Estimation of biomass and carbon stock in young teak plantations in Thailand

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Abstract

We estimated biomass and carbon stock from allometric relationships between tree size parameters (diameter at breast height [DBH], tree height) and plant part biomass (leaves, stems, total root biomass) in young teak (*Tectona grandis* L.f.) plantations of different ages (5–33 years) and with different site index values in Thailand. In total, 101 trees from 18 sites and 76 trees from 15 sites (stand age: 5–33 years) were harvested to estimate above-ground biomass (stems, branches, leaves), and below-ground biomass. The coefficients of correlation for the obtained allometric relationships between tree DBH and stem, branch, and above-ground biomass showed high values, ranging from 0.94 to 0.99 at each site. DBH also had a high correlation with below-ground biomass (R^2=0.90). Similar wood density of the sampled trees might have reduced site-specific differences. The present results indicated that stem, branch, above-ground biomass, and below-ground biomass might be estimated from our allometric equations with DBH data even when collected from site with different index values, and climatic conditions. Stand-level carbon stock amount was estimated using the present equations. Above-ground and below-ground carbon stock ranged from 1.3 to 67.7 Mg ha^{-1} and from 0.4 to 13.7 Mg ha^{-1}, respectively. These values were similar to other studies in Thailand.

Keywords: Biomass estimation, Root biomass, Wood density, Carbon stock, *Tectona grandis*

Introduction

Estimation of biomass and/or carbon storage in forests plantations is important not only to understand forest ecological traits (production, carbon cycling, etc.), but also to develop new initiatives to manage forests, for example reducing emissions from deforestation and degradation in developing countries (REDD+) as part of the United Nations framework convention on climate change (UNFCCC 2008).

Teak (*Tectona grandis* L.f.) is one of the most important timber species in tropical areas. It is naturally distributed in seasonal tropical areas of India, Myanmar, Laos, and Thailand. Teak has also been planted widely in tropical countries across Africa and Central and South America. It can grow in a wide variety of soils, and tolerates a wide range of climates. In Thailand, the natural habitat of teak is mixed deciduous forest in the northern and central regions. Teak plantations have been cultivated by the Royal Forest Department (RFD) in Thailand since 1906. Plantation intended for wood production has been undertaken by commercial enterprises, the private sector, and by farmers as part of a Thai governmental subsidy project (Royal Forest Department 2002). In 2000, the area of teak plantation was estimated at 836,000 hectares in Thailand (FAO 2001). Thus, teak is an important plantation tree species and it is important for evaluating carbon stocks in teak stands in Thailand.

To estimate tree and forest biomass and/or carbon storage accurately, it is preferable to develop allometric relationships between plant-part biomass and tree size parameters such as tree height and diameter in order to avoid destructive estimations, and it is possible to investigate large areas (Brown 1997; Chave et al. 2005). Many studies have been conducted to develop allometric equations to estimate biomass in teak plantations in several countries (Kraenzel et al. 2003; Pérez Cordero and Kanninen 2003; Hase and Foelster 1983; Nwoboshi 1983; Ola-Adams 1993; Buvaneswaran et al. 2006; Negi et al. 1995; Singh et al. 1980; Jha 2015; Purwanto and Shiba 2005). In Thailand, biomass estimation on teak plantation has been mainly conducted in northern and western regions (Viriyabuncha and Peawsa-ad 2003; Vacharangkura et al. 2005; Hiratsuka et al. 2005; Meunpong et al. 2010). To reduce the variation in collected data and to produce accurate allometric equations, most of these studies made site-specific equations or equations developed from several sites. However, estimation of biomass and carbon stock in teak plantations is needed at a national or international level.

To estimate stand-level biomass, it is necessary to estimate below-ground biomass. Although many studies of above-ground biomass have been reported, data on below-ground biomass is still limited in tropical regions because of the difficulty in sampling (Niiyama et al. 2010; Ziegler et al. 2012). So, the information on below-ground biomass for teak plantation is limited in Thailand (Hiratsuka et al. 2005; Meunpong et al. 2010; Takahashi et al. 2011) and other regions (Kraenzel et al. 2003; Negi et al. 1995; Prasad and Mishra 1984). To estimate below-ground biomass accurately, it is necessary to determine the allometric relationship between tree size parameters (e.g. diameter as breast height [DBH], and $DBH^2 \times H$) and root biomass.

