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Tree allometry in Central Africa: Testing the validity of pantropical multi-species allometric equations for estimating biomass and carbon stocks

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ABSTRACT

There is a lot of uncertainty in the amount and spatial variations of above-ground biomass in Africa, partly because very few allometric equations are available. The aim of this study was to assess the validity of using pan-tropical multispecies allometric equations developed by Chave et al. (2005) for estimating the above-ground biomass of trees in Central Africa and/or to develop site-specific equations. The study was conducted in lowland tropical forests of South-eastern Cameroon, at the edge between evergreen and semi-evergreen forests. Data of above-ground woody biomass were obtained from destructive sampling of 138 trees belonging to 47 taxa across a huge range of diameter (5.30–192.50 cm) and wood specific gravity (0.284–1.152 g cm^{-3}). A set of local site-specific multi- and single-species models relating above-ground biomass to tree diameter and wood specific gravity were fitted to the data. The best model was selected using information criterion. Both tree diameter and wood specific gravity were important predictor to consider for the estimation of above-ground biomass at tree scale. Single-species models were not necessarily better than multi-species models including wood specific gravity as a predictor. The best local multi-species model had the same structure and parameters as the pan-tropical equation developed by Chave et al. (2005) for moist forests. The estimates from the pan-tropical multi-species equation were nearly as good as those of the local multi-species equation. Using wood specific gravity from the global data base only slightly increased the estimation errors, because for the study taxa wood specific gravity was highly correlated to wood specific gravity from the global data base. In this study, we showed that the pantropical multi-species allometric equation developped for moist forests can be used to produce accurate estimates of biomass and carbon stocks from diameter measurement in forest inventory and wood specific gravity from global data base at species level. These findings are especially timely given the urgent need to quantify biomass and carbon stocks in the tropics, and given the spatial extent of moist forests in Central Africa.

1. Introduction

Tropical forests are a key component of the global carbon cycle (Cramer et al., 2004; Malhi and Grace, 2000). While the Congo basin is the second largest block of continuous tropical forest after the Amazonian basin, there is still a lot of uncertainty about the amount and spatial variations in above-ground biomass (biomass hereafter) and carbon stocks (Baccini et al., 2008; Mitchard et al., 2011; Zhang et al., 2002).

Many techniques exist to estimate forest biomass at different spatial scales, but they all ultimately rely on ground and destructive measurements of individual tree biomass to calibrate allometric equations (Gibbs et al., 2007). An allometric equation is a statistical model relating tree biomass to a set of predictors such as tree diameter and/or height, wood specific gravity, or forest type (Chave et al., 2005). Allometric equations are used to convert forest inventory data into biomass estimates at tree-level, and the sum of all data for the trees allows a biomass estimate to be obtained at plot level (Chave et al., 2004; Wharton and Cunia, 1987). Since existing allometric equations for tropical trees in African moist forests are restricted to a few specific species or sites (Deans et al., 1996; Djomo et al., 2010; Henry et al., 2010, 2011), pantropical multi-species equations are being used instead to estimate biomass from inventory data (Gourlet-Fleury et al., 2011; Lewis et al., 2009; Maniatis et al., 2011a). The pantropical multi-species equations developed by Chave et al. (2005) were calibrated on an extensive dataset of 2410 trees ⩾5 cm diameter from 27 study

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sites across the tropics, but excluding Africa. Although widely used to estimate biomass from forest inventory data, the validity of these pantropical equations has been tested only rarely in Africa, i.e. for a small number of species and trees in Ghana (Henry et al., 2010), in the Democratic Republic of Congo (Ebuy et al., 2011) and in Madagascar (Vieilledent et al., 2012). Since the choice of allometric model is an important source of error in biomass estimation at landscape scale (Chave et al., 2004; Molto et al., 2012; Van Breugel et al., 2011), there is an urgent need to test the validity of pantropical equations in Africa in order to obtain accurate estimates of biomass and carbon stocks.

The allometry of tropical trees varies greatly with forest type, and specific allometric equations have been developed separately for wet, moist, and dry forests (Brown et al., 1989; Chave et al., 2005). Global analyses have recently shown that allometric relationships between height and diameter for tropical trees vary with geographic location (Feldpausch et al., 2011). In addition, location within a specific continent has been found to explain almost 50% of variations in tree allometry (Banin et al., 2012). These studies both demonstrated that mean and maximum height tend to be greater for Asian, than for African, and American tropical trees, respectively. These results are in agreement with existing empirical knowledge. The geographic variations found in tree allometry have been mostly attributable to environmental and structural variations between forests rather than to floristic variations (Banin et al., 2012; Feldpausch et al., 2011). This finding suggests that the high rate of endemism in tropical Africa (White, 1983) may be less important for tree allometry than particular environmental conditions. The same environmental or structural conditions that have been found to influence diameter:height allometry could also influence biomass allometric equations.

