Forest Ecology and Management 312 (2014) 1–9

Contents lists available at ScienceDirect

Forest Ecology and Management

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

Site-specific *versus* pantropical allometric equations: Which option to estimate the biomass of a moist central African forest?

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ARTICLE INFO

Article history:
Received 17 July 2013
Received in revised form 10 October 2013
Accepted 14 October 2013
Available online 14 November 2013

Keywords:
Aboveground woody biomass
Carbon stock
Congo basin
Gabon
Pantropical equation
Plant allometry

ABSTRACT

Fewer data on tree biomass and allometric equations are available in African tropical moist forests than in the other tropical continents. When needing a biomass allometric equation, one thus faces the dilemma of using either a pantropical equation with the risk that it is biased for Africa, or a site-specific equation that is imprecise. Using a data set on aboveground biomass for 101 trees destructively measured at Zadié in northeastern Gabon, we fitted site-specific allometric equations and assessed the validity of ten existing equations. The best fitted model without height as a predictor was: $B = \exp[-4.0596 + 4.0624 \ln D - 0.228(\ln D)^2 + 1.4307 \ln \rho]$, whereas the best fitted model with height was: $B = \exp[-2.5680 + 0.9517 \ln(D^2H) + 1.1891 \ln \rho]$, where B is the aboveground biomass in kg, D the diameter at breast height in cm, H the height in m, and ρ the wood density in g cm^{-3}. Separate allometric equations for the stem, stump, foliage and branches were also fitted. Chave et al. (2005)'s pantropical equations for moist forests, that are currently the most commonly used allometric equations in central Africa, were not valid at Zadié with an overestimation of biomass of about 40%. The allometric equations of the same authors for wet forests were valid at Zadié, even though the climatic zone does not correspond. More data on tree biomass are needed in central Africa to explore the natural range of variability in tree biomass and identify the factors that influence variations among sites.

1. Introduction

With the development of the REDD+ mechanism and the emphasis put on the possible revenue that could be gained from the conservation of forest carbon stocks, precise and verifiable estimates of forest carbon stocks in central Africa are insistently required (Lewis et al., 2013). Estimating the carbon stocks of forests may rely on different techniques at different scales, from remote sensing at the national level to direct weighing at the local level (Gibbs et al., 2007; Clark and Kellner, 2012), but all techniques ultimately rely on the biomass measurement of individual trees. Because direct tree biomass measurements are destructive and costly, one generally uses an allometric equation, that is a statistical model that predicts the biomass of a tree from other dendrometrical characteristics (such as diameter or height) that are easier to measure and non-destructive. As an alternative to biomass allometric equations, the IPCC guidelines (Eggleston et al., 2006) also allow REDD+ practitioners to use volume equations, thus requiring the estimation of biomass conversion and expansion factors (BCEF) to convert merchantable log volume into aboveground tree biomass.

Although the data used for their fits did not include any data from Africa, the pantropical allometric equations by Chave et al. (2005) are currently the most commonly used equations in central

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http://dx.doi.org/10.1016/j.foreco.2013.10.029

Africa (Lewis et al., 2009, 2013). Given the regional differences in diameter-height allometry that have recently being evidenced (Banin et al., 2012), the lack of data originating from Africa in the building of Chave et al.'s equations may question their validity for central Africa (Fayolle et al., 2013). As an alternative to Chave et al.'s equations, one may use site-specific equations that have been developed from African tropical rain forests (Deans et al., 1996; Ibrahima et al., 2002; Djomo et al., 2010; Henry et al., 2010; Ebuy Alipade et al., 2011; Vieilledent et al., 2012; Fayolle et al., 2013). The limitation of these site-specific equations, inherent to the cost of biomass measurement, is that they are generally based on a small sample size. In central Africa specifically, the allometric equation by Fayolle et al. (2013) is the only published one so far that is based on more than 30 trees with a diameter at breast height (dbh) greater than 10 cm (with a maximum dbh in this case of 192.5 cm). Therefore, one is confronted in central Africa with the dilemma of using a pantropical plurispecific equation that is based on many data but might be biased, or using a site-specific equation that is based on few data and thus presumably with a lower precision of prediction.

According to Fayolle et al. (2013), Chave et al.'s pantropical equation is valid to predict tree biomass in the forests of south-eastern Cameroon. Outside central Africa, contrasted answers have been brought to the dilemma between pantropical and site-specific equations. Whereas Vieilledent et al. (2012) found that Chave et al.'s equations were valid in Madagascar as soon as height was included as a predictor, important bias for Chave et al.'s equation have locally been reported by Basuki et al. (2009) in Kalimantan, Indonesia, by Henry et al. (2010) in Ghana, by Alvarez et al. (2012) in Columbia, and by Lima et al. (2012) in Amazonia, Brazil.

