

# **A review of the factors influencing changes on C dynamics in the miombo woodland ecosystems of Southern Africa**

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## **Abstract**

Provision of accurate carbon (C) measurements and analysis are critical components in quantification of C stocks. The objectives of this review are to (a) compile and synthesis current knowledge of available methods for C stock estimation (b) examine socio-economic drivers of land use and land cover change and their influence on woodland C stocks and (c) identify gaps of knowledge and methodological inadequacies in understanding factors affecting C stocks of major C pools namely: aboveground, belowground and soil C pools for miombo woodlands of Southern Africa. major C pools. We reviewed and evaluated a wide range of literature from peer reviewed articles. It was evident from the review that quantification of forest C is a challenging task, mainly associated with knowledge gaps and methodological challenges. This has brought about a high level of uncertainty and inconsistencies, mainly due to the accounting methods applied. We emphasise that comprehensive understanding of socio-economic drivers of land use and land cover change (LULCC) is necessary to ensure better informed sustainable forest

management policy direction, strategy and practice to deliver C and livelihood options. Furthermore, our view suggests that considerations of the inherent spatial heterogeneity of the landscape and stand density are necessary to ensure development of accurate C estimation methodologies when developing C models. Notwithstanding, developing widely applicable biomass models for Southern Africa requires detailed assessments of including different aspects of wood C fractions.

**Keywords:** Land Use, Land Cover Change, carbon stock, Phytomass, soil carbon, Climate-Smart

## **1. Introduction**

Increasing greenhouse gas (GHG) concentrations in the atmosphere create a threat to the global climate system and the environment. Intergovernmental Panel on Climate Change (IPCC) (2014) indicated that there is a strong, consistent, almost linear relationship between cumulative carbon dioxide (CO<sub>2</sub>) emissions and projected global temperature change to the year 2100. CO<sub>2</sub> is the main greenhouse gas (GHG) responsible for the global warming. Therefore, the importance of CO<sub>2</sub> to climate has provided the impetus for research on the global carbon (C) cycle with particular attention on C stocks in main terrestrial compartments, mainly soils and phytomass (Henry et al. 2009). Research that provides for measurement and monitoring C pools and fluxes in order to provide for prediction in changes in C concentrations and also the development of strategies for managing C becomes of paramount importance not only in the miombo woodlands of Southern Africa but in many other vegetation formations globally.

The terrestrial ecosystems, in which C is held in the living plant biomass (above and belowground biomass), decomposing organic matter and soil play a pivotal role in the global C

(C) cycle and their relation to human-induced changes have currently been widely acknowledged in many parts of the world (Pan et al. 2013). Studies on preservation and dynamics of C stocks in tropical ecosystems' major C pools *visa viz*: Miombo ecoregion (Syampungani and Chirwa 2011); Savannas (Lal 2008); Tropical forests (Gibbs et al. 2007) are becoming an increasingly important component of climate science especially in the context of increasing atmospheric CO<sub>2</sub> concentrations in the atmosphere. Furthermore, the impact of the land conversions and land cover change on the total C stocks held in the major terrestrial compartments (soils and phytomass) has resulted in increased interest in investigation (Henry et al. 2009). The terrestrial ecosystems' ability to mitigate climate change has triggered anxiety to consider soil organic C sequestration for possible emissions credit (Henry et al. 2009). This is mirrored by the number of initiatives advanced between and within countries for the purpose of effective and efficient mitigation of GHG emissions.

The need for accurate reporting of the C stocks across various vegetation types, land use and land cover is of great significance in undertaking C projects. However, accurate methodological applications in the assessment of C stock are lacking due to many factors such as; inappropriate accounting for spatial dynamics of most vegetation formations (Schmidt et al. 2011), absence of scientific data, inappropriate models and variation in sampling strategy (Vagen et al. 2005). The focus of this study is to explore and review literature related to C dynamics on woody biomass and soil C for the miombo woodland ecosystem in order to identify the existing knowledge gaps on existing C stock/biomass estimation models. The study objectives are to (a) compile and synthesis current knowledge of available methods for C stock estimation (b) examine socio-economic drivers of land use and land cover change and their influence on woodland C stocks and (c) identify gaps of knowledge and methodological inadequacies in understanding factors

affecting C stocks of major C pools for miombo woodlands of Southern Africa. We focus largely on Southern Africa, a target area best suited to provide baseline information on current knowledge base of carbon estimation methods for miombo woodlands. There is important knowledge-base on critical challenges in C estimation that can improve our methodological applications.

In the following sections, we first highlight miombo woodlands potential to recover and store C. We then highlight what we feel are the most pertinent knowledge gaps and methodological challenges that hamper development of accurate and reliable C estimation methods. The final section provides a summary of the main points and concluding remarks.

## **2. Miombo woodlands recovery and C storage potential**

Miombo woodland is capable of recovering quickly upon the cessation of anthropogenic disturbances. Miombo woodland species like many savanna species have vertical and horizontal extensive root system which facilitates recuperation after cutting (Mistry 2000). Miombo may develop from either stump coppices or root suckers or suppressed saplings present in the herbal layer at the time of clearing (Syampungani 2008, Handavu et al 2011). The high coppicing ability of miombo woodland makes it to be a high productive ecosystem as the developing shoots tend to establish quickly from already established root system (Geldenhuys 2005) and consequently important for C sequestration. In this regard, understanding C stores, how carbon stores change after disturbance, the rate and extent to which forests recover from disturbance along the recovery trajectory has important implications in the emerging C-based payment for ecosystem services (PES) (Mwampamba and Schwartz 2011), which has taken centre stage in the United Nations Framework Convention on Climate Change (UNFCCC) climate negotiations.

