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Improvement of Utilization Techniques of Forest Resources to Promote Sustainable Forestry in Thailand

Edited by
Masazumi Kayama and Woraphun Himmapan




March 2017
Japan International Research Center for Agricultural Sciences
Tsukuba, Ibaraki, Japan.

Photographs on the cover page

Measurement of stem diameter on coppiced teak at Thong Pha Phum, Kanchanaburi Province.	Thinning experiment plot at teak plantation in Uttaradit Province.
Measurement of branch weight for biomass estimation at teak plantation in Na Duang, Loei Province.	Furniture shop in Udon Thani Province.

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Preface

The present Working Report titled “Improvement of Utilization Techniques of Forest Resources to Promote Sustainable Forestry in Thailand” is the collection of fruitful results from the Joint Research Project “Improvement of Utilization Techniques of Forest Resources to Promote Sustainable Forestry” between Royal Forest Department (RFD) and Japan International Research Center for Agricultural Sciences (JIRCAS) in 2011 – 2016, the second phase of the joint research since 2006.

Thailand had once suffered from a severe deforestation in the latter 20th Century, consequently declining to an almost halved forest coverage of 26% in 1993 within merely three decades. The Thai Government responded to this serious situation proactively. RFD enacted the Forest Plantation Act in 1992 and launched a project to promote the involvement of local farmers in re/afforestation in 1994. As a result, the forest coverage has been stabilized and the private plantations of valuable indigenous timber-tree species were established by farmers throughout Thailand, including the northeast region.

Under such circumstances, RFD and JIRCAS have implemented collaborative research projects since 2006 to grapple with the suitable methods for on-farm tree plantations. In the first phase in 2006 – 2011, they developed silvicultural techniques to convert the plantations of exotic fast-growing tree species into those of indigenous species as well as an agro-forestry management model with profit prediction. Varied results and outputs were shared with the farmers and the stakeholders through trainings, events and publications, including the previous JIRCAS Working Report No. 74 in 2012.

In the second phase in 2011 – 2016, RFD and JIRCAS were working together on improvement of the forest resource utilization techniques for the local farmers, emphasizing on the development of both user-friendly techniques and ways to promote the market demands for the timbers of the economically high-valued indigenous species, such as teak (Tectona grandis), from the plantations established in 1990s and later. This Working Report provides to the readers the research results including silvicultural techniques that can lead to cost reduction and productivity improvement as well as effective evaluation and management methods of the forest resources.

This Working Report is a new milestone of the achievement through the long-lasting collaboration between RFD and JIRCAS. I sincerely hope that the research results presented here would contribute to the farmers and the stakeholders not only in Thailand but also in other countries that are striving for promoting both re/afforestation and local farmers’ livelihood together.

Gen Takao

Director of Forestry Division

JIRCAS

Contents

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).

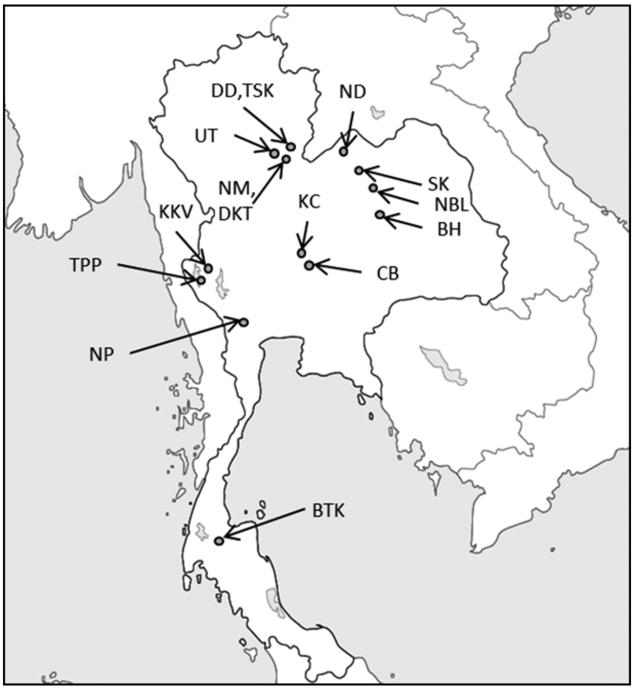

Fig.1. Location of each research site in Thailand.

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 ($40 \times 40\ m^2$ 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

