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Original article

Development of general biomass allometric equations for *Tectona grandis* Linn.f. and *Eucalyptus camaldulensis* Dehnh. plantations in Thailand

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ABSTRACT

Some common, general biomass allometric equations were developed and tested for estimating the stem and aboveground biomass (AGB) of *Tectona grandis* and *Eucalyptus camaldulensis* plantations. In total, 84 datasets for *T. grandis* and 94 datasets for *E. camaldulensis* were gathered from published papers. The general allometric equations were then developed and the slopes and elevations were tested using ANCOVA. Spacing of 2 m × 4 m, 2 m × 8 m, 3 m × 3 m and 4 m × 4 m for *T. grandis* and 2 m × 3 m, 2 m × 4 m, 2 m × 8 m and 3 m × 3 m for *E. camaldulensis* were used as control factors. The results confirmed that diameter at breast height (D) and total height (H) were the best parameters for biomass estimation, of which the simple combination D^2H produced the best estimation. The general allometric equations which gave the best fit ($p < 0.01$) for the estimation of *T. grandis* was $AGB = 0.045(D^2H)^{0.921}$ and for *E. camaldulensis* was $AGB = 0.033(D^2H)^{0.959}$. Comparison of the measured and estimated datasets showed no statistically significant differences ($p > 0.05$). The range of D and H was 4.4–41.2 cm and 5.5–31.0 m, respectively, for *T. grandis* and 0.5–19.8 cm and 1.7–26.0 m, respectively, for *E. camaldulensis*.

Introduction

The area of industrial, fast-growing forest plantations globally is 54.3 million ha, of which Asia has the largest portion (approximately 17.7 million ha), followed by North America (approximately 12.8 million ha) and Latin America (approximately 12.8 million ha), Africa (almost 5 million ha) and Europe (2 million ha) according to Indufor (2012). In Thailand, the increased demand for wood, particularly fuel wood, has led to a rapid expansion of plantations of fast-growing species such as eucalypt and teak and of slower-growing species including more than 183,000 ha of land that has been planted in the last decades (FIO, 2010). The Forest Industry Organization (FIO, 2010) has been well known as a leading owner of commercial forest plantation in Thailand. Teak was mostly planted in the North (94,000 ha), with eucalypts in the Northeast (32,000 ha) and rubber in the South (10,000 ha) with the remaining approximately 48,000 ha composed of other species such as *Xylia xylocarpa*, *Pterocarpus macrocarpus*, *Hopea odorata* and *Acacia mangium* (FIO, 2010). Currently, the rotation lengths of FIO's commercial plantations are 30 yr for teak, 20 yr for rubber and 5 yr for eucalypt. In the future, FIO is dependent on further intensive establishment and the management of these commercial species (Thaiutsa, 2009).

Estimation of tree biomass is important for assessing productivity and carbon sequestration and Henry et al. (2010) reported that measurements to develop allometric equations could be carried out by either direct or indirect methods. Direct methods measure the biomass by weighing trees in the field while indirect methods involve the estimation of difficult-to-measure parameters from easy-to-measure tree parameters. The most accurate method to determine tree biomass is the destructive method, which requires felling trees and the subsequent measurement of tree components. This method is labor intensive and time consuming and is in most cases restricted to small trees on a small scale basis (Li and Xiao, 2007; Djomo et al., 2010; Addo-Fordjour and Rahmad, 2013). An allometric equation is an indirect method to estimate the whole or partial weight of the tree (stem, leaves, branches and roots), from measurable tree dimensions, including the diameter at breast height (D) and total height (H); thus, weight can be estimated non-

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destructively. Several biomass prediction equations have been developed for specific species (Viriyabuncha et al., 2002; Cole and Ewel, 2006) as well as groups of species (Wang, 2006; Basuki et al., 2009). Species-specific allometric equations developed on site provided better biomass estimation than generalized equations (Pilli et al., 2006). However, a standard allometric equation which reasonably predicts the biomass in a tree is considered to be convenient and required in many cases, especially when allometric equations cannot be developed on site. Thus, there is additional value in deriving generalized biomass regression equations.

In Thailand, allometric equations are available for natural forests (Ogawa et al., 1965; Sukwong et al., 1976) and economic plantations species (Tirasankka, 1985; Viriyabuncha et al., 2002). Most biomass equations have been developed on an experimental scale and have been site-specific and restricted to small trees and a small number of sample trees. So far, no attempts have been made to combine data across sites for the development of general biomass allometric equations. Generalized models will provide great potential for large-scale biomass estimation derived from inventory data and directly lead to the estimation of carbon sequestration in the forest sector in Thailand.

The objectives of this study were to: 1) develop general allometric equations to estimate the aboveground biomass of *Tectona grandis* and *Eucalyptus camaldulensis*—two major economic plantation species in Thailand; and 2) validate the newly developed equations for *T. grandis* in the SaiYok plantation (Kanchanaburi province) and for *E. camaldulensis* in the Ong Phra plantation (Suphan Buri province).