Miombo woodlands are dynamic landscapes, with significant importance as reservoirs of above and belowground C stocks (Ribeiro et al. 2013). Given that miombo woodlands play an importance role as a pool of above and belowground C, it presents significant prospects for execution of Reduced Emissions from Deforestation and Forest Degradation (REDD+) policies aimed at fostering environmental sustainability and socio-economic development (Grace et al. 2006; Williams et al. 2008; Munishi et al. 2010). Miombo ecoregion is considered to have high potential for C sequestration due to a number of reasons. Firstly, although the miombo ecoregion stores less C per hectare compared to tropical forests (du Preez 2014), it is one of the major vegetation formation in Africa and therefore, its extensive nature makes it possible for it to sequester large amounts of C from the atmosphere. Additionally, comparatively, miombo has higher stocking than many other dryland African forest and woodland formations (Table 1). The C storage in mature miombo is reported as follows; Kalaba et al (2013) reported  $39.6 \pm 1.5$  Mg C ha<sup>-1</sup> for Zambia, a figure higher than that reported in Tanzania by Shirima et al. (2011) and Munishi et al. (2010) i.e. 23.3 Mg C ha<sup>-1</sup> & 19.1 Mg C ha<sup>-1</sup> and Mozambique by Williams et al. (2008) ( $19.0 \pm 8.0$  Mg C ha<sup>-1</sup>). There is a marked difference in the reported figures above. This could be attributed to a number of factors such as use of generic models which may be insensitive to spatial heterogeneity of area and stand density, hence rendering the model's applicability in new sites be questionable.

**Table 1: Stocking and basal area of major woodlands types of Southern Africa**

<b>Range of variables</b>		<b>Vegetation type</b>	<b>Authors</b>
<b>Density</b> (stems/ha)	1121-6926	Re-growth (miombo)	Syampungani et al. 2010; Campbell et al. 1995; Strang, 1974)
	2434-2773	Uneven aged mature miombo woodland	Syampungani, 2008
	837-9700	Regrowth Kalahari woodland	Timberlake et al. 2010
<b>Basal area</b> (m <sup>2</sup> )	7-22	Uneven aged mature miombo woodland	Lowore et al. 1994; Freson et al. 1994
	30-50	Regrowth stand	Chidumayo, 1985; Grundy, 1995a
<b>Mean biomass</b> (Mgha <sup>-1</sup> )	1.5-90	Uneven aged mature woodlands (Miombo & Mopane)	Chidumayo, 1990, 1991; Tietema , 1989
	22-44.47	Uneven aged Woodland-Mopane woodland	Guy, 1981

Source: Adopted from Chirwa et al. 2011

The storage of C in miombo woodlands includes phytomass C and soil C (Lal 2005). Furthermore, Lal (2005) postulated that the total ecosystem C stock is enormous and in dynamic balance with the environment. As such, when these woodlands are cleared in preference for short-duration agricultural crops, it could lead to release of enormous quantities of CO<sub>2</sub> into the atmosphere equating to 50 Mg C ha<sup>-1</sup> or approximately 14 Pg C, if the entire miombo ecoregion were to be transformed (Desanker et al. 1997). This is potentially an enormous contribution relative to the prevailing annual global flux resulting from land use change, which accounts for an estimated total of 1.6 Pg C<sup>-1</sup> (IPCC 1996). On the other hand, Desanker et al. (1997) noted that, given a situation where miombo woodlands are managed for the purpose of maximizing C

storage, considerable amounts of C could be sequestered in biomass, soils and woodland products.

However, the Miombo woodlands are facing a variety of threats, including unsustainable timber harvesting, destructive fuel-wood collection, rampant charcoal production (Syampungani 2008) and bushfire, whose impact is attributed to timing and intensity in relation to phenology (Chidumayo 1997). This has given a continuum from untouched miombo to completely deforested area, as well as a continuum from agricultural fields to regenerated/reforested secondary forests. All these land-uses, with varying degrees of degradation and/or regeneration need to be understood in a C sequestration perspective to be able to understand their potential role and value in REDD and Clean Development Mechanism C trade arrangement (Walker and Desanker 2004).

## **2.1 Land-use systems and their implications on C stocks**

The emergence of land change science in the past two decades sought to understand the dynamics of human impacts on the earth through the changes in land use and land cover (Brown et al. 2013). Land use and cover change affects both the rate of C accumulation and the maximum amount of C that can be stored. The human population density across much of the miombo region are proportionately much higher than those of humid forests (Campbell, et al. 2007), implying that the more human activities, the more forces of woodland degradation, cover loss and consequently a continued downward trend in the C stock of forest biomass. As a result of mixed intensive and extensive land uses, miombo woodlands have wide-ranging land covers (Chirwa et al. 2008) including cropland, abandoned fields and fallow at various stages of recovery. These variations in land cover can influence the amount of biomass and C a woodland can hold. These land use practices to a larger extent have affected the spatial integrity of the

woodland which in turn has an effect on the C sequestration processes over time. As such, ignoring these drivers of change and the spatial variations in vegetation can produce inaccurate C stock estimates.

