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Original article

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

Waraporn Ounban,* Ladawan Puangchit, Sapit Diloksumpun

Department of Silviculture, Faculty of Forestry, Kasetsart University, Bangkok 10900, 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-

* Corresponding author.
E-mail address: warapornounban@gmail.com (W. Ounban).

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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.

Table 2
Data sets of aboveground biomass allometric equations of *Eucalyptus camaldulensis* in 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	
The Agroforestry Research and Demonstration plots, Srisaket	12	2 × 4	2–4	3.5–18.7	6.2–21.7	0.054	0.897	0.995	Chakrapholwararit, 1985
Somdet Plantation, Kalasin	5	2 × 8	4	3.0–12.5	5.5–19.6	0.038	0.919	0.996	Tirasankka, 1985
Bandan-Lanhoy Plantation, Sukothai	5	2 × 4	4	4.5–11.5	7.8–13.7	0.006	1.175	0.994	Tirasankka, 1985
Lad Krathing Plantation, Cha Choeng Sao	5	2 × 3	1	1.9–3.5	2.8–6.2	0.077	0.780	0.983	Phanthavong, 2004
Lad Krathing Plantation, Cha Choeng Sao	5	2 × 3	2	3.2–7.0	5.5–10.8	0.028	0.936	0.987	Phanthavong, 2004
Lad Krathing Plantation, Cha Choeng Sao	5	2 × 3	3	4.3–11.8	7.8–13.7	0.068	0.815	0.996	Phanthavong, 2004
Lad Krathing Plantation, Cha Choeng Sao	5	2 × 3	4	4.4–16.7	7.8–22.1	0.027	0.962	0.998	Phanthavong, 2004
Lad Krathing Plantation, Cha Choeng Sao	5	2 × 3	5	6.4–17.9	7.2–20.9	0.056	0.876	0.998	Phanthavong, 2004
Lad Krathing Plantation, Cha Choeng Sao	5	2 × 3	6	5.7–18.7	10.5–21.7	0.029	0.968	0.999	Viriyabuncha et al., 2004
PuParn Royal Development Study Centre, SakonNakhon	5	2 × 4	23	12.2–16.5	19.6–22.1	0.030	1.028	0.940	Sripattanasuwan et al., 2009
KlongTakrao Plantation, Cha Choeng Sao	10	3 × 3	5	2.6–13.4	2.3–16.9	0.076	0.838	0.993	Viriyabuncha et al., 2009
KlongTakrao Plantation, Cha Choeng Sao	10	2 × 4	13	4.4–19.8	8.9–26.0	0.019	1.027	0.997	Viriyabuncha et al., 2009
Mancha Khiri Plantation, KhonKaen	22	2 × 3	1–4	0.5–12.2	1.7–14.2	0.296	0.630	0.250	Jundang, 2010
OngPhra Plantation, SuphanBuri	15	2 × 3	3, 5, 6	2.9–17.5	5.1–24.1	0.060	0.889	0.992	This study

R^2 = correlation coefficient.

Validation of biomass allometric equations

To validate the newly constructed general allometric equations, tree harvestings for biomass determination was undertaken in *T. grandis* and *E. camaldulensis* plantations. The *T. grandis* plantation was selected at Sai Yok, Kanchanaburi province located at 14° 16′N and 98° 55′E with a mean annual temperature and rainfall of 27.0 °C and 1338 mm, respectively. The plantation covered 3927.29 ha and consisted of stands aged. 25 yr, 29 yr, 30 yr, 34 yr and 35 yr. The *E. camaldulensis* plantation was chosen in Ong Phra plantation, Suphan Buri province located at 14° 43′N and 99° 25′E with 28.4 °C and 1107 mm mean annual temperature and rainfall, respectively. The plantation covered 988 ha and consisted of stands aged 3 yr, 5 yr and 6 yr. Both plantations were selected for validation because they were not included in the data used to construct the equations and the diameters of trees were in the range of the data used to construct the equations.

Before conducting the destructive sampling, the diameter distribution of each species was explored by setting up three randomly located sample plots of 40 m × 40 m in stands of each age with a total of 15 plots for *T. grandis* and 9 plots for *E. camaldulensis*. The diameter at breast height (D) of all trees in the sample plots was measured. Sample trees were selected with the D distributed across all D size classes, 7 trees (ranging from 16 cm to 41 cm) for *T. grandis* and 15 trees (ranging from 2.9 cm to 17.45 cm) for *E. camaldulensis*. All sample trees were required to be single-stemmed and to have a uniform canopy. The total height of trees was measured after felling. Harvested trees were dissected into their component parts (stem, branches and leaves). The fresh weight of each component was obtained in the field using a spring scale recorded to the nearest gram. Subsamples of approximately 200–300 g for each component were taken for dry-weight determination in the laboratory. Dry weights to the nearest 0.1 g were obtained by drying the samples at 80 °C until constant weight was achieved. The dry biomass of each component was then calculated by multiplying the fresh weight of each component by the dry weight: fresh weight ratio of the corresponding samples. The aboveground biomass of the tree was obtained by summing the dry weights of the stem, branches and leaves.