The most important predictors of tree biomass have been shown to be, in order of decreasing importance, its trunk diameter, wood specific gravity, and total height (Chave et al., 2005). Although it is important to consider tree height in biomass estimation (Feldpausch et al., 2012), it is extremely difficult to measure this variable accurately within the structurally complex tropical forests, and this measurement is only rarely available in forest inventory data. A proper test of the pantropical multi-species equations and/or the development of site-specific equations require a large sampling effort in terms of individuals (at least 100, Chave et al., 2004), diameters and species, but also rigorous measurements of wood specific gravity (Chave et al., 2005; Ebuy et al., 2011; Woodcock and Shier, 2002). It has been shown in Central Panama that wood specific gravity is even more important than the number of trees used for fitting the multi-species equation (Van Breugel et al., 2011). To the best of our knowledge, there are only a small number of published studies reporting tree biomass data in the Congo basin. Biomass data have been reported for Eucalypt hybrid trees in plantations in the Republic of Congo (Saint-André et al., 2005), three forest species in plantations in the Democratic Republic of Congo (Ebuy et al., 2011), five pioneer species in plantations and/or previously logged secondary forests in Cameroon (Deans et al., 1996) and a total of 31 forest species in old-growth forest in Cameroon (Djomo et al., 2010). In all cases, available biomass data concerned only a small number of trees, diameters and species. In addition, in natural forests of Central Africa, it is quite common to find trees with a diameter far beyond the validity threshold of pantropical equations (i.e. 150 cm), and these trees store the greatest proportion of biomass (Feldpausch et al., 2012). The classical approach to obtaining biomass estimates is to combine diameter measurements from forest inventories and information on species wood specific gravity from external sources (Gourlet-Fleury et al., 2011; Maniatis et al., 2011a). This is possible because between-species variations in wood specific gravity are more important than within-species variations (Molto et al., 2012), and because huge efforts have been made to gather information on species wood specific gravity at a global scale (Zanne et al., 2009). The validity of pantropical equations thus needs to be tested across a huge diameter range and using wood specific gravity information from external sources.

The aim of this study was to assess the validity of using pantropical multi-species allometric equations developed by Chave et al. (2005) to estimate the above-ground biomass of trees in Central Africa and/or to develop site-specific equations. In this study, we focused on above-ground woody biomass rather than on total above-ground biomass. This is because woody organs (stump, stem and branches) contain the majority of the biomass, 96.7% and 98.1%, respectively, for 12 and 42 trees in the Democratic Republic of Congo (Ebuy et al., 2011) and Ghana (Henry et al., 2010). In addition, the biomass contained in leaves, flowers, and fruits, varies greatly both within and between years. Based on an extensive dataset of 138 trees destructively sampled in South-eastern Cameroon across a huge range of diameter (5.30–192.50 cm) and wood specific gravity (0.284–1.152 g cm^{-3}), we tested the null hypothesis that the allometry of African tree species does not differ from common allometric patterns that have been reported across the tropics. Because tree height measurements are rarely available in forest inventory data, we focused solely on diameter and wood specific gravity as explanatory variables of tree biomass, and assumed that the particular allometric relationship between tree height and diameter was modeled in the biomass equation. We addressed the following specific questions: (1) Do pantropical equations differ from and perform worse than local site-specific equations? (2) Does using wood specific gravity from the global data base significantly impact biomass estimates? (3) Are single-species models better than multi-species models?

2. Materials and methods

2.1. Study area

The study area is located in South-eastern Cameroon, in the Haut-Nyong Department, close to the city of Mindourou, about 450 km east of Yaoundé. The study was conducted in the logging concessions sustainably managed by the Pallisco company. The extremes encompassed by the study were 3°01′N and 3°44′N (southern and northern); and 13°20′E and 14°31′E (western and eastern). Average annual rainfall in the area varies between 1500 and 2000 mm with a 3 to 4-months dry season (November/December–February). The annual average monthly temperature varies at around 24 °C. Altitude varies between 600 and 760 m. The study site lies on a Precambrian substrate. Soils are deep ferralitic red or yellow soils. The vegetation belongs to the dense forest of the Guineo–Congolian region (White, 1983). The study site is located at the edge between evergreen and semi-evergreen forests (Letouzey, 1985).

2.2. Data collection

Above-ground biomass data were obtained from the destructive sampling of 138 trees across a huge range of diameter (5.30–192.50 cm, Table 1). The trees belonged to 23 families, and 47 identified taxa, of which 42 were determined to species level and five to genus level. Two individuals remained undetermined. In order to comply with national legislation, for trees with a diameter at breast height (*dbh*) larger than the minimum diameter for exploitation (*MDE*), we focused on three timber species harvested by the logging company (*Entandrophragma cylindricum*, *Erythrophleum suaveolens* and *Pericopsis elata*, Table 1). Smaller trees were