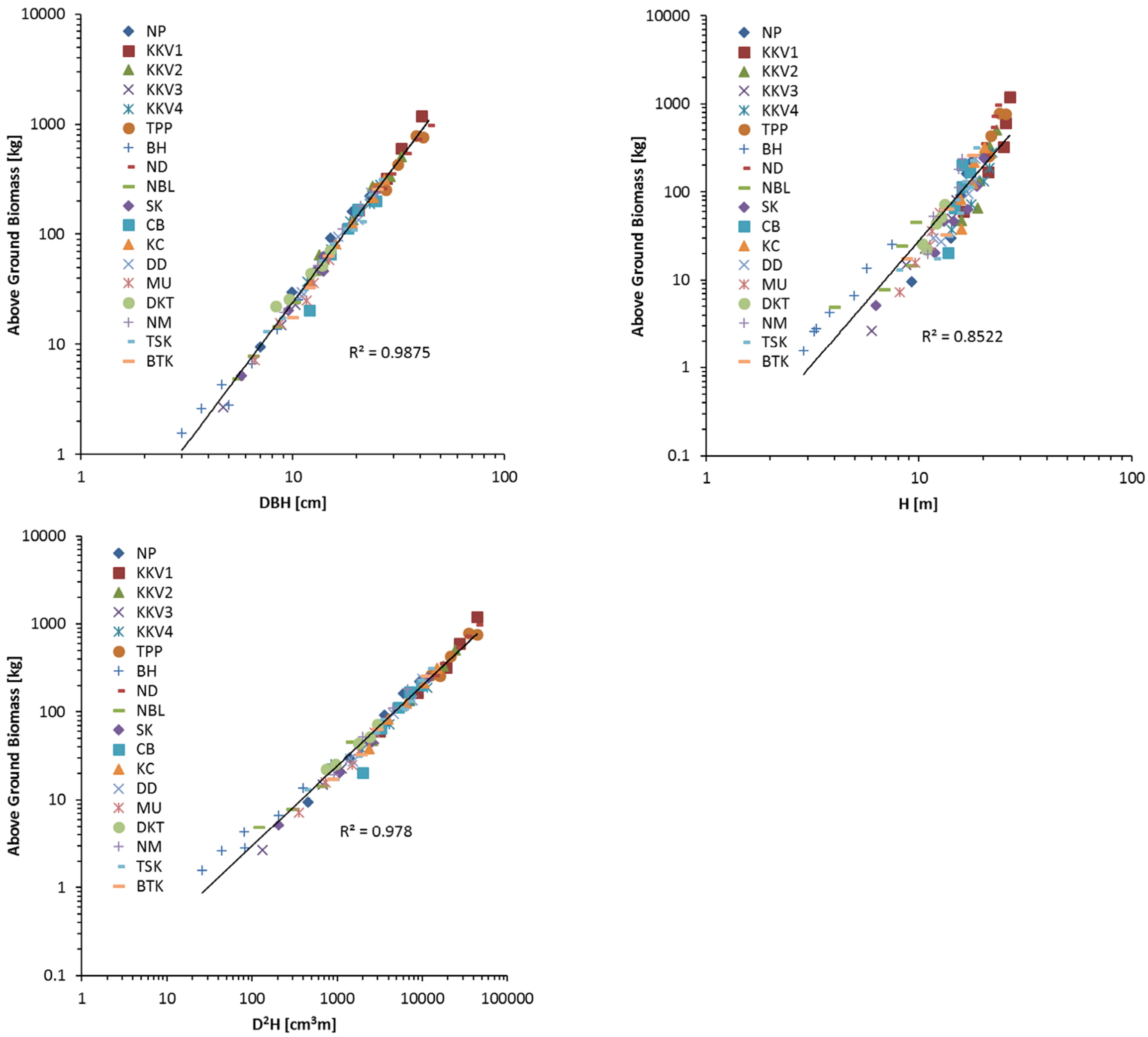

Fig.2. Relationship between DBH, $DBH^2 \times H$, H, and above-ground biomass

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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Potential stereoscopic tree height measurement of teak plantations using Pléiades high-resolution satellite imagery

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Abstract

There is a broad demand for technical development of methodologies for large-scale monitoring of tree plantations. Stereoscopic tree height measurement using optical high resolution satellite imagery is one of the potential means. In this study, the potential of dominant tree height estimation was examined in teak plantations located in the agricultural land mosaics of the northeast Thailand. Terrains were modeled based on the surface measurements surrounding teak plantations. Tree height was estimated as the difference between the tree top position and the estimated terrain. The result was evaluated based on the comparison with the field surveyed dominant tree height. There was a correlation between the estimated and the field-surveyed dominant tree heights. The root-mean-square error was under 2 m. The result clarified the potential of stereoscopic tree height measurement using stereo-paired high resolution satellite imagery targeting on small-scale teak plantation established in the moderate terrain area. Large deviations of dominant tree estimation (< 4 m) were mainly caused by the deviations of terrain modeling. The accuracy of terrain modeling also caused the underestimation and/or the overestimation of dominant tree height at some cases.

Keywords: Thailand, Teak plantation forest, High-resolution satellite imagery, Stereoscopic measurement

Introduction

Teak (*Tectona grandis*) is one of the premier hardwood timbers in the world (Pandey and Brown 2000), but supplies from natural forests have dwindled in most countries. In Thailand harvesting from natural forests was banned in 1989, and thereafter supplies from plantation-grown teak have increased (Pandey and Brown 2000). Across Thailand, large areas of teak plantation had been established through a private tree plantation promotion program using subsidies by the government (Mahannop 2004; Sharp and Nakagoshi 2006). It is important to meet the demand for teak wood with supplies from teak plantations in a sustainable manner. However, there is currently no system or database for monitoring resources, demand, or supply (Mahannop 2004). Therefore, the growth of teak plantations or even information about whether they are still present is unknown because of a lack of monitoring schemes after the large-scale establishment of teak plantations. In the shortage of human resources and budgets for field data collection, an efficient large-scale monitoring scheme using remote sensing is highly expected.