## **2.2 Uncertainties and opportunities in C stock assessments**

Assessment of vegetation and soil C stocks is an important issue in the context of escalated rates of increase in atmospheric CO<sub>2</sub> concentrations. A key challenge for successfully implementing REDD+ and similar mechanisms is the reliable estimation of biomass C stocks in tropical forests. The main challenge for C stock management is to comprehend the observed variation in vegetation and soil C stocks in woodlands, and use this knowledge to manage existing and new forests for better C storage (Williams et al. 2008).

### **2.2.1 Land use and land cover change dynamics**

Land-use and land cover change is dynamic in nature, whose effect may have positive and/or negative effect on vegetation dynamics and its potential for C storage. People's actions play a critical role in fostering release or sustaining forest C pools. In this regard, the characteristics of their actions are exhibited through the interaction of complex socioeconomic and political factors that drive land cover change. Notwithstanding, land tenure system too has a direct link to individualisation of decision-making process on land management (Smucker 2002). Having control over land, shapes the manner in which it will be used and the land users' willingness incur costs in implementing land management practices (Place 2009). The effect of land-use and land cover change is currently recognized as complex and driven by human activities. As such, there is need for comprehensive understanding of the complex interdependence of a human-environment system and its effect on C stock and overall ecosystem functioning.



Among the anthropogenic disturbance factors, deforestation is a major concern and has been identified as one priority area for regional action. According to Brown (2002), charcoal production and use of land for agriculture are the major drivers of deforestation and forest cover loss. The increasing rates of deforestation have diminished forests' capacity to act as CO<sub>2</sub> sinks (Lesolle 2012) whilst providing the ecosystem goods and services beneficial for sustainable livelihood. The available statistics on woodland cover of the miombo countries continue to show a decline in woodland cover (Luoga et al. 2005). Zimbabwe, Tanzania and Malawi had the highest rates of deforestation among six countries where miombo woodlands predominates (FAO 2011).

Campbell et al. (2007) attributed woodland cover loss to two major processes: wood extraction for energy and land clearing for agricultural purposes. Land under agriculture presents a number of mosaic land cover types, including cropland, abandoned fields and fallow at various stages of recovery all because of the nature of cultivation widely practiced in most parts of the Miombo ecoregion (Timberlake et al. 2010).

Houghton and Goodale (2004) noted that land-use changes bring about biogeochemical effects, through for example, modification of vegetation and soil C pools. Despite the overwhelming evidence of the impacts of these anthropogenic activities, the impact and implications of the spatial gradient of land use and land cover change on vegetation dynamics in miombo woodlands are less well characterised. The understanding of interactions between drivers of land cover change and vegetation hasn't been enhanced because of short-temporal and spatial scales of observation of much of the available studies (Ribeiro et al. 2012). Therefore, assessment of large-spatial and temporal-scale variation of vegetation production, disturbances and their

interactions are critical in understanding the existing data gaps that provide adequate understanding of the role of this crucial ecosystem in the global C budget.

### **2.2.2 Biomass and biomass assessment**

Terrestrial vegetation biomass plays an active role in shaping the environmental systems of the earth (Ni 2001). The above and belowground biomass are critical components of terrestrial ecosystem C stocks in the global terrestrial C cycling system. Therefore, accurate estimation of their size and dynamics is an essential input to climate change forecasting models and formulation of mitigation and adaptation strategies (FAO 2009).

#### **Woody biomass and associated models**

Aboveground and belowground biomass are important components of terrestrial ecosystem C stocks. However, it has been noted that precise forest biomass and C estimation is a complex endeavour requiring sound statistical formulations (Temesgen et al. 2015). Most of the studies on woody biomass models have been based on aboveground biomass (AGB). AGB varies across different land use practices and the miombo ecoregion in general due to varying environmental gradients and anthropogenic disturbances (Chidumayo 2002; Luoga et al. 2002). Sources of error in estimating forest biomass abound. For example, accuracy of biomass models depends to a large extent on the scope and extent of data used in development, on variability in biomass within population and the method applied to calibrate the model (Temesgen et al. 2015). Thus, sources of error can be considered to arise from three major phases of model development: sampling - arising from plot and tree selection due to the intrinsic variability in tree attributes such as wood density and crown architecture, measurement errors resulting from irregularities of tree form and instrument errors and model misspecification arising from method of model identification and calibration (Temesgen et al. 2015). Given this scenario, it evident that model

input variable, vegetation type, stocking density and geographical location from which the model is developed are critical components to improve the accuracy of biomass and C models.

Belowground biomass and C in root systems are other noteworthy components of the forest C pool that demand increased attention. These components are not tracked mainly not because they are expensive but also that techniques for biomass/C estimation are either lacking or poorly developed compared to aboveground tree components (Temesgen et al. 2015). Cias et al. (2011) noted that very few studies are available on root biomass because these studies are costly, time-consuming and difficult, implying a large uncertainty in the component of the inventories. The limited data available on root biomass studies is in some countries namely; Zambia (Chidumayo 2013); Tanzania (Malimbwi et al. 1994) and Zaire (now the Democratic Republic of Congo) (Malaisse and Strand 1973). Chidumayo (1995) estimated a total belowground biomass of 38.8 Mgha<sup>-1</sup>, accounting for 37% of the total biomass. Understanding the dynamics of root biomass, root profile and rooting depth is significant and rather critical if we are to improve our comprehension of the allocations and storage of C in terrestrial ecosystems (Bonan, 2002). There is need to explore the relationship that exist between root biomass and shoot biomass (Mokany et al. 2006). Furthermore, understanding aboveground C allocations, root profiles and root architecture is very essential for local, regional and global-scale assessment of major C pools.

