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Review Article

An evaluation of carbon dynamics in miombo woodlands

Weston D. Sakala[1*] and Royd Vinya[2]

[1]*Zambia Forestry College, P/Bag Mwekera, Kitwe, Zambia.*

[2]*Copperbelt University, School of Natural resources, P.O. Box 21692, Kitwe, Zambia.*

*Corresponding author email: westonsakala35@gmail.com

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ABSTRACT

The vegetation of the miombo woodland is a highly heterogeneous phenomenon which makes it hard to assess biomass. Hence very little is known of their carbon dynamics and factors causing biomass variations. Estimating forest biomass is the first step towards carbon stock calculation. Current knowledge of miombo's carbon (C) pools is limited despite its importance in the global C budget. The article will address questions on how soil and vegetation carbon stocks differ across a miombo woodland landscape to enhance understanding of C stocks in African woodlands, and to what degree and scale are those stocks linked? A 5 km transect cyclic sampling scheme was used to allow geostatistical analysis. Vegetation and soil C stocks were coupled in the landscape in the top 5 cm of soil (r2 = 0.24) but not with deeper soil C stocks, which were coupled to soil clay content (r2 = 0.38). This study suggests that C stock distributions are strongly linked to topography and soil texture. To optimise sampling strategies for C stock assessments in miombo, soil C should be sampled at > 26 m apart, and AG C should be sampled at > 1430 m apart in plots > 0.5 ha.

*Keywords***:** Africa, biomass, carbon dynamics, carbon stocks, miombo woodland, variation of biomass.

1. INTRODUCTION

The Intergovernmental Panel on Climate Change (IPCC) estimates between 0.9 and 4.3 Gt of Carbon (C) are absorbed annually in soil and vegetation (Stocker et al., 2013), and therefore, forests play a vital role in increasing the C sink and reducing C emissions. Therefore, it is imperative to assess and monitor terrestrial C stores in forests. In miombo woodlands, the variation of biomass remains poorly understood, and it is unclear what other factors apart from precipitations cause biomass variation (Woollen, 2013). The large variability in canopy cover and vegetation structure occurs due to a hierarchy of factors such as climate and rainfall at a regional level, soil properties at the landscape scale, and various disturbance factors locally (Sanom, 2017).

Miombo woodlands are also characterised by large heterogeneity in tree and grass cover, determined by multiple mechanisms. The heterogeneity of miombo translates into highly varied above and below ground C stocks (Ryan et al., 2011), which complicates estimates of their C stocks and their monitoring requirements, leading to significant uncertainty in the assessment of C stocks and changes at the landscape scale. According to

Chidumayo (2013) woody biomass and soil C stock distributions have been linked to slope and soil physical properties. However, these links are unclear (Ryan et al., 2011), due to other disturbances such as fire (Ryan and Williams, 2011) and human influences (Chidumayo, 2012) impacting on vegetation structure, and de-coupling above and below-ground C stocks (Ryan et al., 2011). In order to reduce uncertainty surrounding C stock assessments in a miombo woodland landscape, there is need to understand what determines the distributions of C stocks in soils and vegetation and at what scales they vary.

Woollen et al., (2012) reported that miombo woodlands are dynamic ecosystems and are driven by multiple disturbances and environmental variability at a range of scales, with complex interactions, defining the carbon dynamics of miombo woodlands. However, very few studies have quantified the C stocks and changes of miombo woodland, or assessed the impacts of climate variability and anthropogenic pressures on carbon dynamics. Day et al. (2014) found that the causes of variability in biomass density within forest ecosystems, has been identified as an important knowledge gap. The purpose of this review paper is to assess varying levels of carbon and compare the variation with a view to contribute towards a better understanding of miombo woodlands. The Introduction should provide a clear statement of the problem, the relevant literature on the subject, and the proposed approach or solution. It should be comprehensible to academicians around the globe of scientific disciplines. This document is a template. An electronic copy can be downloaded from the conference website. For questions on paper guidelines, please contact the publications committee as indicated on the website. Information about final paper submission is available from the website. An easy way to comply with the paper formatting requirements is to use this document as a template and simply type your text into it.