The destructive biomass data sets for *T. grandis* and for *E. camaldulensis* were compared with the biomass data estimated from the reconstructed biomass allometric equations of the corresponding species in the study. The differences between the measured data and estimated biomass values were analyzed using paired t tests.

Results and discussion

Construction of general allometric equations

The objective was to determine the most suitable predictor variables to produce general, non-site-specific biomass relationships for *T. grandis* and *E. camaldulensis*, which are the major economic plantation species in Thailand. This would provide useful information for the large scale estimation of carbon sequestration. General biomass allometric equations have been examined and successfully reported for many species (Jenkins et al., 2003; Montagu et al., 2005). Traditionally, D and H are used as separate predictor variables in biomass allometric equations for the various tree components (stem, branches and leaves) and the total

Table 3
General allometric equations used to predict biomass of each component of tree (kilograms dry weight per tree) from D^2H (cm^2 m) for *Tectona grandis* where D is diameter at breast height and H is height.

Equation	R^2	SE	*F* value	*p* value
$W_s = 0.031(D^2H)^{0.932}$	0.988	0.155	6853.108	<0.001
$W_l = 0.022(D^2H)^{0.694}$	0.692	0.703	184.666	<0.001
$W_b = 0.004(D^2H)^{0.984}$	0.800	0.748	327.910	<0.001
$AGB = 0.045(D^2H)^{0.921}$	0.975	0.224	3198.532	<0.001

R^2 = correlation coefficient; W_s = weight of stem; W_l = weight of leaves; W_b = weight of bark; AGB = above ground biomass.

Table 4
General allometric equations used to predict biomass of each component of tree (kilograms dry weight per tree) from D^2H (cm^2 m) for *Eucalyptus camaldulensis* where D is diameter at breast height and H is total height.

Equation	R^2	SE	*F* value	*p* value
$W_s = 0.019(D^2H)^{1.005}$	0.977	0.228	3927.272	<0.001
$W_l = 0.013(D^2H)^{0.721}$	0.705	0.691	220.258	<0.001
$W_b = 0.015(D^2H)^{0.697}$	0.757	0.585	287.237	<0.001
$AGB = 0.035(D^2H)^{0.953}$	0.982	0.190	5065.877	<0.001

R^2 = correlation coefficient; W_s = weight of stem; W_l = weight of leaves; W_b = weight of bark; AGB = above ground biomass.

Table 5
General allometric relationship of *Tectona grandis* using D and H as predictor variables with different combinations where D is diameter at breast height and H is total height.

Equation	R^2	SE	*F* value	*p value*
$Ws = 0.031(D^2H)^{0.932}$	0.988	0.155	6853.108	<0.001
$Ws = 0.055(D)^{2.558}$	0.978	0.212	3613.501	<0.001
$Ws = 0.023(D + 1)^{2.808}$	0.977	0.214	3544.717	<0.001
$Ws = 0.015(H)^{3.106}$	0.915	0.416	879.633	<0.001
$Ws = 0.023(DH)^{1.457}$	0.986	0.170	5663.376	<0.001
$AGB = 0.045(D^2H)^{0.921}$	0.975	0.224	3198.532	<0.001
$AGB = 0.077(D)^{2.546}$	0.978	0.212	3592.911	<0.001
$AGB = 0.032(D + 1)^{2.795}$	0.977	0.214	3522.573	<0.001
$AGB = 0.025(H)^{3.024}$	0.875	0.501	575.206	<0.001
$AGB = 0.034(DH)^{1.436}$	0.967	0.257	2404.393	<0.001

R^2 = correlation coefficient; W_s = weight of stem; AGB = above ground biomass.

