Forest Ecology and Management 417 (2018) 184–196

Contents lists available at ScienceDirect

Forest Ecology and Management

journal homepage: www.elsevier.com/locate/foreco

Species-specific allometric models for estimation of the above-ground carbon stock in miombo woodlands of Copperbelt Province of Zambia

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ARTICLE INFO

Keywords:
Carbon stock
Allometric models
Miombo woodlands

ABSTRACT

Substantial amounts of carbon have been known to be stored in the miombo woodlands, which are the most widespread dry forests in the African biosphere. Efforts to get precise estimates of carbon stock in the miombo woodlands are limited by a general lack of models for estimating carbon stock. This study aimed at developing species-specific allometric models for estimating aboveground carbon stock (AGC) in Copperbelt miombo woodlands of Zambia. A total of 60 individual trees representing 4 tree species were destructively harvested for carbon analysis by Ash method. Allometric models relating diameter at breast height (DBH), total tree height (H) and basic wood density (ρ) to the AGC in form of Log_{10} (AGC) = a + b ($Log_{10}X_1$) + c ($Log_{10}X_2$) + d ($Log_{10}X_3$) were developed using Ordinary Least Squares (OLS) estimation method. Models with DBH alone performed better than those with DBH along with H and/or ρ. Evaluation of model performance was done by using R^2 (Coefficient of determination), AIC (Akaike Information Criterion), Root Mean Square Error (RMSE) and the Mean Percentage Error (MPE%). Computation of MPE%, R^2 and RMSE was based on the results from the *k*-fold cross validation technique. R^2, RMSE and MPE% values for the selected models ranged from 77.3% to 98.4%, 0.065 to 0.169 and −6.09 to 1.35% respectively. Model performance and evaluation of other previously developed general and species-specific models in our dataset depicts that the models in the present study are acceptable to be applied to species in areas with similar climatic conditions. The models developed will serve as an important tool for predicting and monitoring carbon pool sizes in long-term studies. They can also be used to establish conservative carbon stock schemes required to determine avoided emissions in performance-based payment schemes.

1. Introduction

Miombo ecoregion is an important biome covering about 10% of the Africa land area (c: a 2.5–4 million km^2) (White, 1983; Millington et al., 1994). According to Kalinda et al. (2008) and Stringer et al. (2012), miombo woodlands are the most widespread dry forests of Africa which are subdivided into wet (occurs in areas with annual precipitation above 1000 mm) and dry (found in areas with annual precipitation below 1000 mm) miombo woodlands (White, 1983; Chidumayo, 1987). Dry miombo woodlands are dominated by canopy tree species such as *Brachystegia boehmii*, *Brachystegia spiciformis* and *Julbernardia globiflora* whereas widely distributed canopy tree species such as *Brachystegia floribunda*, *Brachystegia longifolia*, *Brachystegia wangermeeana*, *Julbernardia paniculata*, *Isoberlinia angolensis* and *Marquesia macroura* dominates wet miombo woodlands (Fanshawe, 1971; Chidumayo, 1987).

Miombo woodlands are rich in plant diversity, with about 8500 species of higher plants, 54% of which are endemic (Chirwa et al., 2008), making them one of the world's high biodiversity hotspots (Mittermeier et al., 2003). Significantly, miombo woodlands acts as either source of carbon dioxide due to land use change (such as clearing land for charcoal production, agriculture) or sink for carbon dioxide (Syampungani & Chirwa, 2011). They have great potential to minimise the carbon dioxide content of the atmosphere. Stromgaard (1985), Frost (1996), Chidumayo (1997) and Williams et al. (2008) reported miombo woodlands to sequester carbon of between 0.5 and 0.9 t ha^{-1} yr^{-1}. On the other hand, Kalaba et al. (2013) reported mature miombo to store carbon of 39.6 ± 1.5 Mg C ha^{-1} for Zambia, a figure higher than what was reported in Tanzania by Munishi et al. (2010) and Shirima et al. (2011) as well as in Mozambique by Williams et al. (2008) i.e. 23.3 Mg C ha^{-1}, 19.1 Mg C ha^{-1} and 19.0 ± 8.0 Mg C ha^{-1} respectively.

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https://doi.org/10.1016/j.foreco.2018.02.044
Received 23 May 2017; Received in revised form 26 February 2018; Accepted 26 February 2018
0378-1127/

However, subjecting these woodlands to frequent disturbance through fires and land clearance leads to forest degradation (Frost, 1996; Chidumayo, 2002). On the other hand, sustainable management would maximise carbon storage which can take up 6–10 Petagram (10^{15} g) of carbon (Scholes et al., 1996).

Carbon sequestration has in recent past gained a considerable attention worldwide due to its commoditization. This is as a result of emissions of greenhouse gases from land-use, land-use change and forestry (LULUCF) which account for about 12.5% of global emissions (Baccini et al., 2012; Houghton et al., 2012). Deforestation and forest degradation account for 17.4% of the world's greenhouse gas emissions (Bhishma et al., 2010). Globally, about 500 gigatonnes of carbon are stored in terrestrial vegetation (Bhishma et al., 2010). The interest in understanding the capability of forest ecosystems in developing countries to sequester and store carbon has been heightened (Walker & Desanker, 2004). Various international agreements such as the Kyoto protocol are behind the impetus for developing an understanding of carbon sequestration ability of many woodlands and forests in the developing world (UNFCCC, 1997). Furthermore, the Paris Agreement supports forest restoration as it has placed forests at the centre-stage. It further encourages balancing of emissions of carbon dioxide through the removals of carbon since forest naturally keep carbon out of the atmosphere (UNFCCC, 2015).