The objective of this study was to (1) to collect biomass data from wide area where are different climates, site index values, and ages. (2) to estimate above- and below-ground biomass and (3) to estimate carbon stock of teak plantations in Thailand.

Method and materials

Study sites

In Thailand, teak plantations have been established mainly in the northern and western regions, where soil conditions are generally suitable for teak growth (i.e. nutrient-rich, deep alluvial soils), and are distributed sparsely in other regions (Kaosa-ard 1989). For field measurements and sampling, we selected 18 teak plantations (11 districts) from 7 provinces in western, north-eastern, northern, and central Thailand (Table 1, Fig. 1). Among these, four stands of different ages were further selected at one site in Kanchanaburi Province (KKV1, -2, -3, -4). Ages of the 18 stands ranged from 5 to 33 years old (Table 1).

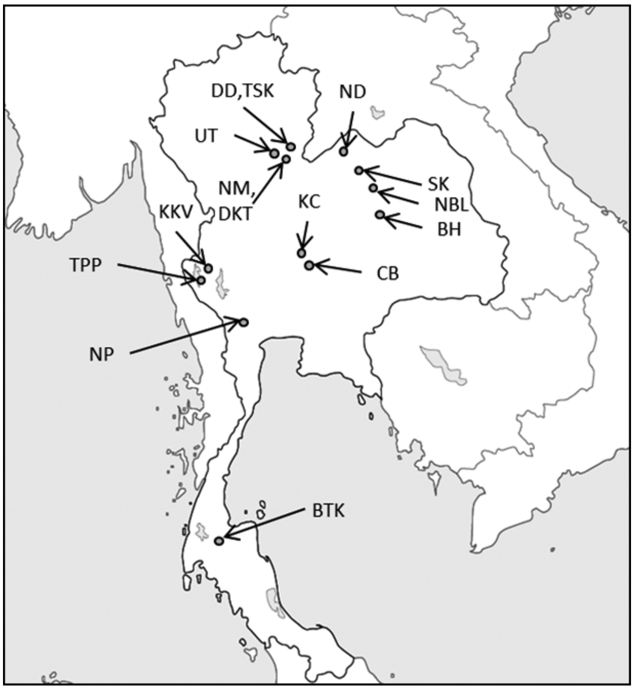

Fig.1. Location of each research site in Thailand.

The climate of these study regions is tropical monsoon, which is characterized by a rainy season from May to September and a dry season from October to April. Mean annual temperature is almost the same in all sites, around 27 °C. Annual precipitation is somewhat different by region, with the total amount (about 1,650 mm) in Thong Pha Phum District (KKV and TPP) in Kanchanaburi province (Marod et al. 2002), western region, being larger than those (about 1200 mm) in other districts in Kanchanaburi Province and some other provinces (Lop Buri, Uttaradit, Nong Bua Lum Phu and Khon Kaen) (Thai Meteorological Department). Soil types at the research sites included seven types from the classification of the USDA soil taxonomy (Vijarnsorn and Jongpakdee 1979) (Appendix I). Topography of the research sites was gentle slopes at KKV3, TPP and ND, and flat at the other sites.

Field measurements and sampling

An experimental plot (40×40 m^2 in area) was established in each of the 17 teak plantations (not established at BTK). In each plot, all living teak trees inside the plot were labeled, and their stem DBH (1.3 m) was measured using measuring tape. Tree height (H) was measured using a Vertex III (Haglöf, Sweden). Stand mean DBH and H ranged from 6.3 to 34.7 cm and from 4.3 to 22.6 m, respectively (Table 1). The values of mean DBH and H differed greatly even among the similar-aged stands for a given province (e.g. TPP versus NM). Tree density varied from 163 to 1,106 trees ha^{-1}, which reflected the differences in stand age but also in other factors, such as initial planting density, thinning treatment and mortality. The site index of each stand, which was defined as the dominant tree height at a stand age of 30 years, ranged from 12 to 32 (Table 1); the value of the dominant tree height was calculated using the height growth model proposed by Vacharangkura (2012).

Three to ten teak trees of different sizes were selected in each plot, and a total of 101 trees were harvested to obtain dry mass data of above- and below-ground components (Table 1). For the selection of sample trees, individuals with damaged crowns or broken trunks were excluded. After felling, some size parameters, such as DBH, H, and stem diameters at ground level (D_0), were measured. The harvested trees ranged from 3.0 to 43.9 cm in DBH and from 2.9 to 26.7 m in H. For each sample tree, above-ground components were separated into stems, branches, and leaves, and their fresh masses were measured in the field.