However, ecotype-specific data on root biomass and root:stem relationship within the vast miombo is missing, implying a high level of uncertainty in C density estimates. Given the spatial heterogeneity of miombo woodlands, suggests that use of generic models may seem to compromise the accuracy and certainties of C allocation estimates. In this regard, there is need to develop models that are recognisant of variations in site, stand density and crown characteristics.

### **2.2.3 Soil organic C stores and fluxes**

Detailed comprehension of the content and allotment of the soil organic C (SOC) in a given area can provide ability to foretell and subsequently to moderate the adverse consequences of climate change (Shelukindo et al. 2014). Forest soils constitute a large pool of C. For example, recent studies (Ryan and Williams 2011, Woollen et al. 2012) indicated that the miombo woodland ecosystem soils act as C sinks because of the woodlands' ability to capture greater quantities of atmospheric C dioxide. Walker and Desanker (2004) indicated that soil C stocks in savanna woodlands exceed woody C stocks and for this reason, loss of C can be a significant flux when the woodland is cleared. Furthermore, IPCC (2000) indicated that releases of C from the soil pool, resulting from human activities such as deforestation and soil erosion, may to a greater extent increase the atmospheric concentration of GHGs. Lal (2004) noted that inclusion of Soil Organic C (SOC) storage in payment schemes is long recognised.

However, Stringer et al. (2012) observed that scientific evidence gaps are a limiting factor to the inclusion of SOC stores and fluxes in valuations of benefit resulting from land management practices. Key factors underpinning uncertainties, among others include: insufficient data on the amount, distribution and form of SOC; lack of empirical data, measurement challenges, methodological uncertainties and high variability of soil organic C (SOC) concentrations from within forest ecosystems (Stringer et al. 2012). IPCC (2003) suggested that since variation of SOC in soil is greater than in vegetation, greater sampling effort is needed. Ryan and Williams (2011) confirmed that soil C varied from 32 to 133tC/Ha and thus presenting major uncertainties in C storage. Reliable soil organic C data across the miombo eco-region are lacking because data is still at a coarse resolution (Stringer et al. 2012). Variability in SOC concentration within field or similar vegetation types is high. Therefore, a precondition to trustworthy C accounting and

evaluation of the linkages between SOC and other ecosystem services are precise information on SOC stores at a much refined scale. It is therefore recognized that detailed field data is needed in this era to enable monitoring of change in SOC storage and the development of modern soil C models (Schmidt et al. 2011).

Various methods of soil organic C analysis do exist (Cias et al. 2011). This presents critical variability in results thereby also posing challenges in accurate reporting of soil C. The variation in methods such as Loss-On-Ignition (LOI), Walkley-Black (wet oxidation - WO) and dry combustion contribute to the uncertainty in SOC estimates (Donovan 2013). It has been noted that even though the Walkley-Black procedure is being widely used in the assessment of soil C, results indicate that it does not completely oxidise organic C (mean recovery being 76%) (Schumacher 2002; Hoogsteen et al. 2015). The study by Hoogsteen et al. (2015) indicated that Loss-On-Ignition so far provides accurate estimation of SOM. However, Hoogsteen et al. (2015) indicated that, there is lack of consistency in literature with regards to the combination of ignition temperature and duration that should be applied to accurately determine SOM contents. For example, a wide variation exists as follows: Ignition temperature (300 – 850 °C: Abella and Zimmer 2007) and Ignition duration (2 – 28 hrs: Konen et al. 2002).

Additionally, variations in sampling strategy and soil analytical procedures for SOC have been observed to contribute to the uncertainty of SOC estimates in the sub-Saharan Africa (Vagen et al. 2005). In the miombo eco-region, different depths have been reported for the assessment of changes in SOC stocks. For example, some studies in the miombo ecoregion and other tropical forest types used; 0, 5, 15, 25 and 50 cm (Ryan et al. 2010) and 0-10, 0-20; 0-30 cm depths (Vagen et al. 2005). Other studies used 0-10, 10-20, 20-30 cm depth (Makipaa et al. 2012); 0-20 and 20-50cm (Walsh and Vagen 2006, Vagen et al. 2013); 0-10, 10-20, 20-40, 60-100 and 100-

150cm depths (Walker and Desanker 2004) respectively. There is need for more precise alternative sampling process to provide accurate SOC measurements (Stringer et al. 2012). Furthermore, variations in sampling techniques and soil analytical procedures for SOC are other compounding effects adding to the uncertainty of current estimates. The timing in sampling has been reported to influence SOC content in the savannah regions (Tiessen et al. 1998). Many studies do not indicate the season of sampling yet this is an important constraint to the interpretation of research results on SOC trends and processes in an ecosystem (Vagen et al. 2005).

#### **2.2.4 Conversion factor for wood C content in forest C accounting**

Investigating the prospects for forest C capture and storage demands accurate determination of C in live tree tissues. In this regard, necessary and accurate data on wood C content based on a broad spectrum of species is needed to inform forest C accounting in various forest types (Thomas and Martins 2012; Table 2). In order to accurately convert aboveground phytomass to C of various ecosystems, determining accurate species-specific C fractions in live wood is critical. However, this essential methodological consideration is largely ignored in forest C accounting (Asner 2011, Qureshi et al. 2012) and hence creating a knowledge gap. Most researchers claim that aboveground biomass (AGB) constitute 50 % C on a weight/weight basis and this value has been largely in estimating C pools and fluxes in natural tropical forests (Chave et al. 2008, Pyle et al. 2008, Saatchi et al. 2011).