This, however, requires developing carbon stock allometric models for carbon accounting in the forest which is one of the most crucial steps for a successful implementation of Reducing Emissions from Deforestation and forest Degradation, as well as conservation, sustainable management of forests and enhancement of forest carbon stock (REDD+) initiatives (Bhishma et al., 2010) which avails a framework which benefit developing countries financially rewarded for the reduction of carbon emissions (Kachamba et al., 2016). This requires developing reliable models for estimating carbon stock across different land uses (Chave et al., 2004; Mugasha et al., 2013). However, models quantifying total carbon stock in the miombo ecoregion are very scarce.

A number of studies have concentrated on biomass models and not on carbon stock models in the miombo (Stromgaard, 1985; Chidumayo, 1990; Chidumayo, 2013). Although these models may be an indirect indication of the carbon stock of particular woodland, they were based on relatively few sample trees from relatively limited geographical areas within the country. Moreover, few dominant tree species and limited tree size interval were considered (Chidumayo, 1990; Chidumayo, 2013). In some cases, although large sample size e.g. Stromgaard (1985) was used, green weight (kg/tree) was used as a dependent variable instead of dry to green weight ratio of individual trees. Besides, Chidumayo (2013)'s models are based on samples from the same region of Zambia (central Zambia) with narrow diameter range and are not species specific.

Species-specific models produce improved biomass estimation (Ketterings et al., 2001; Pilli et al., 2006) while others argue that species-specific allometric equations are not necessary to generate reliable estimates of carbon stock in miombo woodlands (Malimbwi et al., 1994; Gibbs et al., 2007). Saint-André et al. (2005) reported that site variables have shown to improve the performance of equations in both tropical and temperate even-aged forests. According to Martinelli et al. (1994), big trees represent the significant proportion of the forest biomass hence data for generic allometric equations are skewed towards big trees which do not reflect validity in small trees. However, species-specific models sort out this problem. No species-specific carbon stock estimation models have been developed for wet miombo in Zambia.

A common equation for African dry forests has been produced by Chidumayo (2011) in order to estimate wood biomass from the basal area. Therefore, given differences with respect to climate, soil, topography and species, their reliability not only in Zambia but in many other vegetation types may be limited. Chidumayo (2013)'s models also did not include twigs and/or branches which make their applicability limited.

Additionally, other studies (e.g. Mwangi, 2015) in miombo woodlands of Tanzania excluded large diameter tree classes in their biomass model development. This may not extrapolate biomass well beyond the data range. However, inclusion of trees with large diameter classes is critical in biomass model development because regression models with narrow diameter ranges may not extrapolate biomass estimates well beyond the range of data (Jenkins et al., 2001).

The accuracy of the original measurements used in the development of the aboveground biomass estimation models determines the accuracy of the biomass estimates (Smith et al., 2003; Wirth et al., 2004; Wutzler et al., 2008). However, most studies have been based on 10–30 sample trees per species to develop aboveground biomass estimation models which according to Petrokofsky et al. (2012) are too few for biomass estimation. This, therefore, may not accurately predict biomass in both tropics and miombo woodlands.

There is, hence, a great need to develop species-specific carbon stock models which will produce improved carbon stock estimates. These models can also be tools for assessing forest structure and conditions through provision of valuable information on the supply of both industrial wood and biomass for domestic energy. Chambers et al. (2001) add that biomass models are the elements in all attempts of identifying sustainable management of forests and woodland ecosystems. Besides, biomass models are also needed to describe and predict changes over time for forest carbon stock at national and local level. They are also relevant for remote sensing and for all field inventories related to conventional management planning. Furthermore, biomass models are components of an implementation of the emerging carbon credit market mechanism such as REDD+ (Mugasha et al., 2013).

The significance of biomass modeling is summed up into two objectives one of which is, for resource use where it is pointed out that in order to determine how much fuel wood or timber is available, models must be developed which will estimate the biomass content (Parresol, 1999; Zheng et al., 2004). Environmental management is another important objective where it is pointed out that biomass quantification is important to assess the productivity and sustainability of the forest. They also say, biomass quantification is an important indicator in carbon sequestration in that one needs to know the amount of carbon sequestered which can be inferred from biomass change (Parresol, 1999; Zheng et al., 2004) since 50% of the forest according to Losi et al. (2003) of dry biomass is carbon.

Therefore, the objective of this study was to develop species-specific allometric models to estimate tree aboveground carbon stock. This will provide for sustainable management of the forest which will be useful for carbon projects.

2. Methodology and study area

2.1. Site description

The study was conducted in Mwekera National Forest Reserve of the Copperbelt Province of Zambia which lies between 12°45′S to 12°52′S and 28°16′E to 28°30′E with an elevation of 1292–1300 m above sea level (Kalaba et al., 2013; Fig. 1). The study area receives rainfall of between 1000 and 1200 mm per annum and experiences three weather seasons that are eminent based on rainfall and temperature, namely; hot dry (September–November), rainy season (December–March) and the cold dry season (April–August) (Chidumayo, 1997). Wet miombo (*Brachystegia-Julbernardia*) is the main woodland which according to Lees (1962) covers 90% of the study area.

2.2. Tree assessment and data collection

A preliminary tree assessment was carried out in sixteen (16) 25 m by 25 m square quadrats established in the study area where at least two trees from each quadrat were randomly selected and marked for destructive sampling. Species name, DBH and H of trees belonging to