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Simultaneous estimation of above- and below-ground biomass in tropical forests of Viet Nam

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ABSTRACT

For carbon accounting or for developing REDD+ (Reducing Emissions from Deforestation and forest Degradation) programs, allometric equations for estimating both above-ground biomass (AGB) and below-ground biomass (BGB) are useful. We developed systems of weighted nonlinear allometric equations to estimate total, above- and below-ground biomass for Dipterocarp forests (DF) and Evergreen broadleaf forests (EBLF) in the Central Highlands of Viet Nam, as well as for a dominant plant family (Dipterocarpaceae; Dip) in the DF. A total of 175 trees were destructively sampled for both AGB and BGB, with whole root extraction as the method of BGB sampling. Different equation forms for AGB and BGB incorporating diameter at breast height (D), tree height (H), wood density (WD) and crown area (CA) were evaluated. The best system of equations for the DF, Dipterocarpaceae in the DF, and EBLF was selected based on validation statistics of percent bias (PBias), mean absolute percentage error (MAPE), and root mean squared percent error (RMSPE). All three systems of equations developed in this study used $D^2 \times H \times WD$ as a predictor for AGB and a simpler BGB equation form with either $D^2 \times H$ or D as the sole predictor variable. The addition of WD or CA to BGB equation forms did not substantially improve validation statistics over simpler forms. These allometric equations should contribute to advancing our understanding of carbon distribution of trees in these tropical ecosystems.

1. Introduction

Tree roots are an important component in the world's terrestrial carbon budget, with up to half of the annually cycled carbon in forests contributed by roots systems (Vogt et al., 1996). However, due to the inherent increase in cost and time associated with below-ground woody biomass (BGB) measurements, most carbon-related research has focused on above-ground biomass (AGB). While relatively few studies have focused on developing equations for estimating BGB based on easy to measure tree variables, a need still exists for reliable BGB equations (Yuen et al., 2013; Ziegler et al., 2012). This is especially critical for tropical forests in South-east Asia, as the majority of the few studies performed for tropical forest have focused on sites from South and Central America (Hertel et al., 2009).

The United Nations Framework Convention on Climate Change (UNFCCC) program for Reducing Emissions from Deforestation and forest Degradation (REDD+) works with developing countries to promote forest carbon conservation as a means of reducing greenhouse gas emissions. Viet Nam is one of the countries participating in the REDD+ program and is currently updating and producing allometric equations for the estimation of forest biomass and carbon.

Early biomass equations were single-entry equations relating total and component biomass to diameter at breast height (D) through a logarithmic relation. With the increase in demand of forest biomass estimates, considerable efforts have been made in estimating total and component biomass. Since Parresol (2001) introduced the use of seemingly unrelated regression (SUR) to simultaneously fit component and total biomass equations, it became a standard for developing biomass equations because it ensured the additivity among component and total biomass predictions. Additionally the use of SUR over ordinary least squares regression allowed for more efficient parameter estimation as error terms in different component models were correlated (Poudel and Temesgen, 2016b).

Since the publication of Parresol's paper, SUR has been used by many researchers in fitting biomass equations (e.g. Lambert et al., 2005; Brandeis et al., 2006; Navar, 2009; Ritchie et al., 2013; Zhao

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et al., 2015; Poudel and Temesgen, 2016a). Recently, Poudel and Temesgen (2016a, 2016b) used multinomial log-linear regression and Dirichlet regressions for a simultaneous prediction of proportion of biomass in different aboveground components. The predicted proportions were then applied to the predicted total aboveground biomass obtained from a simple log-log model. Zhao et al. (2016) used this approach to predict proportions of biomass in different aboveground components of loblolly pine trees simultaneously. However, the literature on fitting simultaneous equations for above- and below-ground biomass is scarce.

If AGB and BGB are treated as components of a tree's total biomass (TB; kg), SUR can be used to simultaneously fit system of allometric equations in order to estimate TB. Common methods for estimating AGB and BGB include the use of log-linear models (Basuki et al., 2009; Brown, 1997; Chave et al., 2005; IPCC, 2003), and power model (Chave et al., 2014; Kenzo et al., 2009a, 2009b) with or without weighting. However reparametrizing non-linear power models can result in models trivially equivalent to log-linear models (Picard et al., 2015). Predictor variables used in the estimation of tree biomass include D (cm), total tree height (H; m), wood density (WD; g/cm^3), or some combination thereof such as $D^2 \times H$ (D^2H; m^3) or $D^2 \times H \times WD$ (D^2HW; kg), which serve as approximations for volume and AGB, respectively (Picard et al., 2015). Recently, it has also been shown that incorporating a measurement of crown diameter (m) can improve the accuracy of biomass estimates (Huy et al., 2016a; Dietz and Kuyah, 2011; Henry et al., 2010).

