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# Generic allometric models including height best estimate forest biomass and carbon stocks in Indonesia ☆

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ABSTRACT

The choice of an appropriate allometric model is a critical step in reducing uncertainties in forest biomass stock estimates. With large greenhouse gases emissions due to deforestation, a systematic assessment and comparison of the models available in Indonesia is crucial for accurate assessments of forest carbon stocks and implementing REDD+ projects. In the present study, we compared the ability of two regional and two generic (pantropical) allometric models to estimate biomass at both tree and plot levels. We showed that regional models had lower performance in estimating tree biomass, with greater bias (−31–8%) and higher AIC (177–204), compared to generic models (bias: −2–2%; AIC: 57–67). At the plot level, the regional models underestimated biomass stocks by 0–40% compared to the best generic model. The error in plot biomass stocks associated to models relying solely upon DBH ranged between −5 and +15%. The integration of tree height estimated regionally resulted in an overestimate of 5–10% in unmanaged forests. Despite the difficulty to accurately assess tree heights in tropical forests, integrating all or part of them in biomass assessment can reduce uncertainties.



## 1. Introduction

Indonesian tropical forests have been extensively logged from 2000 and 2010 (Miettinen et al., 2011), contributing to *c.* 80% of yearly emissions of greenhouse gases of the country (PEACE, 2007). The ability to accurately estimate forest carbon stocks is essential in Reducing Emissions from Deforestation and Forest Degradation (REDD+) mechanisms in order to establish reliable National Reference Emission Levels (NREL) and to estimate carbon stock changes. However, forest biomass stocks are still poorly estimated in most tropical regions and remain a major uncertainty in our understanding of the potential of tropical forests in mitigating climate change (Houghton, 2005). Several research efforts are under way to fill this gap, relying upon a combination of large-scale remotely-sensed imagery and ground-based measurements (Houghton et al., 2009; FAO, 2010). However, despite strong commitment of the Indonesian Government, its capacity to report carbon stocks from forest inventories remains low (Romijn et al., 2012). More generally, the main source of uncertainty in biomass estimates lies in the choice of a particular allometric model (Molto et al., 2013). To date, only two studies have developed biomass models in unmanaged Dipterocarp forests of Borneo (Yamakura et al., 1986; Basuki et al., 2009). However, the range of application of these models have hardly been tested and compared with more generic ones (but see Laumonier et al., 2010). Harvesting trees and weighing their components is time-consuming and most local allometric models encompassed only a small number of trees, likely not to reflect the full tree size distribution (Chave et al., 2005). To avoid this bias and to fill the lack of site-specific allometric equations, two major studies developed generic models and overcame these caveats in accounting for large pan-tropical datasets and large trees (DBH > 50 cm) (Brown, 1997; Chave et al., 2005). However the use of generic models may introduce errors in biomass stock estimates (Chave et al., 2004; Melson et al., 2011) and in Indonesia, site-specific models showed less bias in biomass estimates than generic ones (Basuki et al., 2009; Kenzo et al., 2009b). Depending on the model used, individual tree above-ground biomass (AGB) can vary by as much as a factor two (Basuki et al., 2009), introducing considerable uncertainties in forest biomass stocks computation (Nogueira et al., 2008; Laumonier et al., 2010). Although the use of generic models relies upon the



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assumption that tree-level errors average out at plot level, bias is rarely assessed for forest stands across landscapes (van Breugel et al., 2011). Height and diameter relationship (H–DBH) greatly varies among forest types and regions (Feldpausch et al., 2011). Hence, at sites where no data were used to calibrate the generic models and with different H–DBH relationship, only generic models accounting for both H and DBH are expected to give reliable results (Henry et al., 2010; Vieilledent et al., 2011). Globally, accounting for tree height resulted in more accurate estimate of biomass at both tree and plot levels (Chave et al., 2005; Feldpausch et al., 2012).

Despite the vivid interest for carbon accounting in the region, no study has yet compared how the choice of allometric models affects biomass estimates in Dipterocarp forests. This study is divided into two parts. First, we compared the general accuracy of available peer-reviewed allometric models on an original destructive sample of 108 trees. Second, we investigated how these models affected carbon stock estimates across 12 forest plots representing a total area of 12 ha, focusing on the impact of tree height inclusion in these models.

Our aim was to provide guidance on estimating forest carbon stocks, in order to develop realistic scenarios of GHG emissions from land use change in Indonesia. We are notably addressing: (1) whether site-specific models better predict biomass at both tree and plot levels than generic models; (2) whether the inclusion of tree height improves biomass stock estimates at our sites and (3) how does the inclusion of tree height affect biomass estimates in forests with different H:DBH relationship.

## 2. Material and methods

### 2.1. Destructive sampling

We compiled data from destructive measurements made between 2007 and 2012 across East Kalimantan province in Indonesia, mainly from unmanaged lowland Dipterocarp forests (Noor'an, unpublished and Samalca, 2007). These trees did not come from one particular forest site and were hence not suitable to develop a local allometric model. However, we used them to test for the goodness of fit of published models. The DBH distribution ranged from 6 to 129.3 cm, not different from the average DBH distribution of primary forest plots used in this study ($X^2 = 89.9167$, $df = 80$, $P = 0.21$). The main families were Dipterocarpaceae (65%), Malvaceae (3%) and Fabaceae (3%).

