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Allometric equations for estimating tree aboveground biomass in evergreen broadleaf forests of Viet Nam

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ABSTRACT

For mitigating climate change through carbon sequestration and for reporting, Viet Nam needs to develop biomass equations at a national scale. These equations need to be accurate and provide quantifiable uncertainty. Using data from 968 trees across five ecoregions of Viet Nam, we developed a set of models to estimate tree aboveground biomass (*AGB*) in evergreen broadleaf forests (EBLF) at the national level. Diameter at breast height (*DBH*), tree height (*H*), wood density (*WD*), and combination of these three tree characteristics were used as covariates of the biomass models. Effect of ecoregion, wood density, plant family on *AGB* were examined. Best models were selected based on AIC, Adjusted R^2, and visual interpretation of model diagnostics. Cross-validation statistics of percent bias, root mean square percentage error (RMSPE), and mean absolute percent error (MAPE) were computed by randomly splitting data 200 times into model development (80%) and validation (20%) datasets and averaging over the 200 realizations. Effects models were used, the best results were obtained by using a combined variable (DBH^2HWD (kg) = (DBH (cm)/100)$^2 \times H$ (m) $\times WD$ (g/cm^3) $\times$ 1000) model $AGB = a \times (DBH^2HWD)^b$. Including a categorical *WD* variable as a random effect reduced AIC, percent bias, RMSPE, MAPE of models $AGB = a \times DBH^b$ and $AGB = a \times (DBH^2H)^b$; ecoregion as a random effect reduced the AIC of models $AGB = DBH^b \times WD$, $AGB = a \times (DBH^2H)^b$, and $AGB = a \times (DBH^2HWD)^b$. For models that did not include *WD* variable, including plant family as a random effect reduced AIC, RMSE, and MAPE; recommendations are provided for models with specific parameters for main families and without *WD* if this variable is not available. The overall best model for estimating *AGB* was the equation form $AGB = a \times (DBH^2HWD)^b$ with ecoregion as a random effect.

1. Introduction

The management of forest ecosystems to mitigate climate change through CO_2 absorption deserves urgent attention from governments. The United Nations' Programme on Reducing Emissions from Deforestation and Forest Degradation (UN-REDD) has been taking actions to help support this need in developing countries and Viet Nam since 2009. The Intergovernmental Panel on Climate Change (IPCC) has also provided guidelines for measuring and monitoring forest carbon (IPCC, 1996, 2003, 2006). However, there is still a need in Viet Nam for national scale models that can provide accurate estimates of biomass and carbon, and produce accurate emission factors.

Due to the diverse nature of tropical forests, the development of species-specific equations is not realistic and researchers have instead commonly focused on generic multi-species models (e.g. Brown et al., 1989; Brown and Iverson, 1992; Brown, 1997; Brown et al., 2001; Ketterings et al., 2001; Basuki et al., 2009; Chave et al., 2005, 2014). However, available models typically do not incorporate the distinction of forest type or ecoregion, nor have they been evaluated for their reliability in evergreen broadleaf forests (EBLF) of Viet Nam, the primary cover type of the country's natural forest spanning 14.2 million hectares (JICA and VNFOREST, 2012). These generic models provide valuable

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information for the tropics but may be biased in cases where a particular ecosystem, such as EBLF, was not represented in the development of such models (Jara et al., 2015). Therefore, developing models for comprehensive biomass estimation that consider differences in forest type or ecoregion is necessary (Temesgen et al., 2015).

Few allometric equations were developed in Viet Nam prior to the implementation of the UN-REDD programme (UN-REDD, 2011). However, as part of the country's effort to engage and prepare for the UN-REDD programme, biomass equations are now being explored. Allometric equations for converting national forest inventory data to biomass and forest carbon stock estimates have been proposed for the main forest types and ecological regions of Viet Nam (Sola et al., 2014a,b; Huy et al., 2013; Huy, 2014; Huy et al., 2016a,b). This study improves and updates national scale allometric equations for estimating AGB in EBLF of Viet Nam by including additional data collected by Huy et al. (2013) from the Central Highlands ecoregion and by improving the methods used to estimate model parameters. We further analyzed this data to increase the reliability of biomass estimates for different forest conditions in Viet Nam by considering the effect of ecoregion, plant family, and wood density (*WD*) on *AGB*, and evaluating the reliability and accuracy of the selected models examined in this study.

2. Methodology

2.1. Study sites

Five of Viet Nam's eight agro-ecological zones, or ecoregions, contain most of the country's forest cover: the central highlands (CH), north central coastal (NCC), northeast (NE), south central coastal (SCC), and southeast (SE). Therefore, this study focused on estimating biomass of EBLF in the five representative ecoregions of Viet Nam (Fig. 1). These ecoregions span a range of ecological, climatic, and structural site characteristics (Table 1).