However, Martins (2012) noted that to merely guess the generic C fractions in tropical woods tends to overestimate forest C stocks by ~3.3 – 5.3 %. Additionally, Lamtom and Savidge (2003), in their study of temperate forests observed that oven-drying wood samples prior to elemental analysis reduced wood C concentration by ~1.5 – 3.5 % and this is attributed to the

**Table 2: Summary data for mean stem wood C and mean volatile C fractions for angiosperms and conifers**

<b>Biome</b>	<b>Type</b>	<b>N (References)</b>	<b>N (Species)</b>	<b>Observed mean C fractions (%)</b>	<b>IPCC (2006) C fractions (%)</b>	<b>C<sub>vol</sub> (%)</b>
<b>Tropical</b>	Angiosperm	7	134	47.1 ±0.4	49	2.5 ±0.3
<b>Tropical</b>	Conifer	1	1	49.3	49	N.A
<b>Subtropical/ Mediterranean</b>	Angiosperm	3	18	48.1 ±0.9	49	N.A
<b>Subtropical/ Mediterranean</b>	Conifer	3	10	50.54 ±2.8	49	N.A
<b>Temperate/Boreal</b>	Angiosperm	10	54	48.8 ±0.6	48 ±2	1.3 ±0.6
<b>Temperate/Boreal</b>	Conifer	13	36	50.8 ±0.6	51 ±4	2.1 ± 1.4
<b>All biomes</b>	Angiosperm	N.A	206	47.7 ±0.3	N.A	2.3 ±0.3
<b>All biomes</b>	Conifer	N.A	47	50.8 ±0.8	N.A	2.1 ±1.4
<b>Complete dataset</b>	N.A	31	253	48.3 ±0.3	47	2.3 ±0.3

Source: Thomas and Martin 2012

volatile C fractions lost upon heating of samples. Martin (2012), observed that currently, there are no studies that analysed C concentrations in tropical woods that accounted for the volatile C fractions, thereby leaving a large gap in our knowledge of the C content in live tropical woods. The findings by Martins (2012) indicated that failing to account for volatile C fractions underestimates wood C concentration in tropical trees by approximately 2.5 % and that errors associated with overlooking species-specific wood C variations (and the volatile C fractions) was 4.1 - 6.8 Mg ha<sup>-1</sup>. Given the situation of miombo woodlands, where the vegetation is spatially heterogeneous, estimations based on ecotype and taking into consideration the volatile C fractions would be the best methodological application option. Ignoring this aspect may reduce the significance of floristic composition as a key determinant of forest C dynamics and thus may produce biased results in forest C inventories.

### **3. Conclusion**

The review has outlined evidence gaps of knowledge and methodological inconsistencies in understanding phytomass and soil C storage in Southern Africa. The challenges identified mainly have to do with complexities in understanding socio-economic drivers of land use and land cover, errors arising from three (3) major phases of model development namely; sampling errors, measurement errors and model misspecification. Therefore, the need to address these complexities and evidence gaps with reliable methodological approaches cannot be over emphasised. Assessing the potential for forest C capture and storage requires accurate assessment of C in live tree tissues and hence information on wood C content from a wide range of species is needed to inform forest C accounting. With regards to soil organic models, challenges identified relate to methodological problems, high variability of soil organic C



concentrations and that data remain at coarse resolution. These aspects too need the highest attention

Accurate estimate of C stocks requires improved and consistent methods for C quantification. An integrated understanding of C storage dynamics and the associated implications of land-use practices and land cover change in major C pools of miombo woodland is important ingredient for improved C accounting, which have of late taken centre stage in the United Nations Framework Convention on Climate Change (UNFCCC) negotiations. Additionally, there is need for in-depth understanding of the link between socio-economic attributes and local forest utilisation and how these can inform better management of the woodlands to enhance ecosystem functioning, ecosystem service provision and C storage.

From literature, it was noted that root phytomass studies are limited in miombo eco-region, thereby indicating a large area of uncertainty. A reliable assessment of roots of woody vegetation is an essential component of C accounting, in the sense that it helps to understand the rooting dynamics and possible contribution of the belowground phytomass to C inputs in a given ecosystem. Variations in methods of soil C assessments present great potential for uncertainties. Therefore, in order to abate major sampling challenges, there is need to develop standardised framework for sampling forest soils.

We emphasise that developing widely applicable biomass models for southern African miombo woodlands requires detailed assessments that provide answers to a series of key questions as: What are the major drivers of land use and cover change and can cover change be remotely assessed? What is the spatial heterogeneity of miombo vegetation and can this heterogeneity influence C dynamics? What methodological applications can improve accuracy of C stock

estimation? What are the possible implications of not including wood C fractions to the accuracy in C stock estimation for miombo woodlands? What are the potential opportunities of Climate-Smart agricultural practices in increasing phytomass and soil C stocks?

### **Conflict of interests**

The authors declare that there is no conflict of interests regarding the publication of this review paper.

