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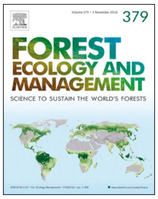

# Using volume-weighted average wood specific gravity of trees reduces bias in aboveground biomass predictions from forest volume data

Le Bienfaiteur Takougoum Sagang[a,c,*], Stéphane Takoudjou Momo[a,b], Moses Bakonck Libalah[a,b], Vivien Rossi[d], Noël Fonton[d], Gislain II Mofack[a], Narcisse Guy Kamdem[a], Victor François Nguetsop[c], Bonaventure Sonké[a], Ploton Pierre[b], Nicolas Barbier[b]

[a] *Plant Systematic and Ecology Laboratory (LaBosystE), Department of Biology, Higher Teachers' Training College, University of Yaoundé I, P.O. Box 047, Yaoundé, Cameroon*
[b] *AMAP, IRD, CNRS, INRA, Univ Montpellier, CIRAD, Montpellier, France*
[c] *Laboratory of Applied Botany, Faculty of Sciences, University of Dschang, Dschang, Cameroon*
[d] *Commission des Forêts d'Afrique Centrale (COMIFAC), Yaoundé BP 2572, Cameroon*

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ABSTRACT

With the improvement of remote sensing techniques for forest inventory application such as terrestrial LiDAR, tree volume can now be measured directly, without resorting to allometric equations. However, wood specific gravity (*WSG*) remains a crucial factor for converting these precise volume measurements into unbiased biomass estimates. In addition to this *WSG* values obtained from samples collected at the base of the tree ($WSG_{Base}$) or from global repositories such as Dryad ($WSG_{Dryad}$) can be substantially biased relative to the overall tree value. Our aim was to assess and mitigate error propagation at tree and stand level using a pragmatic approach that could be generalized to National Forest Inventories or other carbon assessment efforts based on measured volumetric data. In the semi-deciduous forests of Eastern Cameroon, we destructively sampled 130 trees belonging to 15 species mostly represented by large trees (up to 45 Mg). We also used stand-level dendrometric parameters from 21 1-ha plots inventoried in the same area to propagate the tree-level bias at the plot level. A new descriptor, volume average-weighted *WSG* (*WWSG*) of the tree was computed by weighting the *WSG* of tree compartments by their relative volume prior to summing at tree level. As *WWSG* cannot be assessed non-destructively, linear models were adjusted to predict field *WWSG* and revealed that a combination of $WSG_{Dryad}$, diameter at breast height (*DBH*) and species stem morphology ($S_m$) were significant predictors explaining together 72% of *WWSG* variation. At tree level, estimating tree aboveground biomass using $WSG_{Base}$ and $WSG_{Dryad}$ yielded overestimations of 10% and 7% respectively whereas predicted *WWSG* only produced an underestimation of less than 1%. At stand-level, $WSG_{Base}$ and $WSG_{Dryad}$ gave an average simulated bias of 9% (S.D. = ± 7) and 3% (S.D. = ± 7) respectively whereas predicted *WWSG* reduced the bias by up to 0.1% (S.D. = ± 8). We also observed that the stand-level bias obtained with $WSG_{Base}$ and $WSG_{Dryad}$ decreased with total plot size and plot area. The systematic bias induced by $WSG_{Base}$ and $WSG_{Dryad}$ for biomass estimations using measured volumes are clearly not negligible but yet generally overlooked. A simple corrective approach such as the one proposed with our predictive *WWSG* model is liable to improve the precision of remote sensing-based approaches for broader scale biomass estimations.