Elevation of EBLF in these ecoregions ranges from 197 to 1068 m with up to 40° slopes in some areas. Mean annual rainfall is between 1055 and 2500 mm with the dry seasons lasting 3 and 5 months and mean annual temperature ranging from 16.9 to 25.0 °C. The EBLF in Viet Nam is distributed primarily on a soil type of sedimentary rock, crystalline schist, igneous rock, or some combination thereof. Stand density can range from 370 to 3300 trees per ha (DBH > 5 cm) and BA can range from 9.2 to 48.9 m^2 per ha (This study; Hijmans et al., 2005; Fischer et al., 2008).

2.2. Sampling design and data collection

Most of the data used in this study was collected with the support of Vietnam UN-REDD Phase I Programme (Phuong et al., 2012b). Additional data for the Central Highlands ecoregion was collected with support from the Ministry of Education and Training (Huy et al., 2013).

A total of 14 1-ha (100 × 100 m) sample plots were established across the five ecoregions. A total of 26 0.2-ha (20 × 100 m) were added for the Central Highlands where EBLF mainly covers in the country. Within a plot, species and diameter at breast height (DBH) was recorded for all trees greater than 5 cm in *DBH*. Sample trees were selected from each plot and destructively sampled for *AGB* measurements. Sample tree selection focused on the main species. A total of 968 trees were destructively sampled with the *DBH* of sampled trees ranging from 4.7 to 87.7 cm and with heights (*H*) of 3.9–41.4 m. Table 2 shows the number of trees sampled by ecoregion and main plant family.

Fresh biomass of stems, branches, and new and old leaves were measured in the field. Samples from stem, branches, and new and old leaves were taken to obtain the fresh-to-dry mass ratio of each tree component and to calculate the total *AGB*. Dry weight of wood samples was obtained by drying them in ovens until a constant weight was reached. *WD* was then calculated as the ratio of dry mass to the volume of wood samples taken from every one-fourth or one-fifth of stem length (Phuong et al., 2012a). Fig. 2 shows *AGB* against *DBH* of all destructively sampled trees by ecoregion and main plant family. Table 3 shows a summary for each of the predictors and the response variables of the destructive sample trees.

2.3. Model development

Commonly used covariates for estimating *AGB* models are *DBH*, *WD*, and *H*. These easily measurable dendrometric variables have been related to *AGB* through a variety of model forms such as power, logarithmic, and exponential functions (Brown, 1997; Ketterings et al., 2001; Jenkins et al., 2003, 2004; IPCC, 2003; Basuki et al., 2009; Dietz and Kuyah, 2011; Johannes and Shem, 2011; Chave et al., 2005, 2014; Henry et al., 2010, 2015; Huy et al., 2016a,b). The power models are very common and are fitted either as linear models after logarithmic transformation or as non-linear models (Brown, 1997; Chave et al., 2014; Basuki et al., 2009). As biomass models are generally heteroscedastic, the logarithmic transformation can help meet the assumption of error variance homogeneity, but it can also introduce transformation bias. On the other hand, the use of non-linear models allows for flexibility in model forms and can account for heterogeneity of errors (Davidian and Giltinan, 1995).

Large scale biomass estimation requires generic models that account for the variability in biomass due to geographic locations. However, traditionally developed fixed effects models do not take into consideration the grouping of the data by locations. Mixed effect models are appropriate when data are grouped and have errors that are correlated and/or have unequal variances (Bates, 2010; Pinheiro et al., 2014). Our national scale biomass dataset has a location grouping variable of ecoregion. Therefore we used weighted non-linear mixed effects models to develop national scale biomass equations. The models were fit based on the maximum likelihood procedure in R statistical software using the nlme package (Picard et al., 2012; Pinheiro et al., 2014) and model diagnostics were conducted using the ggplot2 package (Wickham and Chang, 2013). The general form of the *AGB* model was:

$$Y_{ij} = (\alpha + a_i) \times X_{ij}^{(\beta + b_i)} + \varepsilon_{ij} \quad (1)$$

$$\varepsilon_{ij} \sim iid\mathcal{N}(0, \sigma^2) \quad (2)$$

$$a_i \sim iid\mathcal{N}(0, \sigma_a^2) \quad (3)$$

$$b_i \sim iid\mathcal{N}(0, \sigma_b^2) \quad (4)$$

where Y_{ij} is the *ABG* (kg) for the *j*th tree from the *i*th class of a variable; α and β are the fixed effect parameters of the model; a_i and b_i are parameters associated with *i*th class of a variable; X_{ij} is the covariate *DBH* (cm), *H* (m), *WD* (g/cm^3), DBH^2H (m^3), or DBH^2HWD (kg) for the *j*th tree in *i*th class of a variable; and ε_{ij} is the random error associated with the *j*th tree from the *i*th class of a variables. The independent combination variables DBH^2H and DBH^2HWD are approximations of volume and AGB, respectively, and were calculated as follows:

$$DBH^2H = \left(\frac{DBH}{100}\right)^2 \times H \quad (5)$$

$$DBH^2HWD = DBH^2H \times WD \times 1000 \quad (6)$$