Some portions of each component (≥ 0.5% of total fresh mass) were brought back to the laboratory, and their dry/fresh mass ratios were determined after oven-drying at 85 °C until a constant value was obtained. The dry mass of each component was obtained using the corresponding dry/fresh ratio.

Of 101 sample trees, 76 individuals were subjected to root excavation. These excavated trees were selected to cover almost the same size range of whole sample trees; from 3.0 to 43.9 cm in DBH, and from 2.9 to 25.5 m in H. Each root system was excavated carefully using heavy shovel machinery and/or hand tools. First, coarse roots (>5 mm in diameter) were collected, then fine roots (<5 mm in diameter) were collected as much as possible. Fresh

Table 1. Comparison of investigation example

Research Site		Age [year]	Site Index	Planted spacing [m]	Initial tree density [trees/ha]	Present tree density [trees/ha]	n AGB	n BGB	Mean DBH [cm]	Mean Height [m]
West Thailand										
Kanchanaburi Province										
Dan Makham Tia District (NP)	13°49'N, 99°26'E	20	21	2 × 4	1250	825	5	5	14.9 ± 3.7	14.9 ± 1.9
Thong Pha Phum District (KKV1)	14°52'N, 98°40'E	27	28	4 × 4	625	513	5		24.0 ± 6.5	21.5 ± 4.0
Thong Pha Phum District (KKV2)	14°52'N, 98°40'E	21	22	4 × 4	625	431	6	6	20.8 ± 6.5	15.8 ± 3.4
Thong Pha Phum District (KKV3)	14°50'N, 98°40'E	10	25	4 × 4	625	481	5	5	10.3 ± 4.5	10.1 ± 4.4
Thong Pha Phum District (KKV4)	14°50'N, 98°40'E	14	32	4 × 4	625	506	5	5	19.8 ± 4.0	19.5 ± 3.5
Thong Pha Phum District (TPP)	14°38'N, 98°36'E	33	24	4 × 4	625	256	5	5	31.3 ± 5.2	22.6 ± 2.1
North-east Thailand										
Khon Kaen Province										
Ban Haet District (BH)	16°15'N, 102°47'E	6	12	4 × 4	625	275	7	7	6.3 ± 2.4	4.3 ± 1.8
Loei Province										
Na Duang District (ND)	17°35'N, 102°01'E	31	23	2 × 8	600	163	5	5	34.7 ± 5.2	21.5 ± 2.7
Nong Bua Lam Phu Province										
Muang Nong Bua Lam Phu District (NBL)	17°12'N, 102°17'E	21	10	2.5 × 2.5	1600	950	5	5	8.3 ± 2.4	6.5 ± 2.0
Suwannakhuha District (SK)	17°33'N, 102°16'E	15	27	2 × 3	1650	306	8		15.8 ± 4.2	16.8 ± 2.8
Central Thailand										
Lop Buri Province										
Chai Badan District (CB)	15°19'N, 101°10'E	11	27	3 × 3	1089	594	5	3	17.2 ± 2.2	16.2 ± 1.1
Khok Charoen District (KC)	15°26'N, 100°52'E	19	27	3 × 3	1089	688	5		19.0 ± 3.5	19.3 ± 2.0
North Thailand										
Uttaradit Province										
Muang Uttaradit District (DD)	17°41'N, 100°17'E	10	25	4 × 4	625	613	5	5	15.2 ± 2.6	14.3 ± 1.2
Muang Uttaradit District (UT)	17°38'N, 100°5'E	5	28	2 × 4	1250	1106	5	5	10.2 ± 1.9	11.6 ± 1.5
Thong Sean Khan District (DKT)	17°35'N, 100°13'E	12	21	2 × 4	1250	606	5	5	11.6 ± 1.6	11.7 ± 1.1
Thong Sean Khan District (NM)	17°32'N, 100°27'E	33	14	2 × 3	1650	575	5	5	15.1 ± 3.1	12.9 ± 1.5
Thong Sean Khan District (TSK)	17°32'N, 100°16'E	19	22	2 × 4	1250	756	10	5	15.8 ± 4.3	15.0 ± 2.7
South Thailand										
Surat Thani Province										
Ban Ta Khun District (BTK)	8°58'N, 98°50'E	9		-	-	-	5	5	-	-
Total							101	76		

masses of these collected roots were measured in the field after removing soil. Dry masses of coarse and fine roots of each sample tree were obtained using the corresponding dry/fresh ratio determined in the same manner as for above-ground components.