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### **References**

- Abella SR, Zimmer BW. 2007. Estimating organic carbon from loss-on-ignition in northern Arizona forest soils. *Soil Science Society of America Journal* 71: 545–550.
- Asner GP. 2011. Painting the world REDD: addressing scientific barriers to monitoring emissions from tropical forests. *Environmental Research Letters* 6.
- Bonan G. 2002. *Ecological Climatology*. Cambridge University Press, Cambridge.
- Brown DG, Verburg PH, Pontius RG Jr, Lange MD. 2013. Opportunities to improve impact, integration and evaluation of land change models. *Current Opinion in Environmental Sustainability* 5(5): 452-457

- Brown S. 2002. Measuring carbon in forests: current status and future challenges. *Environmental Pollution* 116: 363-372.
- Campbell BM, Angelsen A, Cunningham A, Katerere Y, Siteo A, Wunder S. 2007. Miombo woodlands-opportunities and barriers to sustainable forest management. [www.cifor.cgiar/miombo/docs/Miombo2007.pdf](http://www.cifor.cgiar/miombo/docs/Miombo2007.pdf). Date accessed: 29/10/2015.
- Chave J, Olivier J, Bongers F, Chatelet P, Pierre-Michel F, van der Meer P, Norden N, Riera B, Charles-Dominique P. 2008. Above-ground biomass and productivity in a rain forest of eastern South America. *Journal of Tropical Ecology* 24: 355–366.
- Chidumayo EN. 1997. *Miombo Ecology and Management: An introduction*. Intermediate Technology Publishers, London.
- Chidumayo EN. 2002. Changes in miombo woodland structure under different land tenure and use systems in central Zambia. *Journal of Biogeography* 29: 1619-1626.
- Chidumayo EN. 2013. Estimating tree biomass and changes in root biomass following clear-cutting of *Brachystegia-Julbernardia* (miombo) woodland in central Zambia. *Environmental Conservation* 41 (1): 54–63.
- Chirwa PW, Syampungani S, Geldenhuys CJ. 2008. The ecology and management of the Miombo woodlands for sustainable livelihoods in southern Africa: the case for non-timber forest products, Southern Forests: *Journal of Forest Science* 70:3, 237-245.
- Chirwa PW, Syampungani S, Geldenhuys CJ. 2014. Managing Southern African woodlands for biomass production: The potential challenges and opportunities. In: *Bioenergy from Wood:*

*Sustainable Production in the Tropics*, Seifert, T (Ed.). Managing Forest Ecosystems, Volume 26: 67-87. Springer Publication.

Cias P, Bombelli A, William M, Piao SL, Chave J, Ryan CM, Henry M, Brender P, Valentini R. 2011. The carbon balance of Africa: synthesis of recent research studies. *Philosophical Transactions of the Royal Society* 369: 1-20

Desanker PV, Frost PGH, Frost CO, Justice CO, Scholes RJ (eds.). 1997. The Miombo Network: Framework for a Terrestrial Transect Study of Land-Use and Land-Cover Change in the Miombo Ecosystems of Central Africa, IGBP Report 41, *The International Geosphere-Biosphere Programme (IGBP)*, Stockholm, Sweden, 109 pp.

Donovan P. 2013. Measuring soil carbon change: a flexible, practical, local method. Available at: <http://soilCcoalition.org/files/MeasuringSoilCChange.pdf>. [accessed on 20 September 2015].

du Preez ML. 2014. Southern Africa's Dryland Forest, Climate Change, and the Water-Energy-Food Security Nexus. South African Institute of International Affairs, *Occasional Paper* 189

FAO. 2009. *Biomass: assessment of the status of the development of the standards for the terrestrial essential climate variables*. Global Terrestrial System Secretariat NRL, Food and Agriculture Organisation of the United Nations (FAO), 00153, Rome, Italy.

FAO. 2011. State of the world's forests. Rome (Available at: [www.fao.org/docrep/013/i2000e/i2000e.pdf](http://www.fao.org/docrep/013/i2000e/i2000e.pdf) [accessed on 28 August 2015])

Geldenhuys CJ. 2005. *Basic guidelines for silvicultural and management practices in Mozambique*. Report FW-04/05, FORESTWOOD cc, Pretoria. 78 pp.

- Gibbs H, Brown S, Niles J, Foley J. 2007. Monitoring and estimating tropical forest carbon stocks: Making REDD a reality. *Environmental Research Letters* 2 - 045023.
- Handavu F, Syampungani S, Chisanga E. 2011. The influence of stump diameter and height on coppicing ability of selected key Miombo woodland tree species of Zambia: A guide for harvesting for charcoal production *Journal of Ecology and the Natural Environment*. pp 461-468.
- Henry M, Valentini R, Bernoux M. 2009. Soil carbon stocks in ecoregions of Africa. *Biosciences Discussions* 6: 797 – 823.
- Hewitt M. 2007. How to search and critically evaluate research literature. The NIHR RDS for the East Midlands/Yorkshire and the Humber.
- Hoogsteen MJJ, Lantinga EA, Bakker EJ, Groot CJ, Tittonell PA. 2015. Estimating soil organic carbon through loss on ignition: effects of ignition conditions and structural water loss. *European Journal of Soil Science* 66: 320-328.
- Houghton RA, Goodale CL. 2004. Effects of LUC on the carbon balance of terrestrial ecosystems. In: DeFries, R.S., Asner, G.P. & R.A. Houghton, eds. *Ecosystems and Land-use Change*. American Geophysical Union. Washington, D.C.
- Intergovernmental Panel on Climate Change (IPCC). (2000). Watson R, Noble IR, Bolin B, Ravindranath NH, Verardo DJ, Dokken DJ. (Eds) *Land use, Land-use Change, and Forestry: A Special Report*. Cambridge University Press. Cambridge, UK.

Intergovernmental Panel on Climate Change (IPCC). 2003. Good practices guidance for land use, land-use change and forestry for global environmental strategies. Institute for Global Environmental Strategies, Japan.