aboveground biomass can be achieved by summing individual components or be estimated directly from predictor variables. In the present study, the general allometric biomass regressions reconstructed for all tree components showed highly significant relationships ($p < 0.01$) with the predictor variables but relatively low relationships for branches and leaves in both *T. grandis* and *E. camaldulensis*. The slope (*b*) of the branch and leaf components showed significant ($p > 0.05$) differences among the different spacings tested using ANCOVA. According to Zar (2010), if significant differences are found among regression slopes, the common regression is not appropriate. Therefore, general allometric equations for branches and leaves were excluded in the present study—only the stem and total aboveground biomass estimations were reported. This is relevant to the application of regional scale estimates of forest carbon estimation which have a primary emphasis on the stem or total aboveground biomass. Combining the allometric equations for *T. grandis* and *E. camaldulensis* was also tried without success because the *b* coefficients of both species differed significantly ($p > 0.05$), so no further analysis was undertaken. This was probably due to the wood specific gravity of both species as *T. grandis* is slow growing while *E. camaldulensis* is fast growing. Fayolle et al. (2013) suggested that the wood specific gravity at the species level is important information for the accurate estimation of biomass from general multi-species allometric equations. This was confirmed by Arevalo et al. (2007) who considered that a species-specific equation is needed to have an acceptable error for the biomass estimation while a generalized equation could be applied across clones of the same species. Therefore, generalized equations were developed separately for *T. grandis* and *E. camaldulensis*.

In the present study, the general regression models developed for estimating the biomass aboveground and of the stem of *T. grandis* and *E. camaldulensis* all showed a good fit. The R^2, SE and F

Table 6
General allometric relationships of *Eucalyptus camaldulensis* using D and H as predictor variables with different combinations where D is diameter at breast height and H is total height.

Equation	R^2	SE	*F* value	*p* value
$Ws = 0.019(D^2H)^{1.005}$	0.977	0.228	3927.272	<0.001
$Ws = 0.092(D)^{2.429}$	0.946	0.386	1617.705	<0.001
$Ws = 0.017(D + 1)^{3.032}$	0.975	0.265	3520.813	<0.001
$Ws = 0.011(H)^{2.986}$	0.935	0.423	1327.156	<0.001
$Ws = 0.032(DH)^{1.364}$	0.959	0.338	2129.710	<0.001
$AGB = 0.035(D^2H)^{0.953}$	0.982	0.190	5065.877	<0.001
$AGB = 0.199(D)^{2.185}$	0.918	0.434	1035.322	<0.001
$AGB = 0.042(D + 1)^{2.746}$	0.959	0.307	2159.976	<0.001
$AGB = 0.028(H)^{2.702}$	0.918	0.434	1032.086	<0.001
$AGB = 0.074(DH)^{1.231}$	0.935	0.387	1328.353	<0.001

R^2 = correlation coefficient; W_s = weight of stem; AGB = above ground biomass.

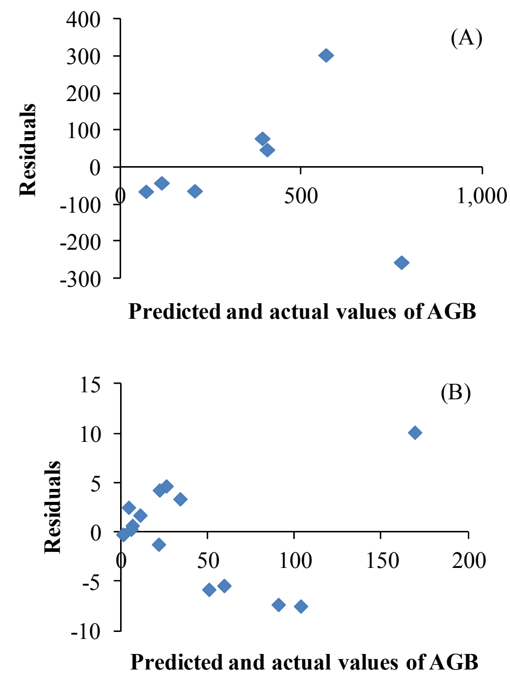

Fig. 1. Residuals of differences between predicted and actual values for aboveground biomass (AGB): (A) *Tectona grandis* and (B) *Eucalyptus camaldulensis*.

values all indicated that the models developed were good and useful for estimating the biomass of all components for both species (Tables 3 and 4). This indicates that robust estimates of biomass for *T. grandis* and *E. camaldulensis* can be made across locations despite different spacing using general allometric regressions without the need for site-specific regressions. This was confirmed by the findings of Arevalo et al. (2007) who found that site factors have less impact on a biomass allometric equation and could be omitted when making biomass estimates.