Wood density is often incorporated as an important parameter in developing allometric equations for forest biomass estimation, especially in tropical forests (e.g., Chave et al. 2005; 2014; Kenzo et al. 2009b). To examine variation in the wood density of teak trees by site and/or age, wood cores were collected from stems at breast height and from coarse roots about 20 cm below ground level for each sample tree in 16 plantations using an increment borer with a 5.15 mm core diameter (Mattoson, Sweden). After collecting the wood core, we divided it into heartwood and sapwood by the wood color. The diameters of both ends and the length of each core were measured using a digital caliper. Wood volume was calculated by multiplying the length by the mean cross sectional area of the two ends. The dry mass of each wood sample was measured after oven-drying at 85 °C until a constant value was obtained, then its wood density (g cm^{-3}) was calculated as the dry mass per unit volume.

Data analysis

DBH and H were tested as independent variables. For the selection of allometric equation types, our preliminary data analysis indicated that a power-form equation ($y = ax^b$; y is the dry mass of each component, x is the size parameter, a and b are coefficients), which was known as the simplest, standard type of allometry (Ogawa et al. 1961; Buvaneswaran et al. 2006). Therefore, hereafter, we describe the procedure of data analysis and results that were confined to this equation type. To determine a good size parameter (x) for estimating each component dry mass, the following three variables were selected and compared; DBH (cm), H (m), and $DBH^2 \times H$ (cm^2 m). For the case of root mass (W_R: coarse plus fine roots), stem diameter at ground level (D_0) was also tested as a potential size parameter. The coefficients of regression (a, b) were determined after logarithmic transformation using the standard major axis method. Then, a correlation factor, CF, was applied for the a-value of each regression to remove systematic bias due to log-transformation (Beauchamp and Olson 1973; Sprugel 1983).

We performed one-way analysis of variance (ANOVA) in a comparison of mean values of wood density among the study stands. Tukey's HSD test ($p < 0.05$) was used for multiple pairwise comparison. The significance of each allometric regression was tested by the coefficient of determination (R^2). We also tested site-specific differences in regressions. Differences were tested by analysis of covariance (ANCOVA). All statistics were calculated by JMP software (version 9.0; SAS).

Results and Discussion

Allometric equations

For each component, all allometric equations using different size variables were significant ($p < 0.01$). When the three variables (DBH, $DBH^2 \times H$, and H) were compared, the correlation (R^2) of DBH-base allometry was the highest or nearly equal to that of ($DBH^2 \times H$)-base allometry. H-base allometry always produced the lowest correlation. For the above-ground components, the allometry for leaves (W_L) showed much weaker correlations (R^2 = 0.28–0.50) than those for stems (Ws, R^2 = 0.89–0.99) and branches (W_B, R^2 = 0.70–0.94) irrespective of size variables (Table 2). Correlations of allometry equations were also high for the above-ground total dry mass (W_{Top}: sum of leaves, branches, and stems) irrespective of size variables: DBH (R^2 = 0.99), $DBH^2 \times H$ (R^2 = 0.98) and H (R^2 = 0.85) (Fig. 2, Table 2).

Below-ground total mass, or the sum of coarse and fine roots (W_R), showed high correlation with DBH-base and D_0-base allometry (R^2 = 0.90 and 0.92, respectively. Table 2). However, ($DBH^2 \times H$) -base and H-base allometry showed lower correlations (R^2 = 0.66–0.85) (Table 2).

Several studies employed tree height as a size parameter (e.g. $DBH^2 \times H$) of allometric equations (Hase and Foelster 1983; Viriyabuncha and Peawsa-ad 2003). Watanabe et al. (2009) reported that precipitation influenced tree height and above-ground biomass in teak. This phenomenon indicated tree heights might be different among the planting sites even though the stem diameter of trees were similar. However, the present results clearly showed that the parameter of DBH alone had high correlations with biomass, though tree heights were different among trees with similar DBH. In this study, a negative correlation between H:DBH ratio of sampled trees and the ratio of W_B per W_{top} was confirmed ($p < 0.0001$; R^2 = 0.53). This result indicated taller teak trees had less W_B than of shorter teak trees when W_B was compared in the same DBH class. So, W_{top} might be similar amount by changing the branch ratio per W_{top} when the tree heights were different in the same DBH class. Other studies also reported that DBH had a high correlation with biomass in teak (Negi et al. 1995; Ola-Adams 1993; Pérez Cordero and Kanninen 2003). The same tendencies were reported for other tropical species in South East Asia (Basuki et al. 2009; Kenzo et al. 2009a; Kenzo et al. 2009b). For the relation with W_R, DBH had a higher correlation than D^2H or D_0 data. It is difficult to measure the D_0 accurately for large teak trees because of the development of butt swelling. Thus DBH data should be used for W_R estimation.