## 1. Introduction

Above ground biomass in tropical forests constitute a major component of the global carbon cycle, but our ability to measure and predicts its carbon stocks and dynamics is limited (Chave et al., 2014; Fayolle et al., 2014). In an effort to conserve tropical forests, the United Nations Framework Convention on Climate Change (UNFCCC) has developed a mechanism called Reducing Emissions from Deforestation and Forest Degradation in tropical countries (REDD+). There is high interest in seeing such initiatives take form, but a key limitation for successful implementation of REDD+ lies in the lack of reliable methods for quantifying forest aboveground biomass (AGB) over large areas (Gibbs et al., 2007; Joseph et al., 2013). Sample-based (Maniatis et al., 2011) or remote sensing (RS) based (Ploton et al., 2017) methods

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[*] Corresponding author at: PO Box 47, Yaoundé, Cameroon.
*E-mail address:* sagang.bienfaiteur@yahoo.fr (L.B.T. Sagang).

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both rely on AGB estimations in forest sample plots to derive larger scale estimations. Chave et al. (2004) reported four types of uncertainties that could lead to statistical error in plot AGB estimates: (i) error due to tree measurement; (ii) error due to the choice of an allometric model relating AGB to other tree dimensions; (iii) sampling uncertainty, related to the size of the study plot; (iv) representativeness of a network of small plots across a vast forest landscape. Most allometric models for biomass estimation are based on three variables: tree diameter at breast height, tree height and wood specific gravity (*WSG*). The latter refers to the oven-dried mass of a wood sample divided by its green volume (Williamson and Wiemann, 2010). The two first variables serve to assess tree volume, while *WSG* allows converting this volume into a mass. Such models are in general calibrated using datasets (global) of destructively sampled trees, and only account for interspecific differences through the *WSG* variable.

We see that any methodological advance that could improve the quality of volume and *WSG* estimations will help improve on (at least) the two first sources of statistical errors reported by Chave et al. (2004). With the increasing use of terrestrial LiDAR (Light Detection And Ranging) technologies for forestry applications, and the improvement of dedicated post-treatment algorithms, precise volume estimation at tree or even plot level are now at hand (Ferraz et al., 2016; Hackenberg et al., 2015; Momo et al., 2017; Stovall et al., 2017). *A minima*, it will be possible to calibrate improved local allometric models, possibly accounting for structural variations between species or group of species. Eventually, it is expected that volumes will be directly extracted in routine from stand level scans, eliminating the need for allometric equations altogether (Calders et al., 2015; Disney et al., 2018).

A crucial deadlock will remain, however, in the proper estimation of *WSG*. As *WSG* is rarely measured in the field and most studies (Gourlet-Fleury et al., 2013; Slik et al., 2013; Bastin et al., 2015a; Alvaro et al., 2017) use species-average *WSG* values extracted from global repositories such as Dryad (Chave et al., 2009; Zanne et al., 2009).

Yet, variation in *WSG* have been observed between individuals of the same species, along the length of individual tree trunk (Wassenberg et al., 2015), between trunk and branches (Swenson and Enquist, 2008) and from the heartwood to the bark (Bastin et al., 2015b; Nock et al., 2009; Osazuwa-Peters et al., 2014). As a consequence, the use of global repositories (Zanne et al., 2009) can lead to marked bias in local studies; for instance, an overestimation of the wood specific gravity of approximately 16% for the species community was obtained at the forest stand level in Madagascar (Ramananantoandro et al., 2015). When *WSG* is measured on site, it is generally via increment cores or wood disc samples collected at a given distance from the ground on the tree trunk. Therefore, such samples ignore any vertical variation that may exist within the tree. As global biomass allometric models were often calibrated using global *WSG* repositories, it is likely that systematic bias are in fact compensated through the parameters of the allometric equations themselves (Picard et al., 2015). As a result, predictions of allometric equations would not be biased, as long as the same repositories are used to provide *WSG* values, or as long as similarly biased protocoles are used to obtain local *WSG* data (e.g. coring from the stem base). However, this would not be the case for approaches aiming at direcly converting tree volumes (e.g. from terrestrial LiDAR data) into biomass. Here, *WSG* values for each tree compatrment would be needed, or at least some tree level unbiased estimate of *WSG*. Ideally the estimator should be individual and account for vertical and radial variations. Approaching this ideal *WSG* would require taking complete increment cores (*i.e.* on at least a full diameter) in all tree compartments, followed by a volume-weighted average across compartments to obtain the tree-level volume weighted average *WSG* (*WWSG*), and this for each individual tree in a census. Obviously, the measurements required to reach this estimate can hardly be done on a standing tree, even less so in the frame of an operational, large scale application. The alternative is to look for simple correction models based on available *WSG* data (samples from the tree base or from Dryad) and the morphology of trees.