2. MATERIALS AND METHODS

A comprehensive literature search had been performed with the help of the Google scholar, literature databases such as ISI web of knowledge, Web of science search for miombo woodlands, Science Direct, Wiley Interscience, and CAB Abstracts. The search used the following keyword terms: Africa, miombo woodland, biomass, carbon dynamics, carbon stocks and variation of biomass. The references obtained from interesting articles were used in additional search. However, the selection was somehow arbitrary but covered the most important aspects of the topic in this review paper. Moreover, locally available materials from Forestry research and academic institutions were also useful. Major components addressed in this review include carbon dynamics, soil organic carbon, variation of biomass and comparison of biomass.

3. RESULTS AND DISCUSSION

3.1 Carbon dynamics

Dewees et al. (2010) and Munishi et al., (2010) have reported that the miombo woodlands that dominate the region are the most extensive tropical seasonal woodland and dry forest formation in Africa, covering around 2.4– 3.6 million km2. While earlier studies have identified key ecological processes related to biomass accumulation and storage and the effect of human activities on C stocks in the region (Chidumayo, 2013), including fire and other disturbances (Ryan and Williams, 2011). Yet, little is known of the factors that may affect the distribution of biomass at broader geographic scales that are relevant for C management. To mitigate net global C emissions effectively requires reduction in sources of CO2 to the atmosphere as well as maintaining and increasing terrestrial and aquatic sinks (Munishi et al., 2010). Apart from the atmosphere, other sinks of C, such as forests, soil and oceans have evoked much interest in their ability to sequester C. Given the importance of forests to act as a C sink, it is imperative to understand the variation of biomass in miombo woodlands.

Furthermore, the Intergovernmental Panel on Climate Change (IPCC) estimated that terrestrial ecosystems had a net uptake of C from 1.0 to 2.6 Pg C per year (Nabuurs & Karjalainen, 2007). However, a more recent study reported higher estimates of 2.0 to 3.4 Pg C per year (Pan et al., 2011). Thus the United Nations Framework Convention on Climate Change (UNFCCC) has recognised the importance of forests as a C sink as well as a source and requires countries to include changes in forest C stocks in their annual greenhouse gas (GHG) inventories. Given that forest C balance is crucially linked to the atmosphere, the 7th Conference of Parties (COP) to the UNFCCC agreed that countries under the Kyoto Protocol must account for all forest C pools in their annual GHG inventories. Therefore, COP has recognised the above and below ground biomass, deadwood, litter and soil organic C as components of the forest C stock (Liski et al., 2010). According to Dixon et al., (2011) the world's forests are estimated to contain up to 80% of all aboveground and 40% of belowground terrestrial C.

Changes in temperature and/or precipitation influence the forest soil moisture regime (Dai et al. 2011) and drive C dynamics in forest ecosystems, (Hernandez- Stefanoni et al. 2011) especially in tropical dry forest ecosystems where precipitation is less than potential evapotranspiration (Bauer-Gottwein et al. 2011). Furthermore, secondary tropical dry forests may be more sensitive to climate change and anthropogenic disturbances than humid tropical forests (Haug et al. 2003).

Many studies on C dynamics in tropical wet forests, including observations and simulations using various C models, have been conducted in the last several decades (Kato et al. 2013). However, C dynamics in tropical dry forests has received less attention than other tropical ecosystems (Dupuy et al. 2012). There are substantial differences in forest structure, composition, and environmental conditions between tropical wet and dry forests although air temperature and soils may be similar. Many evergreen species can become deciduous or semi-deciduous in tropical dry forests and grow slowly due to water stress during the dry season (Daubenmire 1972). All in all, tropical dry forests are substantially different from tropical wet forests not only in species diversity but also in C accumulation and consumption. Soil organic carbon in terrestrial ecosystems