When we compared the slopes of each allometric equations among 18 plantations, there was no significant difference in the slopes (ANCOVA, $p < 0.0001$), except for the BH and CB sites where were young stands. In the BH and CB, there was small range in DBH and Height data because these stands were relatively younger than other study sites. From the present study, tree size parameters (e.g. DBH and $DBH^2 \times H$) had high correlations with plant-part biomass (e.g. W_B, W_S, W_{top}, and W_R) in 18 teak stands. This result indicated that the allometric equations can estimate biomass in 18 teak plantations even where their site index, plant spacing, and region of plantations are different.

Variation in wood density

Mean wood density of stem samples from the plots ranged from 0.49 ± 0.04 to 0.59 ± 0.05 g cm^{-3} for heartwood and 0.47 ± 0.05 to 0.60 ± 0.08 g cm^{-3} for sapwood. Mean wood density of coarse root samples from the plots ranged from 0.50 ± 0.02 to 0.65 ± 0.07 g cm^{-3} for heartwood and from 0.54 ± 004 to 0.68 ± 0.10 g cm^{-3} for sapwood. The values of wood density tended to be larger for teak trees in older stands (e.g. plot ND) than for younger stands (e.g. plot

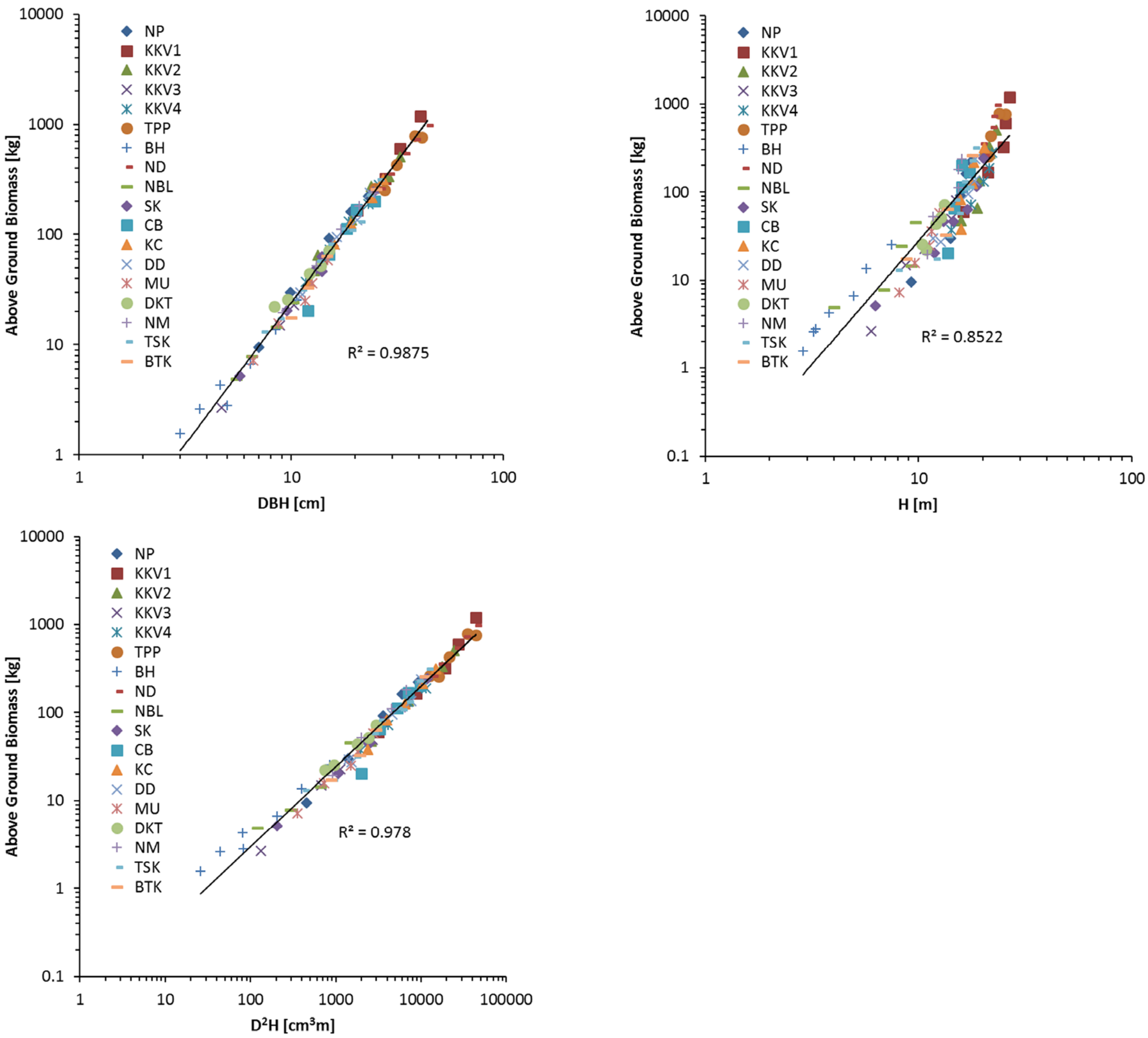

Fig.2. Relationship between DBH, $DBH^2 \times H$, H, and above-ground biomass

Table 2. Coefficient of equations for leaves, branches, stems, and above-ground and below-ground biomass. Corrected coefficient by correction factor (CF). Stem diameter at breast height (DBH), stem diameter at the lowest branch (D_B), and tree height (H)

Dependent variable (y)	Independent variable (x)	n	a	b	R^2	CF	correcting bias using CF a
Leaf dry biomass (kg)	DBH (cm)	100	0.0199	1.7702	0.50	1.100	0.0219
	$DBH^2 \times H$ (cm^2m)	100	0.0201	0.5951	0.44	1.111	0.0223
	H (m)	101	0.0387	1.5726	0.28	1.146	0.0443
Branch dry biomass (kg)	DBH (cm)	100	0.0044	2.8904	0.94	1.018	0.0045
