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Research paper

Aboveground biomass partitioning and additive models for *Combretum glutinosum* and *Terminalia laxiflora* in West Africa

Kangbéni Dimobe[a,b,c,*], Sylvanus Mensah[d,e], Dethardt Goetze[c], Amadé Ouédraogo[b], Shem Kuyah[f], Stefan Porembski[c], Adjima Thiombiano[b]

[a] Department of Botany, Faculty of Sciences, Laboratory of Botany and Plant Ecology, University of Lomé, P.O. Box. 1515, Lomé, Togo
[b] University Ouaga I Pr Joseph Ki-Zerbo, UFR/SVT, Laboratory of Plant Biology and Ecology, 03 B.P. 7021 Ouagadougou 03, Burkina Faso
[c] Institute of Biological Sciences, Department of Botany, University of Rostock, D-18051 Rostock, Germany
[d] Laboratory of Biomathematics and Forest Estimations, University of Abomey-Calavi, 03 BP 2819, Benin
[e] Regional Universities Forum for Capacity Building in Agriculture (RUFORUM), Makerere University Main Campus, Kampala, Uganda
[f] Department of Botany, Jomo Kenyatta University of Agriculture and Technology (JKUAT), P.O. Box 62000-00200, Nairobi, Kenya

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ABSTRACT

Accurate estimates of aboveground biomass (AGB) strongly depend on the suitability and precision of allometric models. Although additive allometric equations are expected to reduce uncertainties due to additivity property between biomass of tree components, methods for developing biomass equations do not comply with the additivity property. This study aimed to evaluate biomass allocation patterns within tree components, and to develop additive allometric equations for *Combretum glutinosum* and *Terminalia laxiflora* in West Africa. Sixty trees were destructively sampled and measured for stem, branch and leaf biomass in Sudanian savannas of Burkina Faso. Biomass allocation to stem, branch and leaf was assessed by calculating the biomass fractions for each component. Bivariate relationships between biomass fraction and diameter at beast height (dbh) were further examined. For each biomass component we tested three non-linear allometric equations based on dbh alone, and dbh in combination with height and/or crown diameter as independent variables. Seemingly Unrelated Regressions were used to fit a system of additive biomass allometric equations. Branch biomass accounted for between 60 and 70% of the AGB. Branch mass fraction increased with increasing stem diameter while a reverse trend was observed for leaf and stem mass fractions. The decline in the mass fraction was more pronounced for the leaf than the stem. Additive biomass models developed for the two species exhibited good model fit and performance, with explained variance of 68–89%. The models developed in this study provide a robust estimation of tree biomass components and can be used in Sudanian savannas of West Africa.

1. Introduction

Reliable, accurate and cost effective methods for estimating tree biomass are required in order to determine geographic distribution of carbon stocks, understand changes in carbon stocks due to land use change, and to quantify feats of global initiatives that address climate change such as REDD+ (Reducing Emissions from Deforestation and forest Degradation in developing countries *plus* conservation of forest carbon stocks, sustainable management of forest and enhancement of forest carbon stocks). Carbon estimates are primarily derived from assessments of biomass. Biomass estimates are specifically essential for understanding the role of forests as carbon sinks or sources, and for sustainable forest management [1,2]. Aboveground biomass (AGB) is a useful measure for comparing structural and functional attributes of forest and savanna ecosystems across a wide range of environmental conditions [3] and can serve as an indicator for the distribution and abundance of vegetation above the ground [4]. Current estimates of biomass stocks for the Sudanian savanna range are highly variable, and range between 21.32 Mg/ha [5] and 46 Mg/ha [6]. Some of the variations in the estimates can be attributed to the method chosen for biomass estimation [7–9]. Inconsistencies in biomass estimates can lead to varied conclusions and a fragmented understanding of the role of Sudanian savanna ecosystem in climate change and development.

The most accurate and direct method of estimating tree biomass is destructive sampling [10]. Also known as harvest method, it involves harvesting all the trees in a known area and measuring the weights of the wood and foliage components [11]. Destructive sampling is limited to small areas or small tree sample sizes; it is not recommended on

* Corresponding author. University Ouaga I Pr Joseph Ki-Zerbo, UFR/SVT, Laboratory of Plant Biology and Ecology, 03 B.P. 7021 Ouagadougou 03, Burkina Faso.
E-mail addresses: kangbenidimobe@gmail.com, kangbenidimobe@yahoo.fr (K. Dimobe).

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endangered tree species or in protected areas [12], and cannot be used for repeated measurement over time [13]. Studies show that destructive sampling is time consuming, strenuous, expensive and labour intensive [14,15]. To circumvent these limitations, non-destructive methods such as use of allometric biomass equations (hereafter called allometric equations) have been developed. Once developed, allometric equations can be used to assess biomass on large scale and allow follow up measurements. Allometric equations form the basis for converting non-destructively obtained data, for example from ground-based inventory or from remote sensing to biomass [16]. The equations can be applied to dendrometric parameters of trees such as diameter at breast height (DBH), height, crown diameter (CD) and wood density in forest inventory data; or to indirectly measured (remotely sensed) parameters that are correlated to biomass, such as crown metrics, forest density or leaf area index to obtain biomass density. The role of allometric equations in determining the potential of forests and other ecosystems for climate protection underscores the need to develop robust equations that allow accurate quantification of biomass.

