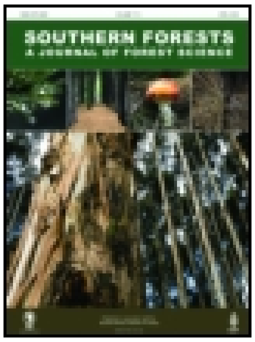

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A review of carbon dynamics and assessment methods in the miombo woodlands[§]

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Review Paper

A review of carbon dynamics and assessment methods in the miombo woodlands§

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Provision of accurate carbon (C) measurements and analysis are critical components in quantification of C stocks. The objectives of this review were to (1) compile and synthesise current knowledge of available methods for C stock estimation, (2) examine socio-economic drivers of land-use and land-cover change and their influence on woodland C stocks and (3) identify gaps of knowledge and methodological inadequacies in understanding factors affecting C stocks of major C pools for miombo woodlands of southern Africa. The review shows 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. Furthermore, it is necessary to consider the inherent spatial heterogeneity of the landscape and stand density in order to ensure development of accurate C estimation methodologies when developing C models. Ultimately, developing widely applicable biomass models for southern Africa will require detailed assessments, including different aspects of wood C fractions. It is evident from the review that a comprehensive understanding of socio-economic drivers of land-use and land-cover change is necessary to ensure better-informed sustainable forest management policy direction, strategy and practice to deliver C and livelihood options.

Keywords: carbon stock, climate-smart, land cover change, land use, phytomass, soil carbon

Introduction

Increasing greenhouse gas (GHG) concentrations in the atmosphere create a threat to the global climate system and the environment. The Intergovernmental Panel on Climate Change (IPCC 2014) indicated that there is a strong, consistent, almost linear relationship between cumulative carbon dioxide (CO_2) emissions and projected global temperature change to the year 2100. Carbon dioxide is the main GHG responsible for global warming. Therefore, the importance of CO_2 to climate has provided the impetus for research on the global carbon (C) cycle with particular attention on C stocks in the main terrestrial compartments, mainly soils and phytomass (Henry et al. 2009). Research that provides for measurement and monitoring of C pools and fluxes in order to provide for prediction in changes in C concentrations coupled with the development of strategies for managing C becomes paramount in many vegetation formations globally, including the miombo woodlands of southern Africa.

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 cycle. In addition, their relation to human-induced changes have currently been widely acknowledged in many parts of the world as contributing to climate change (Pan et al. 2013). Studies on the preservation and dynamics of C stocks in tropical ecosystems' major C pools *vis-à-vis* the miombo ecoregion (Syampungani and Chirwa 2011), savannas (Lal 2008) and tropical forests (Gibbs et al. 2007) are becoming an increasingly important component of climate science, especially in the context of increasing atmospheric CO_2 concentrations. Furthermore, the impacts of land-use conversion and land-cover change have resulted in an increased interest in the total C stocks held in the major terrestrial compartments (phytomass and soils) (Henry et al. 2009). The terrestrial ecosystems' ability to mitigate climate change especially through soil organic C sequestration has also triggered interest to consider soil organic C for possible emissions credit (Henry et al. 2009). This is mirrored by the number of initiatives advanced between and within countries for effective and efficient mitigation of GHG emissions.

The need for accurate reporting of the C stocks across various vegetation, land-use and land-cover types is of great significance in accounting for C contribution in 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 (Vågen et al. 2005). The main objective of this review was to explore literature related to C dynamics on woody biomass and soil C for the miombo woodland ecosystem of southern Africa. Specifically, the objectives were to (1) compile and synthesise current knowledge of available methods for C stock estimation, (2) examine socio-economic drivers of land-use and land-cover change and their influence on woodland C stocks and (3) identify gaps of knowledge and methodological inadequacies in understanding factors affecting C stocks of major C pools for miombo woodlands of southern Africa.

Miombo woodlands recovery and C storage potential

Miombo woodland is capable of recovering quickly upon the cessation of anthropogenic disturbances. Miombo woodland species, similar to many savanna species, have vertical and horizontal extensive root systems that facilitate recovery 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 species make it a highly productive ecosystem as the developing shoots tend to establish quickly from the already established root system (Geldenhuys 2005). In this regard, understanding C storage, how C stocks change after disturbance, and 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). Indeed, PES 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 important 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). The 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 with tropical forests (du Preez 2014), it is one of the major vegetation formations in Africa and, therefore, its extensive nature makes it possible for it to sequester large amounts of C from the atmosphere. In addition, miombo has comparatively 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 ± 1.5 Mg C ha^{-1} for Zambia, a figure higher than that reported in Tanzania by Munishi et al. (2010) and Shirima et al. (2011), i.e. 23.3 Mg C ha^{-1} and 19.1 Mg C ha^{-1}, respectively, and in Mozambique by Williams et al. (2008) (19.0 ± 8.0 Mg C ha^{-1}). The marked difference in the reported figures could be attributed to a number of factors, such as use of generic models that may be insensitive to spatial heterogeneity of area and stand density, hence rendering the model's applicability in new sites to be questionable.