Globally, total soil organic carbon (SOC) content is estimated to be between 3,500 and 4,800 Pg C in the top 0 − 100 cm soil (Lehmann and Kleber, 2015). This makes SOC to be 5 − 10 times larger than the C stocks in the global vegetation (Noble et al., 2010). The SOC pool in the top 100 cm soil can vary from 30 Mg C ha-1 to 800 Mg C ha-1 depending upon soil type and climatic conditions, however most commonly, stocks range between 50 and 150 Mg C ha-1 (Lal, 2014). Total global forest C stock is estimated to be 1146 Gt C and soil C constitutes about 69% of the total forest C stock (Martin et al., 2010). The large quantity of C stored in the soil therefore, makes it an important sink or source of carbon dioxide (CO2), depending upon factors such as climate, land use and land management practices. Apart from sequestering C in the soils (Heimann and Reichstein, 2010), SOM also retains nutrients and buffers pollutants which enhance plant growth and improves water quality (Lal, 2005). The distribution of SOC is affected by numerous factors including forest type as well as slope and aspect (Dorji et al., 2015). A study in the Changbai Mountains of China found no obvious altitudinal effect on SOC distribution (Zhang et al., 2011). In contrast, in the Gharwal hills of India, at altitudes greater than 1700 m the climate influence on C storage in soils was predominant over vegetation type and landform, but at lower altitudes the vegetation type and landforms effects were dominant over climate (Martin et al., 2010).

The SOC pool is in constant flux, with C cycling constantly between the C reservoirs such as the atmosphere, biomass and oceans (Woollen, 2013). Plants through photosynthesis remove CO2 from the atmosphere and store them as plant material. Over time plants die, are burnt as fuel or decompose and release CO2 back to the atmosphere (Liao et al., 2012). However, some of the organic matter (OM) is incorporated into the soil as SOC. Soil organic carbon further decomposes releasing CO2 back to the atmosphere or is bound to clay minerals and preserved in the soil for variable period of time (LaI,2005). Although the importance of SOC has long been recognized, the complexities of the process involved with transformation of biomass into organic products and their association with soil minerals make prediction of general trends of soil C dynamics difficult (Li et al.,2012). In order to consider soil C dynamics, it is important to understand pool sizes, composition and their turnover times.

Soil organic carbon is composed of variable fractions based on functional pools. There is a small pool (1 – 5%) with a rapid turnover time of a few weeks to months and two larger pools with slow turnover rate from a few years to decades and very slow turnover rate of centuries (Tirol-Padre & Ladha, 2014). Litter input, root biomass and microbial biomass responsible for litter and SOM transformation are the main C fractions (Christensen, 2010). Litter inputs and SOM are subdivided into a readily decomposable pool and a resistant pool of lignified materials (Hansen et al., 2011).

3.2 Biomass variation

Based on the results obtained by Ek (2014), the mean annual increments (MAI) of 0.57–2.97 t/ha/year for a period of 13 to 16 years were revealed in Morogoro, Tanzania. However, this was smaller compared to the MAI of young or exploited miombo woodland (0.7 to 4.2 t/ha/year) in the same area. Elsewhere, Grundy (1995), observed the mean annual increment in the area protected from fire and human disturbance to be 0.27 cm−1 year−1. However, Chidumayo (2012), found a mean annual increment of 1.93m3 per ha of trees with stump height (0.3 m) and diameter 9 cm. In mature miombo woodland, the biomass increments are between 0.58 and 3 tons per ha, equivalent to 2-3% of above-ground biomass (Malimbwi & Mugasha, 2010). The increment is vigorously for the young miombo woodland which may range from 1.2 to 3.4 tons per ha, equivalent to 4–7% of above-ground biomass (CHAPOSA, 2002). The MAI in miombo woodland biomass depends on species composition, amount of rainfall, and soil factors (Chidumayo, 2014).

The annual carbon stock increments from selected miombo woodlands managed under participatory forest management (PFM) provide insight of the incremental C stock in miombo woodlands of Tanzania. These results are consistent with the mean annual increment (MAI) of above ground C storage reported elsewhere (Chidumayo, 2012). For example, Chidumayo (2012) reported 0.9 tCha−1 year−1 over 35-year-old miombo in Zambia, while Stromgaard (2012) reported 0.5tC ha−1 year−1 for 16-year-old miombo in northern Zambia. Williams et al. (2011) also reported 0.75tC ha−1 year−1 over 50-year-old miombo woodlands. These variations of incremental carbon stock can be related to species composition and climatic factors (Chidumayo, 2014).