Diameter at breast height or D (1.3 m above ground) is the most common predictor variable and the easiest variable to measure in the field and was strongly related to the stem and aboveground biomass for *T. grandis* and *E. camaldulensis*. Incorporating tree height as the second independent variable to diameter improved the biomass allometric equations in many cases (Schmitt and Grigal, 1981); however, the results in the present study showed that using D alone as a predictor variable provided similar accuracy to that obtained using D and H for both species (Tables 5 and 6). This agreed with the study by Montagu et al. (2005) who demonstrated that an allometric model based on D alone can accurately predict biomass in *Eucalyptus pilularis*. Adding height to the equation slightly increased the performance of the general allometric equations for *E. camaldulensis*, while performance decreased slightly for *T. grandis* except for stem biomass. It seemed that the height variation was greater for *T. grandis* compared to *E. camaldulensis*. Brown et al. (1995) reported that measurement errors associated with height measurement are within 10%–15% while the error for D measurements typically was less than 3%. The constant nature of the D aboveground biomass allometric equations is a biomechanical requirement of the stem to support the increasing weight (Montagu et al., 2005) which can be achieved by increasing the stem diameter (King, 1986). This is consistent with the common scaling laws proposed for trees (Enquist, 2002). Madgwick (1979) suggested that adding the constant to D (that is, D + 1) could increase the biomass relationship because the curvilinearity of the span data sets was correct. However, in the present study, the addition of the constant did not affect the proportion of biomass variation accounted for by D (Tables 5 and 6). Most biomass allometric equations constructed for plantation species in Thailand have indicated that adding tree height as the second independent variable improved the biomass allometric equations which agreed with the results from the present study, while tree height alone was the worst predictor variable for both species. This is consistent with the suggestion made by Feldpausch et al. (2012) that tree height is an important allometric factor that needs to be considered to improve the forest biomass estimate. However, due to the difficulty of height measurement, if general biomass allometric equations without a height parameter prove to be accurate, biomass estimation would be easier and more practical. This is particularly useful for estimating biomass and carbon sequestration using forest inventory data.

Validation of biomass allometric equations

The newly constructed allometric equations for *T. grandis* and *E. camaldulensis* were used to compare estimates with the destructive samples for both species. The generalized regression of all models accounted for greater than 90% of the variation in prediction by the original regression in which the simple combination of D^2H as the prediction parameter produced the best estimation. Estimations from all the models with D as a predictor parameter were very close for teak with no significant differences with D^2H (Table 5). However, variation in the biomass of large-sized trees is commonly high in *T. grandis* since it is a long rotation species and the variation in growth performance becomes larger as the trees grow older and so it is difficult to construct any simple allometric equations to fit all sizes. For *E. camaldulensis*, which is short rotation species, the general equation produced very good estimates that were much better compared to other published equations (Fig. 1–2). The residual plot showed a fairly random pattern for

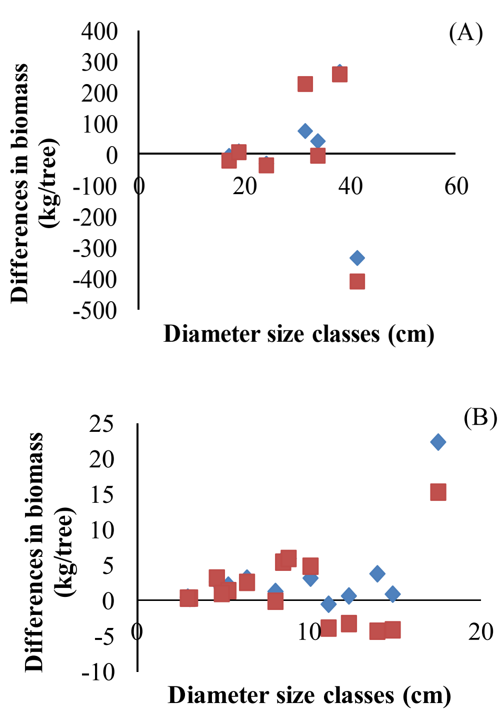

Fig. 2. Differences between estimated and measured biomass by diameter size classes: (A) *Tectona grandis*; (B) *Eucalyptus camaldulensis* (◆ = weight of stem difference; ■ = aboveground biomass difference).

both species. This random pattern indicated that a good model had provided a decent fit to the data. The best-fit models to estimate stem and aboveground biomass adjusted well in the interval of diameters sampled (4–50 cm) for *T. grandis* and (5–20 cm) for *E. camaldulensis*. These models should be carefully used outside the specified diameter range. The range of D and H should be 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*; which were considered to be the most appropriate and nearest to the acceptable ranges of statistics.

Conflict of interest

The authors declare that there are no conflicts of interest.

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