There is a general lack of allometric models suitable for biomass estimation in West African Sudanian savanna ecosystems. This presents a major problem since the region lack species specific models for most important local tree species [17,18]. Recent studies have reported allometric models that are specific to African ecosystems, for example afrotemperate and moist central African forest [7,12], agroforests [14,19,20] and other vegetation types [21,22]. Only a limited number of studies have focused on dryland environments; for example Sawadogo et al. [23] in Burkina Faso, Chabi et al. [6] in Benin and Tredennick et al. [24] in Mali. Biomass models from these studies are commonly used across neighboring countries. Because of limited number of species-specific or site-specific allometric equations, estimation of biomass in this region largely relies on general purpose equations cited in Brown [11], Chave et al. [25], and Chave et al. [26]. It is difficult to obtain accurate biomass estimates with such approach. The Sudanian savanna vegetation is highly heterogeneous; tree cover and structure is greatly influenced by environmental variability and anthropogenic disturbances. This limits the use general purpose equations such as Brown [11] developed using data from savanna ecosystems of South America and dry forests of India, as well as regional equations that have not been validated. A major limitation to development of allometric equations in dryland regions relates to difficulties in obtaining measured field data in these species-rich ecosystems [25]. Data for development of allometric equations primarily come from destructive sampling; although few studies have tried to develop allometric equations from non-destructive measurements [27,28].

The value of the allometric model depends on empirical data used. This determines how accurate a given model estimates AGB for a particular vegetation [8,9]. There is mounting evidence that application of models not suitable to the target environment and species results in large systematic deviations from observed data [4,14]. Studies have tried to correct such uncertainties by varying the number of predictor variables in the equations. The majority of studies develop allometric equations that use dbh [4,23,29] as the lone predictor variable. Other tree parameters that have been investigated as the main predictor variables include basal diameter [14], total tree height [4], CD or crown area [30–32] and wood density [12,26]. Allometric equations with dbh alone are commonly used because of the ease of measuring diameter with high accuracy. However, allometric equations that includes height and/or wood density as additional predictor variables have been published [5,33]; integrating height and wood density in biomass assessment can improve the predictive abilities of equations as well as their appropriateness to different locations [7,25,26,32,34], although the improvement can be species-sensitive [12]. The challenges of using allometric equations with multiple predictors include inability to accurately measure parameters such as CD and height [30], lack of (or variable) wood density data for most tree species, and to ill-understood relationships between the many variables [8].

Allometric equations that account for the additive property of biomass components are scarce [35–37]. Additive allometric equations reduce uncertainties due to additive property between biomass components. Unlike additive allometric equations, non-additive allometric equations fit the biomass data of total, sub-total and components separately [38]. Consequently, the sum of predictions from allometric equations of components may not be equal to the model prediction from the total biomass model. Previous studies have reported the importance of accounting for biomass additivity [39,40]; the system developed should ensure that the sum of the predictions for the tree components obtained from allometric equations of stem, branches and leaves equals the prediction for the whole tree [35,41]. Three methods are used to achieve additivity in a set of nonlinear models: adjustment in proportion (AP), ordinary least square with separating regression (OLSSR) and seemingly unrelated regression (SUR) [35,42]. SUR is commonly used to fit the system of additive allometric equations [37,38,43] because it ensures high efficiency of additivity and has strong ability to account for correlations among the components [20,35,41].

The vegetation of the Sudanian zone of Burkina Faso is dominated by species of Combretaceae, especially individuals of *Combretum glutinosum* and *Terminalia laxiflora* [44]. These species are well-known for their socio-economic and ecological importance [45]. So far, there are no validated specific allometric equations for estimating the aboveground biomass for these species in Burkina Faso. As a result, the role of these species in climate change mitigation through carbon sequestration is poorly understood and is either underestimated or overestimated depending on the allometric equation chosen for biomass estimation. To fill this gap, this study aims to evaluate biomass allocation patterns within tree components and develop additive allometric equations for *Combretum glutinosum* and *Terminalia laxiflora*. The specific objectives of this study were to (1) assess, within sampled trees, the patterns of biomass allocation and variation of component mass fractions according to tree diameter; (2) evaluate the performance of species-specific allometric equations developed to estimate stem, branch, leaf biomass of *Combretum glutinosum* and *Terminalia laxiflora*; (3) determine the system of additive allometric equations that best predicts the total aboveground biomass of the two studied species.

2. Material and methods

2.1. Study area

The study was conducted in three experimental sites located in Dano watershed, Total Wildlife Reserve of Bontioli and Nazinga Game Ranch in Burkina Faso, West Africa (Fig. 1). These sites are located in the southern Sudanian agro-ecological zone of Burkina Faso across a flat area with an average altitude of 300 m. They are situated within the Sudanian regional centre of endemism [46,47]. The widespread vegetation types in the study area are tree and shrub savannas with a grass layer dominated by the annual grasses such as *Andropogon pseudapricus* Stapf. and *Loudetia togoensis* (Pilger) C.E. Hubbard, as well as the perennials such as *Andropogon gayanus* Kunth. and *Andropogon ascinodis* C.B.Cl. The climate is tropical with a unimodal rainy season, lasting for about 6 months from May to October. The mean annual rainfall for 30 year period (1983–2013) is 879.15 ± 149.44 mm for Dano, 1062.78 ± 147.99 mm for Bontioli and 996.3 ± 172.53 mm for Nazinga. The temperature ranges from 16 to 32 °C in December–January and 26–40 °C in March–April. The most frequently encountered soils are Lixisols [48].

2.2. Description of tree species

Combretum glutinosum Perr. ex DC. is a fairly fast-growing deciduous shrub species with a maximum height of 12 m (Photo 1), widely spread across the Sahel from Senegal to Cameroon and eastwards to the Sudan