, the zone is close to Dar es Salaam city in which wood volume consumption per capita is higher (MNRT, 2015). This further escalate more emissions in the zone. In contrast, Lake, Southern highland and Central zones recorded least volume and carbon from ESH. This could be due to effective laws enforcement in these zones and unprecedented deforestation recorded in the previous years (MNRE, 1995).

NAFORMA survey recorded more than 450 species in the miombo woodlands ecosystems (MNRT, 2015). Wood volume and carbon loss from ESH in miombo woodlands depend much on the type of species and thus dictating species consumption preference. In this study, thirty most species with the highest volume and carbon loss from ESH are reported (Table 5.4). The highest loss by these species could be attributed by the species preference mainly for timber and charcoal. Timber harvesting in miombo woodlands are both legally and illegally harvested. When much illegal and inefficiency law and regulations enforcement characterizes harvesting, harvesting of trees at ESH happens. This would eventually imply higher volume and carbon loss by these species. Furuya *et al.*,unpublished cited by Eriko *et al.* (2010), found that some illegally logged stumps of evergreen dipterocarpus species were more than 1.3m tall (n=189) whereas others averaged 0.76m ranged from 0.3m to 1.2m in height (n=118). Likewise, most of the species recorded for the highest volume and carbon loss in the present study were *Brachystegia sp.* These species are mostly harvested for charcoal in which cutting does not follow harvesting standards. The findings of this study are in line with that of other scholars (Sawe *et al.*, 2014; Chiteculo and Surovy, 2018; Chansa, 2018), who found that *Brachystegia sp*. are mostly used for charcoal because of good embers, high heat content value, last long in burning, hot fire, unsparking and little smoke (Chansa, 2018). Furthermore, Chansa, 2018 found that all the stumps surveyed for charcoal production were cut at a height of 48cm from the ground.

Although high stump height has negative effect to wood removals and carbon emissions, ecologically it has positive effects. Higher stump height enables higher resprouting ability especially for miombo woodlands for which resprouting is important for regeneration. Notable studies (Syampungani *et al.*, 2017; Shackleton, 2000; Mishra *et al.*, 2003; Amri *et al.*, 2010; Ferdinand *et al.* (2011) have shown that stump height has a strong influence on the coppicing ability of miombo woodlands that, the shorter the stump height, the less number of coppices and vice versa. The positive influence of stump height could be caused by the availability of more reserved food and dormant buds on longer stumps together with discouraging of fungal infections because of moisture from the ground or stump decay (Matowo *et al.*, 2019). However, the positive ecological effect of increased cutting height must be balanced against the negative economic loss and climate change induced due to biomass left behind as a stump that would eventually either rot out or burnt and release the stored carbon. In addition, the height of the stump is also function of the end use of the harvested product. For commercial purpose, tree should be harvested at recommended height to avoid extra wood volume removals

5.10 Conclusions

In this paper, we have demonstrated that ESH caused by illicit tree harvesting in different categories in which miombo woodlands falls escalate substantial wood volume and carbon removals. The study revealed that volume and carbon loss from ESH per hectare per year escalate 6% and 5% of more volume and carbon removals respectively in the entire miombo woodlands and its categories in mainland Tanzania. This suggests that if proper tree harvesting were adhered, 6% and 5% extra volume and carbon removals respectively would be avoided in each category and in the entire miombo woodlands. We recommend that laws and regulations regarding tree harvesting at 15 cm high from the ground level in miombo woodlands should be strictly enforced. In particular, the enforcement should be strengthened in the Eastern, Southern and Northern zones. Moreover, enforcement must be strengthened also in private forestland, general land, village land, production forestland, in the woodlands with scattered cropland and in all species with large volume and carbon loss. Since the wood volume calculated by the use of formula applicable to cylinder is slightly underestimated due to tapering, taper functions should be developed to enable volume calculations of a tree at any height. Furthermore, present study should be conducted at district level, individual forest unit and other vegetation types like montane and mangrove forests. NAFORMA data is between six to ten years old. A lot might have happened during this period. It is recommended that remeasurement of permanent plot should be done to assess the current situation.

5.11 Conflict of interests

The authors declare no conflict of interest regarding the publication of this paper.

5.12 Acknowledgments

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CHAPTER SIX

6.0 Key contributions, conclusions and recommendations

6.1 Key contributions of the present study

This study has made five key contributions. First, this study is the first to the best of my knowledge, to develop biomass and volume regional models based on stump diameter for assessing removals in miombo woodlands of mainland Tanzania. Secondly, it is the first large scale study to provide estimates of volume and carbon removals in miombo woodlands of Tanzania. Thirdly, it is the first to investigate the drivers and their influences on the variations of AGC removals in miombo woodlands of mainland Tanzania. Fourth, it is the first to evaluate the implication of ESH in escalating more volume and carbon removals in miombo woodlands of Tanzania. Fifth, the study has empirically shown that ESH contribute about 6% and 5% extra volume and carbon removals respectively in miombo woodlands. These informations are important to policy makers, planners, researchers, NGOs and international organization like IPCC.