	$DBH^2 \times H$ (cm^2m)	100	0.0033	1.0067	0.89	1.029	0.0034
	H (m)	101	0.0048	2.9488	0.70	1.082	0.0052
Stem dry biomass (kg)	DBH (cm)	100	0.0446	2.6074	0.98	1.004	0.0448
	$DBH^2 \times H$ (cm^2m)	100	0.0289	0.9328	0.99	1.003	0.0290
	H (m)	101	0.0241	2.9273	0.89	1.022	0.0246
Above-ground biomass (kg)	DBH (cm)	100	0.0647	2.5715	0.99	1.003	0.0649
	$DBH^2 \times H$ (cm^2m)	100	0.0447	0.9125	0.98	1.004	0.0449
	H (m)	101	0.0436	2.8063	0.85	1.030	0.0449
Below-ground biomass (kg)	DBH (cm)	75	0.0453	2.1839	0.90	1.017	0.0461
	D_0 (cm)	75	0.0794	1.9571	0.92	1.014	0.0132
	$DBH^2 \times H$ (cm^2m)	75	0.0393	0.7553	0.85	1.026	0.0403
	H (m)	76	0.0577	2.1754	0.66	1.061	0.0612

KKV3). There was few difference in mean wood density of stems among the research sites even though these stands were of different ages, for both of heartwood and sapwood (ANOVA; $F = 2.09$, $p = 0.0073$). Wood density of CB and KKV3 where were younger stand, showed lower than other stand. The average wood density of roots for relatively young stands (CB and KKV3) was significantly lower than those for older sites (ANOVA; $F = 4.17$, $p < 0.0001$).

In this study, stem wood density of teak showed little difference among 12 plantation sites. In addition, there was no significant difference in densities between heartwood and sapwood among the sites. It was reported that the juvenile wood was not inferior to mature wood in terms of wood density or strength in teak wood (Sanwo 1987; Wanneg et al. 2014). Anish et al. (2015) also reported that wood traits such as heartwood percentage, heartwood color, and vessel frequency did not differ between fast and slow grown teak. Thus, the minor differences in wood density among research sites with different environments, growth rates, and plant spacing were one of the reasons for the similarity in the allometric equation in the present study.