Additional difficulty exists in modelling tree biomass for tropical forests due to their complex nature in both structure and diversity of species. Therefore, researchers have commonly focused on developing pan-tropical or generic multi-species models (e.g. Basuki et al., 2009; Brown, 1997; Chave et al., 2005, 2014; IPCC, 2003). While valuable information can be provided by generic models, results can be biased if they are applied to a particular forest type under, or not, represented in that model's development data (Chave et al., 2014). Thus, considering differences in forest type when developing models is beneficial for more accurate tree biomass estimation (Temesgen et al., 2015).

This study contributes to that larger body of work by estimating total tree biomass (TB), as the sum of above- and below-ground biomass components, for tropical forests of Viet Nam. The primary goals of this study are to: (i) develop reliable and accurate models for the estimation of TB, AGB, and BGB in two forest types of Viet Nam; (ii) examine if family-specific equations for a dominant plant family (Dipterocarpaceae) provide more accurate estimations of biomass than broad forest type specific equations; and (iii) assess the predictive abilities of simultaneous fitting strategy for estimating AGB and BGB.

2. Materials and methods

2.1. Study sites

This study was carried out in the Central Highlands eco-region of Viet Nam (Fig. 1); one of eight such zones that partition the country and consider environmental variability with respect to soil, climate, and elevation (Phuong and Linh, 2011; Sola et al., 2014). The Central Highlands has the highest cover of tropical forests of all eco-regions in Viet Nam. We focused on the main tropical forest types of this region: the dipterocarp forest (DF) and the evergreen broadleaf forest (EBLF). The EBLF study sites were located in the provinces of Gia Lai, Dak Lak, and Dak Nong, while the DF sites were located in Dak Lak province (Fig. 1).

Both forest types are structurally complex with mixed-species composition. The primary plant family in the DF is Dipterocarpaceae and dominant genera of that family include *Dipterocarpus* and *Shorea*. Elevation for the DF sites ranged from 197 to 417 m. Mean annual precipitation and temperature for DF are 1600 mm and 25.5 °C, respectively. Stand density of live trees ⩾5 cm D for DF ranged between 256 and 1292 trees per hectare (TPH) and basal area ranged between 3.3 m^2/ha and 23.0 m^2/ha. Unlike the DF, the EBLF is not dominated by any particular plant family, although members of the Fagaceae, Myrtaceae, and Lauraceae plant families are common. The TPH for EBLF was between 370 and 3330 while basal area ranged between 8.1 m^2/ha and 49.0 m^2/ha. Elevation for the EBLF sites ranged from 403 to 1068 m. Mean annual precipitation ranged from 2100 to 2500 mm with mean annual temperatures from 22.2 to 25.0 °C. The dry season lasts for 3 months in both forest types.

2.2. Data collection

A total of 27 plots were installed in EBLF (14 plots; 20 × 100 m) and DF (13 plots; 50 × 50 m) of the Central Highlands. Within a plot, species and D was recorded for all live trees ⩾5 cm D. In each plot, a sample of trees were selected for AGB measurements, and a sub-sample of those trees were additionally selected for BGB measurements. Sample tree selection for biomass focused on the main species present on the plot with the number of trees sampled determined by the ratio of trees in each 10 cm diameter class. Fig. 2 shows representatives of structure of D and BA distributions in both forest types. A sample tree's selection for additional sampling of BGB was determined similarly to the selection of AGB trees but at a lower selection rate due to cost. The BGB tree selection rate for DF sites was 60–65% of trees sampled for AGB. The selection rate was lower for EBLF sites (30–35%) as this forest type had higher average tree density than DF sites. In this study, we only used sample trees that were destructively sampled both ABG and BGB. This resulted in a total of 175 sample trees, representing 48 species, 40 genera, and 28 families (Table 1).

For sample trees used in this study, an additional measurement of crown diameter (m) was recorded before felling and was obtained as the average of two cardinal direction (North-South and East-West) measurements. H was measured after sample trees were felled. For large trees, the stems were cut to a maximum weight of 200 kg to obtain total above-ground fresh weight. Whole sample tree root systems were excavated for each tree and coarse root measurements were obtained. Use of industry vehicles was necessary for some large trees to uproot the entire root system. Smaller roots were then excavated by hand. In this study the term coarse root refers to roots that were able to be excavated by hand, there was no attempt in this study to collect fine root data and no diameter break was set to differentiate between coarse and fine root, as has been done in other studies.

The fresh-weight of tree components (leaves, branches, stem with bark, and coarse roots) were also recorded in the field. To determine the fresh-to-dry mass ratio of each component, samples were sealed and taken to the laboratory. For each tree, roots were classified based on the sample tree's D into 3 sizes categories (large, medium, and small), and approximately 300 g was sampled from each of these three categories. Tree stem samples of wood (500 g), bark (300 g), and wood disks (for calculating WD) were taken at five replications along a tree's stem. For each tree, three branch samples (500 g per sample) were taken; the first sample from the largest branch, the second from a medium sized branch, and lastly a sample from the smallest branch. Two foliage samples (300 g per sample) of new and old leaves were taken for each tree.

In the lab, fresh volume of wood samples was obtained using the water displacement method. All samples were then chipped into small pieces and dried at 105 °C until a constant weight was