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 the release of enormous quantities of CO_2 into the atmosphere equating to 50 Mg C ha^{-1} 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^{-1} (IPCC 1996). On the other hand, Desanker et al. (1997) noted that, given a situation where miombo woodlands are managed for the purpose of maximising 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 bushfires, whose impact is attributed to timing and intensity in relation to phenology (Chidumayo 1997). This has generated a continuum from untouched miombo to completely deforested areas, as well as a continuum from agricultural fields to regenerated/reforested secondary forests. All of 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).

Table 1: Stocking and basal area of major woodlands types of southern Africa. Adapted from Chirwa et al. (2011)

Variable	Range	Vegetation type	References
Density (stems ha^{-1})	1 121–6 926	Regrowth (miombo)	Strang (1974), Campbell et al. (1995), Syampungani et al. (2010)
	2 434–2 773	Uneven aged mature miombo woodland	Syampungani (2008)
	837–9 700	Regrowth Kalahari woodland	Timberlake et al. (2010)
Basal area (m^2)	7–22	Uneven aged mature miombo woodland	Freson et al. (1994), Lowore et al. (1994)
	30–50	Regrowth stand	Chidumayo (1985), Grundy (1995a)
Mean biomass (Mg ha^{-1})	1.5–90	Uneven aged mature woodlands (miombo and mopane)	Chidumayo (1990, 1991), Tietema (1989)
	22–44.47	Uneven aged woodland–mopane woodland	Guy (1981)

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 is proportionately much higher than that 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.

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_2 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).

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 impacts on vegetation dynamics and the 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 socio-economic and political factors that drive land-cover change. Notwithstanding, the land tenure system also has a direct link to individualisation of the decision-making process on land management (Smucker 2002). Having control over land shapes the way it will be used and the land users' willingness to incur costs in implementing land management practices (Place 2009). The effect of land-use and land-cover change is currently recognised 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_2 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 predominate (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 has not been enhanced because of short-temporal and spatial scales of observation of many 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.

Biomass, biomass assessment and associated models

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).

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 studies on woody biomass models have been based on aboveground biomass. Aboveground biomass 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 largely on the scope and extent of data used in development, within-population variability in biomass 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 is evident that model input variables, 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 because they are expensive, but also that techniques for biomass/C estimation are either lacking or poorly developed compared with aboveground tree components (Temesgen et al. 2015). Ciais 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. In southern Africa, limited studies on root biomass have been reported from Zambia (Chidumayo 2013), Tanzania (Malimbwi et al. 1994) and the Democratic Republic of Congo (Malaisse and Strand 1973). Chidumayo (1995) estimated total belowground biomass of 38.8 Mg ha^{-1} in Zambia accounting for 37% of the total biomass. Understanding the dynamics of root biomass, root profile and rooting depth is significant and 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 exists between root biomass and shoot biomass (Mokany et al. 2006). Furthermore, understanding belowground C allocations, root profiles and root architecture is 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 ecosystem are missing, implying a high level of uncertainty in C density estimates. Given the spatial heterogeneity of miombo woodlands, the use of generic models may seem to compromise the accuracy and certainties of C allocation estimates. In this regard, there is a need to develop models that are recognisant of variations in site, stand density and crown characteristics.

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) indicate that the miombo woodland ecosystem soils act as C sinks because of the woodlands' ability to capture greater quantities of atmospheric CO_2. 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 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 benefits resulting from land management practices. Key factors underpinning uncertainties, among others, include the following: insufficient data on the amount, distribution and form of SOC; lack of empirical data; measurement challenges; methodological uncertainties; and high variability of SOC concentrations from within forest ecosystems (Stringer et al. 2012). Given that variation of SOC in soil is spatially greater than C stored in above- and belowground phytomass (Scharlemann et al. 2014), greater sampling effort is needed. Ryan and Williams (2011) confirmed that soil C varies from 32 to 133 t C ha^{-1} and thus presents major uncertainties in C storage. Reliable soil organic C data across the miombo ecoregion are lacking because data are 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 is precise information on SOC stores at a much refined scale. It is therefore recognised that detailed field data are needed on present-day SOC stores to enable monitoring of change in SOC storage and the development of modern soil C models (Schmidt et al. 2011).