Intergovernmental Panel on Climate Change (IPCC). 2014. Summary for Policymakers, In: *Climate Change* 2014, Mitigation of Climate Change. Contribution of Working Group III to the Fifth Assessment Report of the Intergovernmental Panel on Climate [Edenhofer, O., R. Pichs-Madruga, Y. Sokona, E. Farahani, S. Kadner, K. Seyboth, A. Adler, I. Baum, S. Brunner, P. Eickemeier, B. Kriemann, J. Savolainen, S. Schlömer, C. von Stechow, T. Zwickel and J.C. Minx (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Kalaba FK, Quinn CH, Dougill AJ, Vinya R. 2013. Floristic composition, species diversity and carbon storage in charcoal and agriculture fallows and management implications in miombo woodlands of Zambia. *Forest Ecology and Management* 304: 99 – 109.

Konen ME, Jacobs PM, Burras CL, Talaga BJ, Mason JA. 2002. Equations for predicting soil organic carbon using loss-on-ignition for North Central U.S. soils. *Soil Science Society of America Journal* 6: 1878–1881.

Lal, R. 2004. Soil carbon sequestration impacts on global climate change and food security. *Science* 304: 1623-1627.

Lal R. 2005. Forest soils and carbon sequestration. *Forest Ecology and Management* 220: 242-258.

- Lal R. 2008. Savannas and Global Climate Change: source or sink of atmospheric carbon dioxide. In: Faleiro, G.F., Lopes, A., Neto, D.F. (Eds.), *Savannas Desafios e estrategias para o equilibrio entre sociedade, agronegocio e recursos naturais*. Embrapa Cerrados, Planaltina, pp. 81-102.
- Lamlom SH, Savidge RA. 2003. A reassessment of carbon content in wood: variation within and between 41 North American species. *Biomass and Bioenergy* 25:381-388
- Lesolle D. 2012. SADC Policy paper on climate change: assessing policy options for SADC member states. Available at: [www.sadc.int/REDD/index.php/download\\_file/134/](http://www.sadc.int/REDD/index.php/download_file/134/) [ Accessed on 31 August 2015].
- Luoga EJ, Witkowski ETF, Balkwill K. 2002. Harvested and standing wood stocks in protected and communal miombo woodlands of eastern Tanzania. *Forest Ecology and Management* 164: 15-30.
- Luoga EJ, Witkowski ETF, Balkwill K. 2005. Land cover and use changes in relation to the institutional framework and tenure of land and resources in eastern Tanzania miombo woodlands. *Environment, Development and Sustainability* 7:71-93
- Makipaa R, Liski J, Guendehou S, Malimbwi R, Kaaya A. 2012. *Soil carbon monitoring using surveys and modelling: General description and application in the United Republic of Tanzania*. Food and Agriculture Organization of the United Nations, FAO Forestry Paper, 168.
- Malaisse FP, Strand MA. 1973. A preliminary miombo forest seasonal model. In: Kern, L (ed), *Modelling forest ecosystems*. IBP Woodland Workshop, Oak Ridge, USA, pp. 291-295.

- Malimbwi RE, Solberg B, Luoga E. 1994. Estimation of biomass and volume in miombo woodland at Kitulangalo Forest Reserve, Tanzania. *Journal of Tropical Forest Science* 7: 230-242.
- Martin AR. 2012. Interspecific and size-dependent variation in carbon concentration and wood chemical traits of tropical trees. PhD Thesis, University of Toronto.
- Mistry J. 2000. *World Savannas: Ecology and Human Use*. Pearson Education Limited, Edinburgh
- Mokany K, Raison RJ, Prokushkin AS. 2006. Critical analysis of root:shoot ratios in terrestrial biomes. *Global Change Biology* 12: 84–96, doi: 10.1111/j.1365 2486.2005.001043.x
- Munishi PKT, Mringi S, Shirima DD, Linda SK. 2010. The role of the Miombo Woodlands of the Southern Highlands of Tanzania as carbon sinks. *Journal of Ecology and the Natural Environment* 2(12): pp. 261-269.
- Mwampamba TH, Schwartz MW. 2011. The effect of cultivation history on forest recovery in fallows in the Eastern Arc Mountain, Tanzania. *Forest Ecology and Management* 261:1042 – 1052
- Pan Y, Birdsey RA, Phillips OL, Jackson RB. 2013. The structure, distribution and biomass of the world's forests. *Annual Reviews of Ecology, Evolution and Systematics* 44: 593-622
- Place F. 2009. Land tenure and agricultural productivity in Africa: a comparative analysis of the economics literature and recent policy strategies and reforms. *World Development* 37: 1326-1336.