6.2 Conclusions

The following conclusions have been drawn from the findings as per specific objectives of the study.

6.2.1 Biomass and volume models based on stump diameter for assessing removals

This objective is discussed in detail in CHAPTER 2 “Biomass and volume models based on stumps for assessing degradation in miombo woodlands in mainland Tanzania”.This study developed robust volume, AGB and BGB models utilizing SD as the predictor that can be used to estimate forest degradation carried out through tree cutting in miombo woodlands. The study found that SD was inferior to D in explaining variation in volume and BGB but not AGB. However, the accuracy of BGB and volume estimates emanating directly from SD are far better than those obtained indirectly, i.e. volume or BGB estimates obtained from estimated D from SD, since the latter are affected by the accumulation of regression equation errors. This implies that when estimating volume and BGB of standing trees, models that utilize D should be applied whereas when estimating volume and BGB of the removed trees, models that utilize SD only should be applied.

6.2.2 Estimates of volume and carbon stock removals

This objective is discussed in detail in CHAPTER 3, “Estimates of volume and carbon stock removals in miombo woodlands of mainland Tanzania”. The study presents the systematic estimates of volume, biomass and carbon removals in the entire miombo woodlands and based on regions, TFS zones, ownership, vegetation, species and land use types. It is concluded that volume, and carbon removals in the entire and 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. However, the sustainability of removals in the protected woodlands and wildlife reserves should not mean that more removals be allowed but it should be used as an indicators that removals are even happening in the conservation areas.

6.2.3 Drivers and their influences on variation of aboveground carbon removals

This objective is discussed in detail in CHAPTER 4, “Drivers and their influences on variation of aboveground carbon removals in miombo woodlands of mainland Tanzania”. It is concluded from this study that AGC removals in miombo woodlands of mainland Tanzania are caused by timber, fire, shifting cultivation, charcoal, natural death, firewood collection, poles, grazing by wildlife animals, carvings, grazing by domestic animals, and mining which carbon removals ranging from 0.0 - 1.273$tCha^{-1}year^{-1}$. However, the prominent ones includes removals bycharcoal, timber, shifting cultivation, fire, firewood collections, poles and natural death. Furthermore, charcoal, shifting cultivation and fuelwood remove higher number of stems/ha that jeopardizes future carbon sink but its share to the estimated carbon removals is lower than timber and natural death that account for higher AGC removals.

6.2.4 Stump height: A potential escalator of volume and carbon emissions

This objective is discussed in detail in CHAPTER 5, “Stump height: A potential escalator of volume and carbon emissions in miombo woodlands in mainland Tanzania”. In this chapter, we demonstrated that ESH caused by illicit tree harvesting in different categories in which miombo woodlands falls escalate substantial wood volume and carbon removals. The study concluded that volume and carbon loss from ESH per hectare per year escalate 6% and 5% more volume and carbon removals respectively in miombo woodlands of mainland Tanzania. This suggests that if proper tree harvesting were adhered, 6% and 5% more volume and carbon removals respectively would be avoided in miombo woodlands of mainland Tanzania.

6.1.3 Recommendations

Based on the conclusions of this study, I make the following recommendations;

i) For improved accuracy of volume, ABG and BGB estimates, site-specific models be used for thelocal inventories in their respective sites or sites of similar conditions. However, for areas without site-specific models, regional models should be used.

ii) For reducing emissions emanating from removals and by considering national circumstances, all categories of miombo woodlands and drivers should be managed although the management (in terms of tree cutting) intensity and priorities should consider shifting cultivation, production forest, grazing land, general land, village land, Eastern and Southern zones. Moreover, management intensity and priorities should consider timber, fire, shifting cultivation, charcoal, natural death, firewood collection, poles, grazing by wildlife animals, carvings, grazing by domestic animals, and mining as drivers of removals in the order of impotance. Likewise, the management of miombo species should be species specific rather than holistic.

iii) Stumps data collected by NAFORMA should be used to estimate volume and carbon 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 in all vegetation types thereby understanding inferred forest degradation and hence improve future FREL.

iv) Since NAFORMA data sets provide national picture on the studied objectives (Chapter 3, 4 and 5), site-specific studies should be conducted to bring information that would be used to devise appropriate strategies at local settings.

v) Since the wood volume of ESH calculated by the use of formular applicable to cylinder is slightly underestimated due to tapering, taper functions should be developed to enable volume calculations of a tree at any height.

vi) Since the developed models are not species specific, it is recommended that species specific models based on stumps diameter could be developed for high value species including plantation species to minimize future inventory errors and enable volume estimation of removed trees in plantations.