Various methods of SOC analysis exist (Ciais 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, Walkley–Black (wet oxidation) and dry combustion, contribute to the uncertainty in SOC estimates (Donovan 2013). It has been noted that even though the Walkley–Black procedure is widely used in the assessment of soil C, results indicate that it does not completely oxidise organic C (mean recovery is 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 soil organic matter. 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 soil organic matter contents. For example, wide variation exists in ignition temperature (300–850 °C; Abella and Zimmer 2007) and ignition duration (2–28 h; Konen et al. 2002).

In addition, variation in sampling strategy and soil analytical procedures for SOC have been observed to contribute to the uncertainty of SOC estimates in sub-Saharan Africa (Vågen et al. 2005). In the miombo ecoregion, 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 and 0–30 cm depths (Vågen et al. 2005). Other studies used 0–10, 10–20 and 20–30 cm depths (Makipaa et al. 2012), 0–20 and 20–50 cm depths (Walsh and Vågen 2006; Vågen et al. 2013), and 0–10, 10–20, 20–40, 60–100 and 100–150 cm depths (Walker and Desanker 2004). Therefore, there is need for a more precise alternative sampling process to provide accurate SOC measurements (Stringer et al. 2012). Furthermore, variation in sampling techniques and soil analytical procedures for SOC are other compounding effects adding to the uncertainty of current estimates. Finally, the timing in sampling has been reported to influence SOC content in savanna 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 (Vågen et al. 2005).

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 are needed to inform forest C accounting in various forest types (Thomas and Martin 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 creates a knowledge gap. Most researchers claim that aboveground biomass constitutes 50% C on a weight/weight basis and this value has been largely used in estimating C pools and fluxes in natural tropical forests (Chave et al. 2008; Pyle et al. 2008; Saatchi et al. 2011).

However, Martin (2012) noted that to merely guess the generic C fractions in tropical woods tends to overestimate forest C stocks by approximately 3.3–5.3%. In addition, Lamlom and Savidge (2003), in a study of temperate forests, observed that oven-drying wood samples prior to elemental analysis reduced wood C concentration by approximately 1.5–3.5% and this is attributed to the volatile C fractions lost upon heating of samples. Martin (2012) observed that, currently, no studies have 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 Martin (2012) indicated that failing to account for volatile C fractions underestimates wood C concentration in tropical trees by approximately 2.5% and the errors associated with overlooking species-specific wood C variations (and the volatile C fractions) was 4.1–6.8 Mg ha^{-1}. The miombo woodlands vegetation is spatially heterogeneous, hence 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.

Conclusion

This review has outlined evidence gaps of knowledge and methodological inconsistencies in understanding phytomass and soil C storage in southern Africa. The challenges identified mainly are associated with complexities in understanding socio-economic drivers of land use and land cover, and errors arising from three 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 regard to soil organic C models, challenges identified relate to methodological problems, high variability of soil organic C concentrations and that data remain at coarse resolution. These aspects also need the highest attention.

Accurate estimation 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 an important ingredient for improved C accounting, which have of late taken centre stage in the UNFCCC negotiations. In addition, understanding C stores, associated changes and recovery after disturbance has important implications in the emerging C-based PES schemes. There is also 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 the miombo ecoregion, 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

Table 2: Summary data for mean stem wood carbon (C) and mean volatile C fraction (C_{vol}) for angiosperms and conifers. Source: Thomas and Martin (2012)

Biome	Type	*N* (references)	*N* (species)	Observed mean C fractions (%)	IPCC (2006) C fractions (%)	C_{vol} (%)
Tropical	Angiosperm	7	134	47.1 ± 0.4	49	2.5 ± 0.3
Tropical	Conifer	1	1	49.3	49	NA
Subtropical/ Mediterranean	Angiosperm	3	18	48.1 ± 0.9	49	NA
Subtropical/ Mediterranean	Conifer	3	10	50. 54 ± 2.8	49	NA
Temperate/Boreal	Angiosperm	10	54	48.8 ± 0.6	48 ± 2	1.3 ± 0.6
Temperate/Boreal	Conifer	13	36	50.8 ± 0.6	51 ± 4	2.1 ± 1.4
All biomes	Angiosperm	NA	206	47.7 ± 0.3	NA	2.3 ± 0.3
All biomes	Conifer	NA	47	50.8 ± 0.8	NA	2.1 ± 1.4
Complete data set	NA	31	253	48.3 ± 0.3	47	2.3 ± 0.3

the rooting dynamics and possible contribution of the belowground phytomass to C inputs in a given ecosystem. Variation in methods of soil C assessments present great potential for uncertainties. Therefore, in order to abate major sampling challenges, there is a need to develop a standardised framework for sampling forest soils.

We emphasise that developing widely applicable biomass models for miombo woodlands requires detailed assessments that provide answers to a series of key questions posed from this review: 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?

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