Stand level biomass and carbon stock

To estimate stand level biomass of the research plots in this study, for each tree above-ground biomass (W_{Top}) and below-ground biomass (W_R) were estimated using the following equation; $W_{Top} = 0.0637\ DBH^{2.5730}$ and $W_R = 0.0473\ DBH^{2.1836}$ (Table 3). We estimated W_{Top} and W_R by the summation of each tree biomass in the plot, and converted this to an amount per hectare. W_{Top} and W_R ranged from 2.5 to 133.5 Mg ha^{-1} and from 0.8 to 27.4 Mg ha^{-1}, respectively (Table 3). These values were similar to those of similar age stands in other studies in Thailand (Hiratsuka et al. 2005, Meunpong et al. 2010). The difference between present values to other studies might be due to the difference of stand density and site condition. Present study indicated that young teak plantations have similar values of above-ground biomass on natural stand in Dry Dipterocarp Forest (45.0 to 89.7 Mg ha^{-1}, Ogino et al. 1967), and lower value than those of Dry Evergreen Forest (140.1 to 186.2 Mg ha^{-1}, Ogino et al. 1967).

Conversion factors to estimate carbon stock in biomass used 0.50 for teak trees in some studies (Hiratsuka et al. 2005), because the carbon content ranged from 45% to 52% of biomass in teak (Kraenzel et al. 2003; Jha 2005; Muenpong et al. 2010). In this study, stand level carbon stock was calculated by multiplying the above- and below-ground biomass by 0.5. Above-ground and below-ground carbon stock ranged from 1.3 to 67.7 Mg ha^{-1}, and from 0.4 to 13.7 Mg ha^{-1}, respectively (Table 3). Stand level carbon stock also showed a similar value to those at a similar age in Thailand. (Hiratsuka et al. 2005; Meunpong et al. 2010)

The percentage of above-ground and below-ground carbon stock to total carbon stock ranged from 76% to 85% and from 15% to 24%, respectively. Smaller tree size stands showed a higher percentage of below-ground carbon stock to total carbon stock, and bigger tree size stands showed a lower percentage of below-ground carbon stock. Other studies also showed the same tendency in tropical and temperate forests (Cairns et al. 1997; Mokany et al. 2006; Kenzo et al. 2010; Jha 2015). This result indicated that teak trees might allocate a higher ratio of carbon to roots at a small size stage. Below-ground carbon stock showed a similar ratio to that in other study in Thailand (Hiratsuka et al. 2005). Although other studies showed lower below-ground carbon stock ratios than the present data (Jha 2015), it might be caused by different sampling methods. In the present study, we collected as many of the roots as possible. However, another study estimated below-ground carbon stock by collecting roots from soil blocks. The alternative root sampling methods of Mokany et al. (2006) might have resulted the difference in root:shoot ratio values.

Present study could estimate above and below ground biomass and carbon stock in young teak plantations (5–33 years) in Thailand. These values might contribute to estimate carbon stock in forests in Thailand. In addition, present results showed the possibility to make common allometric equation to estimate biomass in young teak plantation in Thailand.

Table 3. Estimated above and below ground biomass [Mg ha^{-1}] and above and below ground carbon stock [Mg ha^{-1}] of teak plantation in various sites in Thailand.