Materials and methods

Compilation of biomass allometric equations

Biomass datasets and allometric regressions of *T. grandis* and *E. camaldulensis* plantations were compiled from conference proceedings, theses and official reports in Thailand. Finally, 12 datasets with a total of 84 trees were chosen for *T. grandis*; while 13 datasets with a total of 94 trees were chosen for *E. camaldulensis* across the country. All the allometric equations used the same predictor variables—diameter at breast height (D) and total height (H), measured in the same units and using the same form for the best comparison. The equations were considered separately in various tree weight components—stem (wood + bark), branches, leaves and total aboveground. The form of all published biomass regression equations was: $y = a(D^2H)^b$. Most references indicated that adding tree height as the second independent variable improved the biomass allometric equations. Details on the sites, ages, spacing, numbers of samples and the *a* and *b* coefficients of selected datasets are provided in Tables 1 and 2. The ranges in the diameters and heights of trees in the dataset were 4.4–41.2 cm and 5.5–31.0 m for *T. grandis*, and 0.5–19.8 and 1.7–26.0 m for *E. camaldulensis* (Tables 1 and 2).

Reconstruction of biomass allometric equations

ANCOVA was used to test the differences in the slopes and elevations of the selected regression lines. The slopes and elevations were compared using ANCOVA to the straight lines obtained by the standard regression method (Zar, 2010). Spacing was used as the main factor (2 m × 4 m, 2 m × 8 m, 3 m × 3 m and 4 m × 4 m spacing for *T. grandis* and 2 m × 3 m, 2 m × 4 m, 2 m × 8 m and 3 m × 3 m spacing for *E. camaldulensis*) whereas location was used as the covariable (Tables 1 and 2). Models that were based on data sets that exhibited no significant difference ($p > 0.05$) detected in the linearly independent, pairwise comparisons among the estimated marginal means were accepted as valid (Fuwape et al., 2010). Combinations of biomass allometric equations for *T. grandis* and *E. camaldulensis* regression models were also tried.

Data from valid regressions were combined and used to fit new allometric equations. Predictor variables were chosen from D and H alone, with differing combinations of D and H. A simple weighing function (D + 1) was applied to correct for possible curvilinearity caused by a large range of D (Montagu et al., 2005). The models based on the mathematical simplicity and applied relevance were tested separately for various tree components consisting of stems, branches and leaves. The models consisted of: $y = a(D)^b$, $y = a(D + 1)^b$, $y = a(H)^b$, $y = a(DH)^b$ and $y = a(D^2H)^b$ where y is the biomass of the aboveground and the tree components are measured in kilograms per tree, D is the diameter at breast height measured in centimeters, H is the height measured in meters and a and b are parameter estimates. Linear regressions of untransformed data were used in the present study because log transformed data introduced a systematic bias that must be corrected when back-transforming values (Sprugel, 1983). The best-fit models were selected by considering the highest coefficient of determination (R^2) value, the lowest *p* value and the lowest SE.

Table 1
Data sets of aboveground biomass allometric equations of *Tectona grandis* of Thailand in the form $y = a(D^2H)^b$ where D is diameter at breast height and H is total height.

Site	*n*	Spacing	Age	D	H	Equation			Source
		(m × m)	(yrs)	(cm)	(m)	*A*	*b*	R^2	
Sop Phueng Plantation, Lampang	10	4 × 4	14	5.6–20.7	7.4–18.6	0.025	0.983	0.988	Petmark, 1977
Thong PhaPhum Plantation, Kanchanaburi	5	3 × 3	6	4.4–11.7	5.5–10.8	0.045	0.880	0.973	Viriyabuncha et al., 2001
Thong PhaPhum Plantation, Kanchanaburi	5	4 × 4	14	13.5–24.3	13.1–17.6	0.021	1.006	0.997	Viriyabuncha et al., 2001
Thong PhaPhum Plantation, Kanchanaburi	11	4 × 4	21	18.3–33.2	20.5–28.7	0.005	1.151	0.995	Viriyabuncha et al., 2001
Mae Cheam Plantation, Chiang Mai	10	2 × 8	8	6.0–19.6	4.8–11.9	0.025	1.019	0.978	Doangsrisen and Viriyabuncha, 2002
Mae Cheam Plantation, Chiang Mai	10	4 × 4	21	9.8–28.3	12.5–18.1	0.022	1.016	0.969	Viriyabuncha et al., 2002
Si Satchanalai Plantation, Sukhothai	5	4 × 4	9	11.6–21.8	14.1–17.1	0.008	1.115	0.993	Viriyabuncha et al., 2002
Si Satchanalai Plantation, Sukhothai	8	4 × 4	13	12.1–23.8	13.9–17.1	0.043	0.928	0.995	Viriyabuncha et al., 2002
Si Satchanalai Plantation, Sukhothai	5	4 × 4	21	17.6–38.0	21.0–29.6	0.026	0.966	0.963	Viriyabuncha et al., 2002
PuParn Royal Development Study Centre, SakonNakhon	5	4 × 4	22	5.6–11.9	7.4–12.9	0.080	0.871	0.990	Sripattanasuwan et al., 2009
Mae Chang Plantation, Lampang	5	2 × 4	17	9.4–22.9	12.6–16.9	0.011	1.088	0.994	Viriyabuncha and Peawsa-ad, 2011
Mae Chang Plantation, Lampang	5	4 × 4	22	12.4–26.9	14.2–19.5	0.015	1.057	0.984	Viriyabuncha and Peawsa-ad, 2011
SaiYok I Plantation, Kanchanaburi	7	4 × 4	30	16.9–41.2	14.0–31.0	0.039	0.933	0.891	This study

R^2 = correlation coefficient.