### 2.2. Study sites and forest inventories

We used plots established in unmanaged lowland Dipterocarp forests in Sumatra and East Kalimantan, Borneo (Table 1). The climate at the Kalimantan sites is equatorial with a mean annual rainfall at Tanjung Redeb (Berau District, East Kalimantan) of 2105 mm from 1987 to 2007. All sites were classified as Ultisols (i.e. Xanthic Hapludox, Arenic Kanhapludults). Two sites were established in Community Protected Areas, where local communities historically harvested a few large trees for their own needs (1–5 trees $ha^{-1}$). Those plots were classified as old logged over forests. In each plot, all trees were tagged, diameter was measured at breast height (130 cm, DBH) or above buttresses and identified by a professional botanist in the field or at Bogor Herbarium. Dry wood specific gravity (WSG) was determined using the lowest level of botanical identification possible (Chave et al., 2006) and taking the appropriate value reported in the Global Wood Density Database (Zanne et al., 2009). When no botanical identification was available, we used plot-averaged WSG.

Total tree height, referred henceforth to as 'height', in the plots located in Kalimantan was systematically measured using a laser rangefinder, with a possible error of a few meters (Nikon, Forestry 550). In the plots of Sumatra, heights were estimated with a Blume Leiss hypsometer and cross-checked with measurements done by climbing trees (accuracy ± 0.5 m for small and medium trees, ±3 m for large emergent and canopy trees, Y.Laumonier pers.com). In all the other sites, a single operator did all the measurements to avoid inter-operator variability (Larjavaara and Muller-Landau, 2013).

### 2.3. Comparison of allometric models at tree level

Despite the importance of Dipterocarp forests in terms of area and carbon stocks, only a few suitable allometric models were found in the literature (Table 2). Two studies (Yamakura et al., 1986; Basuki et al., 2009) proposed site-specific allometric models. Two others (Ketterings et al., 2001; Kenzo et al., 2009a) developed allometric models in secondary logged-over forests. Ketterings et al. (2001) worked in a forest regrowing after slash and burn, in which cultivated species (i.e. *Artocarpus* or *Hevea*) were still present. The second study took place in an industrial logged-over forest concession, where the abundance of pioneer species such as *Macaranga spp*. or *Gluta spp*. indicated a much higher intensity of disturbance (2nd or 3rd rotation). As our study considers 'old-growth secondary forest' i.e. forest stands that have been selectively logged for at least 30 years and have not been clearcut, these last two models were judged irrelevant and were discarded. We also used the generic pan-tropical allometric models developed by Brown (1997), updated by Pearson et al. (2005), and by Chave et al. (2005). These models have been widely used, notably in the context of REDD+, and were recommended by the IPCC guidelines (IPCC 2003, 2006) for estimating carbon stocks in tropical forests.

Using the destructive sample, we compared the performance of prediction of the six models using four *ad hoc* indices, as reported in Vieilledent et al. (2011). We computed the residual standard error RSE, defined as the standard deviation of the residual errors $\varepsilon_i$ (with $\varepsilon_i = \log(AGB_i) - \log(AGB_{iest})$, where $AGB_i$ and $AGB_{iest}$ represent the actual and estimated biomass of a tree *i*). Large RSE values indicate poor regression models. Second, we computed the coefficient of determination of each model, defined as:

$$R^2 = 1 - \frac{\Sigma_i \varepsilon_i^2}{\Sigma_i[\log(AGB_i) - \log(AGB)_{mean}]} \quad (1)$$

with $\log(AGB)_{mean}$ being the mean of log-transformed observed values. Models with a high number of parameters generally result in a

**Table 1**
Plots location, surface, average elevation, average number of stems per hectare and basal area (BA).

| Plot_ID | Forest type | Location | Long | Lat. | Surface (ha) | Elevation (m) | Stems ($ha^{-1}$) | BA ($m^2$/ha) |
|---|---|---|---|---|---|---|---|---|
| BM_PF | Unmanaged | Batu Majang, East Kalimatan | 115.222 | 0.565 | 2 | 286 | 577 | 33.8 |
| BM_SF | Old secondary | Batu Majang, East Kalimatan | 115.220 | 0.559 | 2 | 213 | 534 | 24.7 |
| BT_PF | Unmanaged | Barong Tongkok, East Kalimatan | 115.415 | −0.024 | 1 | 289 | 496 | 36.5 |
| BT_SF | Old secondary | Barong Tongkok, East Kalimatan | 115.548 | −0.185 | 1 | 180 | 700 | 39.8 |
| PMY_PF | Unmanaged | Pasir Mayang, Sumatra | 102.093 | 1.083 | 6 | 100 | 669 | 30.1 |