Research Site	Age	Stand density [trees ha^{-1}]	Mean DBH [cm]	Mean Height [m]	Above ground Biomas [Mg ha^{-1}]	Below ground Biomas [Mg ha^{-1}]	Above ground C stock [Mg ha^{-1}]	Below ground C stock [Mg ha^{-1}]	Sources
West Thailand									
Kanchanaburi Province									
Dan Makham Tia District (NP)	20	825	14.9	14.9	62.6	15.3	31.3	7.7	present study
Thong Pha Phum District (KKV1)	27	513	24.6	22.1	135.3	27.4	67.7	13.7	present study
Thong Pha Phum District (KKV2)	21	431	20.8	16.1	81.0	17.2	40.5	8.6	present study
Thong Pha Phum District (KKV3)	10	481	10.3	10.3	17.2	4.6	8.6	2.3	present study
Thong Pha Phum District (KKV4)	14	506	19.8	19.5	76.7	16.7	38.4	8.4	present study
Thong Pha Phum District (TPP)	33	256	31.3	22.6	122.7	23.1	61.4	11.6	present study
Prachuap Khiri Khan Province									
Kui Buri District	15		11.8	13.4	92.9	30.2	43.7	13.8	Muengpong et al. (2010)
North-east Thailand									
Khon Kaen Province									
Ban Haet District (BH)	6	275	5.1	4.3	2.6	0.8	1.3	0.4	present study
Loei Province									
Na Duang District (ND)	31	163	34.8	21.5	100.9	18.3	50.5	9.2	present study
Nong Bua Lamphu Province									
Muang Nong Bua Lam Phu District (NBL)	21	950	8.3	6.5	16.6	4.9	8.3	2.5	present study
Suwannakhuha District (SK)	15	306	16.0	16.4	27.4	6.6	13.7	3.3	present study
Central Thailand									
Lopburi Province									
Chai Badan District (CB)	11	594	17.2	16.2	59.7	14.3	29.9	7.2	present study
Khok Charoen District (KC)	19	688	19.0	19.3	92.8	21.1	46.4	10.6	present study
North Thailand									
Uttaradit Province									
Muang Uttaradit District (DD)	10	613	15.2	14.3	45.6	11.4	22.8	5.7	present study
Muang Uttaradit District (UT)	5	1106	10.8	10.6	30.0	8.7	15.0	4.4	present study
Thong Sean Khan District (DKT)	12	606	11.6	11.7	22.5	6.1	11.3	3.1	present study
Thong Sean Khan District (NM)	33	575	15.1	12.9	43.8	10.8	21.9	5.4	present study
Thong Sean Khan District (TSK)	19	756	15.8	15.0	68.5	16.3	34.3	8.2	present study
Lampang Province									
Mae Mo District	17	844	14.4		71.1	18.2	35.5	9.1	Hiratsuka et al. (2005)
Mae Mo District	22	544	18.4		82.4	16.4	41.2	8.2	Hiratsuka et al. (2005)
South thailand									
Surat Thani Province									
Ban Ta Khun District (BTK)	9	-	-	-	-	-	-	-	present study

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Appendix I. Soil types of the research sites (USDA soil taxonomy).

Research Site		Order	Suborder	Soil Name
West Thailand				
Kanchanaburi Province				
Dan Makham Tia District (NP)	13°49'N, 99°26'E	Alfisols	Ustalfs/Ustults	Loamy Haplustalfs/Loamy Paleustults
Thong Pha Phum District (KKV1)	14°52'N, 98°40'E	Histosols	Fibrists	Slope Complex
Thong Pha Phum District (KKV2)	14°52'N, 98°40'E	Histosols	Fibrists	Slope Complex
Thong Pha Phum District (KKV3)	14°50'N, 98°40'E	Histosols	Fibrists	Slope Complex
Thong Pha Phum District (KKV4)	14°50'N, 98°40'E	Histosols	Fibrists	Slope Complex
Thong Pha Phum District (TPP)	14°38'N, 98°36'E	Histosols	Fibrists	Slope Complex
North-east Thailand				
Khon Kaen Province				
Ban Haet District (BH)	16°15'N, 102°47'E	Entisols	Psamments	Sandy Quartzipsamments
Loei Province				
Na Duang District (ND)	17°35'N, 102° 1'E	Histosols	Fibrists	Slope Complex
Nong Bua Lam Phu Province				
Muang Nong Bua Lam Phu District (NBL)	17°12'N, 102°17'E	Ultisols	Ustults	Skeletal Paleustults
Suwannakhuha District (SK)	17°33'N, 102°16'E	Ultisols	Ustults	Skeletal Paleustults
Central Thailand				
Lop Buri Province				
Chai Badan District (CB)	15°19'N, 101°10'E	Mollisols	Ustoiis	Clayey Haplustolls
Khok Charoen District (KC)	15°26'N, 100°52'E	Mollisols	Ustoiis	Clayey Haplustolls
North Thailand				
Uttaradit Province				
Muang Uttaradit District (DD)	17°41'N, 100°17'E	Histosols	Fibrists	Slope Complex
Muang Uttaradit District (UT)	17°38'N, 100° 5'E	Alfisols	Aqualfs	Clayey Tropaqualfs
Thong Sean Khan District (DKT)	17°35'N, 100°13'E	Ultisols	Ustults/Ustalfs	Skeletal Paleustults/Skeletal Haplustalfs
Thong Sean Khan District (NM)	17°32'N, 100°27'E	Histosols	Fibrists	Slope Complex
Thong Sean Khan District (TSK)	17°32'N, 100°16'E	Ultisols	Ustults/Ustalfs	Skeletal Paleustults/Skeletal Haplustalfs
South Thailand				
Surat Thani Province				
Ban Ta Khun District (BTK)	8°58'N, 98°50'E	Ultisols	Udults	Loamy Paleudults/Loamy Tropudults

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