The main goal of this study was (i) to compare site-specific allometric equations fitted to tree biomass data in north-eastern Gabon to existing allometric equations (including Chave et al.'s pantropical equations), to assess if existed equations are valid at the regional level and, if not, to provide new allometric equations. Additional goals were (ii) to estimate biomass expansion factors (BEF) and BCEF, that are needed following the IPCC guidelines to convert log volume into tree biomass, (iii) to investigate the allocation pattern of the biomass among the tree organs, and (iv) to model the diameter-height allometry. To these ends, 101 trees across a wide dbh range were destructively sampled at Zadié, near Makokou. To the best of our knowledge, this data set is the second largest data set on tree biomass ever collected in central Africa.

2. Materials and methods

2.1. Study site

The study site was located in north-eastern Gabon, in the Ogooué-Ivindo Province, close to the city of Makokou. The study was conducted in the Makokou logging concession sustainably managed by the Olam company, in the southern part of the Monts Belinga block, close to the Zadié River (0°57′N, 13°10′E, Fig. 1). Average annual rainfall varies between 1600 and 1700 mm with two dry seasons (July–August and February–March; Lerique, 1983) and 4 months during which evapotranspiration (1302 mm yr^{-1} on average across 2000–2012; Mu et al., 2007) exceeds rainfall. This climatic pattern corresponds to the moist forest type of Chave et al. (2005). The annual average of temperatures is 23.9 °C. The relief consists of an undulating plateau made up of many hills, at an altitude of about 500 m, on an Archean crystalline basement. Soils are shallow ferralitic yellow soils (Martin et al., 1981). The vegetation belongs to the dense forest of the Guineo-Congolian region, more precisely to the lower-Guinean continental forest (White, 1986) and has been classified as a transition type between evergreen and semi-deciduous forests (Caballé, 1978; De Namur, 1990; Doumenge, 1990; Doumenge et al., 2001). Representative species in terms of abundance are *Scyphocephalium mannii* (Benth.) Warb., *Pycnanthus angolensis* (Welw.) Warb., *Pentaclethra eetveldeana* De Wild. & T. Durand, *Celtis sp.*, *Gilletiodendron pierreanum* (Harms) J. Léonard and *Gilbertiodendron dewevrei* (De Wild.) J. Léonard (TEREA, 2010).

2.2. Biomass measurements

The sample of trees was designed to get a joint balanced distribution across size and wood density. Using the forest inventory of the logging company, tree species to be included in the sample were identified depending on their abundance, the size of their individuals, and their wood density. Ten species with a gradient of wood density ranging from 0.46 to 0.92 g cm^{-3} were thus selected, where the wood density values were taken from the Zanne et al. (2009) data base (Table 1). A field survey then enabled us to select the trees belonging to those species and with the desired dbh. The sample of trees finally included 101 trees with a dbh range of 11.8–109.4 cm (Table 1).

Biomass measurements were direct (i.e. based on weighing and not on cubing) and destructive. The dry biomass of a pool of wood material was estimated as its fresh biomass divided by the fresh biomass of an aliquot (i.e. a sample with a mass that is a known fraction of that of the whole) taken from this pool times the dry biomass of this aliquot. This approach makes sense only if the ratio of dry over fresh biomass is homogeneous across the whole pool. Therefore, each tree was divided into nine pools: stump (from ground level to 1.30 m height), stem, large branches (diameter at large end $\geqslant$ 4 cm), medium branches (2 $\leqslant$ diameter at large end < 4 cm), small branches (diameter at large end < 2 cm), dead branches, foliage, fruit, and flowers.

Trees were chosen so as to be close to a forest road. Roads were built recently (<5 years ago) and thus had no influence on the past growth of the trees. Trees were felled so that their crown fell on the roads, which limited the loss of foliage and the risk of confusion with neighbouring trees broken by the felling. Once felled, the total height and stem height of the trees were measured. Trees were then partitioned into the nine pools. All fresh biomasses (of the whole pools and of the aliquots taken from them) were weighed on the field, using different scales with different capacities (from 300 g to 10 tonnes). The aliquot of the stem, of the stump and of the large branches consisted of disks less than 2 cm thick, taken approximately every 2 m along the stem or the branches. The aliquot of the other pools consisted of a sample of about 500–1000 g randomly picked in the pool. Aliquots were brought to the laboratory of the Ipassa Research Station at Makokou. They were oven dried at 105 °C for pieces of wood and at 70 °C for leaves, flowers and fruit. Drying lasted until the mass stabilized (which generally occurred in two days for leaves and flowers, but occasionally took two weeks for the largest pieces of wood). The dry weight of aliquots was weighed using an electronic scale.

2.3. Fit of allometric equations

Eleven models were fitted, all of which were derived from the following expression:

$$\ln B = a + b \ln D + c(\ln D)^2 + d(\ln D)^3 + e \ln H + f \ln \rho \qquad (1)$$

where B is the dry biomass (in kg), D is dbh (in cm), H is height (in m), ρ is wood density according to the Zanne et al. (2009) data base (in g cm^{-3}), and a, b, c, d, e and f are parameters to estimate. Seven models did not depend on height: model 1 assumed $c = d = e = f = 0$; model 2 assumed $d = e = f = 0$; model 3