Although the general increments of C stock in miombo woodlands are very small, these seem to be the general pattern for the vegetation type. According to (Chidumayo, 2014) miombo woodland has much less above-ground biomass per hectare than humid forest and proportionally less aboveground C stock on an area basis. It ranges from 17– 70 tons carbon/ha compared to 193–200 in equatorial forest (Bastien-Henri et al., 2010). On the other hand, the carbon pool in the soil and biodiversity may be much greater (Gibbs et al., 2007).

Based on these findings, it is very clear that the amount of carbon storage and sequestration depends on the level of incremental biomass. This is influenced by different factors including the age of the forests and management practices.

3.3 Comparison of biomass

The amount of C stored in the soil and in the woody biomass depends on the soil and vegetation type (Munishi et al., 2010). Recognizing that little is known of the carbon stocks in dry forests and woodlands, Tables 1 and 2 show the trends in C stocks in above ground living biomass from the major regions and selected African countries with dry forests and woodlands. It is quite clear that the eastern, southern and northern sub-regions of Africa that are covered by the dry forests and woodlands, have less above ground living woody biomass compared to western and central African tropical forests (McNicol, 2014). This is due to the inherently slow growth rates of dry forest and woodland species and the high levels of utilization (leading to high levels of deforestation). Because of the low above ground C stocks in the dry forests and woodlands, not much interest has been given to these areas compared to rainforests (Pan et al., 2011).

Table 1: Trends in C stocks in forest biomass 1990–2005

Region/sub-regions	Carbon in living biomass (Giga tonnes)		
	1990	2000	2005
Eastern and southern Africa	15.9	14.8	14.4
Northern Africa	3.8	3.5	3.4
Western and central Africa	46.0	43.9	43.1
Total Africa	65.7	62.2	60.9

Note: Giga tonne = 1 billion tonnes Source: Based on FAO (2005)

The potential of dry land ecosystems to sequester carbon has been estimated to be up to 0.4–0.6 billion tonnes of carbon per year (UNFCCC, 2006). Munishi et al., (2010) gave estimates of C sequestration in dry land ecosystems and concluded that such areas have a huge potential as C sinks. The large surface area of African dry forests and woodlands, albeit fragmented in places, gives CO2 sequestration in these systems some global significance. To demonstrate the potential of dry forests and woodlands to sequester C, there is need first to assess the C stock currently held and deforestation rates.

Table 2: Carbon stock values for selected vegetation types

Woodland types	Carbon stock (tonnes carbon per ha)
Congo-Guinea and Congo-Zambezian	160–209
Zambezian warm dry forests	88–97
Sudanian Savanna	56–78
Kalahari Highveld	22–34
Sahel with isolated shrubs	12–31.2
Somali-Masai	13–78
Degraded savanna and remnant forests	9–113

Source: Based on FAO (2007)

Table 3 shows that most of the variation in AGB density was explained by stands structure trait-based variables, jointly with diversity measures, highlighting the role of tree species dominance and species composition in determining patterns of tree biomass density. Dominance (or evenness) can directly affect C storage via species identity (dominant trait) and evenness (the frequency distribution of those traits), but also indirectly through its effect on species richness (e.g., competition), which, in turn, influences ecosystem processes (Shirima et al., 2015). These results are consistent with findings from hyper-diverse humid tropical forest sites, where both richness and dominance are important in explaining variation in tree biomass density (Ruiz-Jaen & Potvin 2010, Cavanaugh et al. 2014).