In this study, we used a dataset of 130 trees destructively sampled in south-eastern Cameroon, with a consequent representation of large trees of *DBH* > 50 cm (52% of dataset) as well as 21 ha of forest inventory performed in the same location to (i) compare *WWSG* of trees with radially-averaged *WSG* extracted at breast height (*i.e.* 1.3 m) or with species-level *WSG* from Dryad repository; (ii) propose a new practical model to predict *WWSG*; and (iii) determine the bias yielded when estimating the aboveground biomass from those different *WSG* sources at the tree- and plot-level.

## 2. Material and methods

### 2.1. Study site

Data were collected in south-eastern Cameroon, within Forest Management Units (FMU) 10–051 and 10–53. The FMUs were located between 3°41′59″ and 4°3′43″N, and 14°14′36″ and 14°34′38″E. Average annual rainfall in the area varies between 1500 and 2000 mm, with three to four months of dry season (monthly rainfall < 100 mm). The average monthly temperature oscillates around 24 °C. Altitude varies between 600 and 760 m. The study site lies on Precambrian rocks with deep ferralitic red to yellowish soils. *Terra firme* forests in the area are characterized by a mix of evergreen and semi-deciduous species dominated by *Cannabaceae* and *Malvaceae* families (hence "mixed-forests", Letouzey, 1968), and classified as semi-deciduous *Celtis* forests (Fayolle et al., 2014).

### 2.2. Species and trees sampling scheme

A total of 130 trees belonging to 15 species of 8 families were sampled (Table 1). Two selection criteria were employed: the first criterion included species relative abundance, which was obtained from existing forest management inventory data provided by the logging company; the second criterion was species mean *WSG*, derived from the Global Wood Density (GWD) database (Zanne et al., 2009) hereafter referred to as Dryad database. Each of the species retained were grouped into 6 *WSG* classes as follows: $\geq 0.4\ \mathrm{g.cm^{-3}}$; [0.4–0.5[; [0.5–0.6[; [0.6–0.7[; [0.7–0.8 [ and $\geq 0.8\ \mathrm{g.cm^{-3}}$. Trees were equally distributed into six diameter classes following a 10 cm interval class width from 10 to 50 cm, then three other diameter classes were used for large trees: ]50–100] cm, ]100–150] cm and > 150 cm. This methodology was established by the Regional Project for the strengthening of the institutional capacities on the REDD + initiative of the Commission of Central African Forest (PREREDD+ – COMIFAC). Field campaigns were carried out from July 2015 to December 2016.

### 2.3. Field data collection

Before felling a tree, we measured the *DBH* at 1.3 m above the ground or 30 cm above the top of the last buttress.

After felling the tree, we measured trunk length (from ground-level up to lowest major living branch) and total tree length (up to the apparent crown tip) so to document species morphology: short-bole species (with the ratio between bole height and crown depth < 1) and tall-bole species (with the ratio between bole height and crown depth > 1; see Appendix A). Tree stump was then cut at ground level and the bole and crown were chunked into 1 to 2 m long sections as described by Picard et al. (2012). The tree was subdivided into seven compartments: 1 = stump; 2 = lower portion of the bole with buttresses; 3 = bole; 4 = large crown sections (∅ ≥ 20 cm, with ∅ the basal section diameter); 5 = medium-sized crown sections (5 ≥ ∅ < 20 cm); 6 = small crown sections (∅ < 5 cm) and 7 = leaves and reproductive parts. For sections with ∅ ≤ 70 cm, fresh masses were directly weighed in the field using a *Crane* electronic (3000 kg capacity, precision of 0.5 kg). For sections with ∅ > 70 cm, basal diameter, distal diameter and