- Pyle EH, Santoni GW, Nascimento HEM, Hutrya LR, Vieira S, Curran DJ, van Haren J, Saleska SR, Chow VY, Carmago PB, Laurance WF, Wofsy SC. 2008. Dynamics of carbon, biomass, and structure in two Amazonian forests. *Journal of Geophysical Research* 113: G00B08.
- Qureshi A, Pariva RB, Hussain SA. 2012. A review of protocols used for assessment of carbon stock in forested landscapes. *Environmental Science and Policy* 16: 81–89.
- Ribeiro N, Cumbana M, Mamugy F, Chaúque A. 2012. Remote Sensing of Biomass in the Miombo Woodlands of Southern Africa: Opportunities and Limitations for Research. In: Fatoyinbo L. (ed.) *Remote Sensing of Biomass – Principles and Applications*. Rijeka: InTech. p77-98.
- Ribeiro NS, Matos CN, Moura IR, Washington-Allen RA, Ribeiro AI. 2013. Monitoring vegetation dynamics and carbon stock density in miombo woodlands. *Carbon Balance and Management* 2013 8:11
- Ryan CM, Williams M. 2011. How does fire intensity and frequency affect miombo woodland tree populations and biomass? *Ecological Applications* 21(1): 48-60.
- Ryan CM, Williams M, Grace J. 2010. Above- and belowground carbon stocks in a Miombo Woodland Landscape of Mozambique. *Biotropica*: 1-10, 10.1111/j.1744-7429.2010.00713
- Saatchi SS, Harris NL, Brown S, Lefsky M, Mitchard ETA, Sales W, Zutta BR, Buermann W, Lewis SL, Hagen S, Petrova S, White L, Silman M, Morel A. 2011. Benchmark map of forest carbon stocks in tropical regions across three continents. *Proceedings of the National Academy of Sciences, USA* 108:9899 - 9904.

- Schmidt MWI, Torn MS, Abiven S, Dittmar T, Guggenberger G, Janssens IA, Kleber M, Koegel-Knabner I, Lehmann J, David AC, Manning DAC, Nannipieri P, Rasse DP, Weiner S, Susan E, Trumbore SE. 2011. Persistence of soil organic matter as an ecosystem property. *Nature* 478: 49 - 56
- Schumacher BA. 2002. *Methods for the determination of total organic carbon (TOC) in soils and sediments*. NCEA-C, 1282, United States Environmental Protection Agency, Environmental Sciences Division National Exposure Research Laboratory
- Shelukindo HB, Semu E, Msanya BM, Singh BR, Munishi PKT. 2014. Soil organic carbon stocks in the dominant soils of the Miombo woodland ecosystem of Kitonga Forest Reserve, Iringa, Tanzania. *International Journal of Agricultural Policy & Research* 2: 167-177.
- Shirima DD, Munishi PKT, Lewis SI, Burgess ND, Marshall AR, Balmford A, Swetnam RD, Zahabu EM. Carbon storage, structure and composition of miombo woodlands in Tanzania's Eastern Arc Mountains. *African Journal of Ecology* 49:332 – 342.
- Smucker T. 2002. *Land Use Change Impacts and Dynamics (LUCID) Project Working Paper # 11*, Nairobi, Kenya, International Livestock Research Institute.
- Stringer LC, Dougill AJ, Thomas AD, Spracklen V, Chesterman S, Ifejika Speranza C, Rueff H, Williams M, Beedy T, Abson DJ, Klintonberg P, Syampungani S, Powell P, Palmer AR., Seely MK, Mkwambisi DD, Falcao M, Siteo A, Ross S, Kopolu G. 2012. Challenges and opportunities in linking carbon sequestration, livelihoods and ecosystem service provision in drylands. *Environmental Science & Policy* 19-20: 121-135.

- Syampungani S. 2008. Vegetation Change Analysis and Ecological Recovery of the Copperbelt Miombo woodlands of Zambia. PhD Thesis, University of Stellenbosch, RSA.
- Syampungani S, Chirwa PW. 2011. Miombo Woodland Productivity: The potential contribution to carbon sequestration and payment for environmental services (PES) in East and Southern Africa. In: Wallace, E.B. (ed.), *Woodlands Ecology, Management and Conservation*. New York, Nova Science Publishers, Inc. pp. 185-201.
- Temesgen H, Affleck D, Poudel K, Gray A, Sessions J. 2015. A review of the challenges and opportunities in estimating above ground forest biomass using tree-level models. *Scandinavian Journal of Forest Research*, 30(4), 326-335.
- Thomas SC, Martin AR. 2012. Carbon content of tree tissues: a synthesis. *Forests* 3:332-352.
- Tiessen H, Feller C, Sampaio EVSB, Garin P. 1998. Carbon sequestration and turnover in semiarid savannas and dry forests. *Climate change* 40: 105-117.
- Timberlake J, Chidumayo E, Sawadogo L. 2010. Distribution and characteristics of African dry forests and woodlands. In: Chidumayo E, Gumbo DJ (eds) *The dry forests and woodlands of Africa: managing for products and services*. Earthscan, London, UK
- Vagen TG, Lal R, Singh BR. 2005. Soil carbon sequestration in sub-Saharan Africa: A review. *Land Degradation and Development* 16: 53 - 71
- Vagen TG, Winowiecki L, Tondoh JE. 2013. The land degradation surveillance framework. Field guide. Available at: [http://www1.cifor.org/fileadmin/subsites/sentinel-landscapes/document/LDSF\\_Field\\_Guide.pdf](http://www1.cifor.org/fileadmin/subsites/sentinel-landscapes/document/LDSF_Field_Guide.pdf) . [accessed on 3 August 2016].

- Walker SM, Desanker PV. 2004. The impact of land use on soil carbon in miombo woodlands of Malawi. *Forest Ecology and Management* 203: 345–360.
- Walsh MG, Vagen TG. 2006. *The land degradation surveillance framework*. Guide to field sampling and measurement procedures. World Agroforestry Centre, Nairobi, Kenya.
- Williams M, Ryan CM, Rees RM, Sambane E, Fernandoa J, Grace J. 2008. Carbon sequestration and biodiversity of re-growing miombo. *Forest Ecology and Management* 254:145–155
- Woollen E, Ryan CM, Williams M. 2012. Carbon stocks in an African woodland landscape: Spatial distributions and scales of variation. *Ecosystems* 15: 804-818.