Hosonuma et al. (2012) reported that land use and management were not the driving influences determining the variation in AGB density. This result was surprising since it is expected land use to explain a larger share of the variation in biomass density. Hosonuma et al. (2012) identified three factors that may explain these findings. First, the dominant drivers of deforestation and forest degradation reducing AGB density are the slow expansion of subsistence agriculture, and the extraction of wood fuel, timber, and charcoal production. These drivers are likely to leave more residual trees on sites, and so biomass, than mechanized agriculture would. There would therefore, be more carbon distributed in the landscape generally, regardless of the land use. Second, AGB density is generally much lower in tropical dry forests than in humid tropical forests, so the differences in AGB density between the sites with or without human intervention is necessarily smaller than in the humid tropical forests. Third, there is evidence that Miombo forests are resilient to some intermediate level of disturbances (Chidumayo 2014, Jew et al. 2016).

For example, miombo woodlands in Tanzania having medium utilization levels retain key miombo species, and, maintain tree species diversity and C storage compared to low utilization sites Jew et al. (2016). In terms of C conservation and management, the limited contrast in biomass density between human-modified and natural sites highlights the potential for maintaining C in the landscape outside forestland, and for forests to be managed to fulfill multiple purposes.

Table 3: Carbon stock in forests and woodlands (living woody biomass) and annual forest area change (%) for selected African countries with dry forests and woodlands

Region/Country	Carbon stock (Megatonnes)	Annual forest areas change (%)
Southern Africa		
Botswana	141.5	–0.9
Malawi	161.0	–0.8
Mozambique	606.3	–0.2
Namibia	230.9	–0.8
South Africa	823.0	9 0
Eastern Africa		
Tanzania	2254.0	–1.0
Kenya	334.7	–0.3

Source: FAO (2007)

Table 4 shows that in the case of Zambia’s dry forests, different species contributed disproportionately to carbon storage, with Colophospermum mopane contributing the most to biomass density in deciduous forests, and Julbernardia paniculata and Brachystegia spiciformis in semi evergreen miombo forests. These defining miombo tree species have important adaptive features, including extensive root systems with ectomycorrhizal associations that enhance their ability to access limited soil nutrients, as well as high recovery rates following moderate disturbance from early dry season fires (Ryan and Williams 2011). A recent study suggests that, because of these characteristics, dominant miombo trees may be suppressing non-dominant species (Shirima et al. 2015). The “selection effect,” by which species with these particular traits are favored in comparison with other species without those traits, may therefore be an important mechanism at play in enhancing biomass density in these ecosystems (Dewees et al., 2010).

Table 4 :Tract level Biomass and Carbon stocks

BIOMASS AND CARBON STOCKS IN TONNES				
FAO LUC	AG Biomass (tonnes)	BG Biomass (tonnes)	Total Biomass (tonnes)	Carbon Stock (tonnes)
Evergreen Forest	209.8	50.4	260.2	122.3
Semi-evergreen Forest	17,306.70	4,153.60	21,460.30	10,086.30
Deciduous Forest	6,198.70	1,487.70	7,686.40	3,612.60
Other Natural Forests	45	9	54	25.4
Shrub Thickets	405.4	97.3	502.7	236.3
Wooded Grasslands	1,011.40	242.7	1,254.10	589.4
Grasslands	510.7	122.6	633.3	297.7
Marshlands	72.9	14.6	87.5	41.1
Annual Crop	879	211	1,090.00	512.3
Perennial Crops	26	5.2	31.2	14.7
Pasture	31.3	6.3	37.6	17.7
Fallow	577.5	138.6	716.1	336.6
Rural Built-up	78	15.6	93.6	44
Riverline areas	10.2	2	12.2	5.7
TOTAL	27,362.60	6,556.60	33,919.20	15,942.00

Source: ILUA Field Inventory 2010

4. CONCLUSION

This review paper has provided information on C dynamics in miombo woodlands. Therefore, this review paper was intended to provide information on biomass variation and comparison of biomass. The study has also contributed to the body of knowledge on factors that may affect the distribution of biomass at broader geographic scales and the varying levels of carbon with a view to contribute towards a better understanding of miombo woodlands. In light of this observation, it is envisaged that the results of this study would fill some gaps and at the same time make modest contributions to knowledge.

Other researchable area which needs further attention is the causes of variability in biomass density within forest ecosystems, which has been identified as an important knowledge gap.

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