Dominant tree height (DTH) and age are used for estimating the site index, a productivity index derived from tree height, which can be used for modeling stand yields over time (Ritchie et al. 2012). A yield table was created for teak plantation in the northeast of Thailand based on field survey data (Vacharangkura et al. 2011). Although the growth of teak plantations showed large variations among sites depending on site conditions and management status, DTH was considered to be a good parameter that was independent of stand density or the intensity of stand management (Ishibashi et al. 2010). Forest stand height information, such as mean canopy height, was also found to be an important parameter that can be used for biomass or stand volume estimation (Asner et al. 2012; Drake et al. 2002). Forest stand height information has been collected by intensive field surveys. However, considering the application of large-area assessment of tree plantations, tree height information is expected to be efficiently retrieved from remote sensing techniques.

There are a number of potential methods for height measurement using remote sensing techniques (Sirmacek et al. 2012): 1. Optical stereo image analysis (aerial photos and high resolution satellite imagery), 2. Interferometric SAR processing, and 3. LiDAR data processing. Among these methods, optical stereo satellite image analysis has an advantage in its world-wide applicability over large-scale areas. There are multiple satellites or sensors observing land coverage at very high spatial resolution (Poli and Caravaggi 2012). A new generation of high-resolution satellites or sensors also have an up-to-date acquisition capacity. For example, the French Pléiades satellite has high acquisition capacity combined with a constellation of four satellites, Pléiades 1A and 1B and SPOT 6 and 7 (Astrium 2012). The high agility of the Pléiades satellite also allows for flexible acquisition and especially stereo and tri-stereo acquisition along a single orbit (Astrium 2012). Such technical development in satellites or sensors is rapidly opening up a new era of high-resolution optical image monitoring.

In general, to extract tree height information using optical stereo imagery, there are two basic elements: 1. identification of tree top position or tree canopy surface modeling and 2. terrain modeling. Tree height can simply be calculated as the difference between these two models. Tree top identification or surface modeling can be conducted using very high resolution satellite imagery. However, in general it is difficult to estimate terrain height in forested areas. This is because forests expand in large area and on rugged terrain, and forests also hide the terrain under their tree canopies. This is the reason why there have been few studies on tree height measurement using stereo satellite imagery, while there are plenty of such studies conducted using LiDAR observations that can extract both information on a digital surface model (DSM) and a digital terrain model (DTM) simultaneously. However, in the northeast of Thailand, teak plantations are located on moderate terrain and surrounded by patches of agricultural land. In such a case, the hidden terrain was considered to be estimated by the measurement of terrain surfaces of surrounding teak forests. Errors in such terrain modeling will be relatively small when the terrain is flat or moderate. Therefore, in such a region, there is potential for tree height measurement on a large scale using stereo paired high resolution satellite images.

Therefore, the objective of this study was to examine tree stand height measurements through stereoscopic measurement using high resolution satellite imagery in order to evaluate the potential of stereo observation for extracting height information for growth assessment and resource monitoring of plantation forests over a large area.

Study area

The study area was located in the northern part of Nong Bua Lam Phu province in the northeast of Thailand (Fig.1). Small-scale teak plantations managed by farmers were the target of this study. The terrain in the northeast of Thailand is rather moderate. Therefore, agricultural land is widespread across this region. Teak plantations have also been established in a mosaic pattern intermixed with agricultural lands such as paddy fields, farmland of cassava, sugarcane, and maize, orchards and tree plantations of rubber and short-rotation eucalyptus. The size of the teak plantations was rather small with a mean size of several hectares (Mahannop 2004), which was also separated into several small parcels. Almost all teak plantations were established by a subsidy program in 1990s. Narrow spacing, such as 2 m × 2 m, 2 m × 3 m, and 2 m × 4 m, was mainly applied as the initial plant spacing.

Materials and methods

Paired Pléiades very-high-resolution satellite imagery (Forward and Nadir observation), captured in a triplet mode on 14 November, 2012, was utilized for stereoscopic measurement. Descriptions of the satellite data acquisition are shown in Table 1.

An outline of the Dominant tree height (DTH) estimation by stereoscopic measurement on satellite imagery is shown in Fig.2. A total of 20 rectangular size-variable survey plots (plot size α = 0.06 to 0.16 ha) was set in the teak plantations to measure DTH at the field and on the satellite imagery. Stereoscopic measurement was conducted using the 3-dimensional measurement tool of Stereo analyst (Hexagon Geospatial 2010) of ERDAS

Imagine image processing software (Hexagon Geospatial) to measure the altitudes of tree tops and the bare lands surrounding the teak plantations. Terrain was modeled based on the surrounding bare land altitudes that could be depicted by visual interpretation. A triangular interpolation method of a surface modeling tool of TNTmips GIS analysis software (MicroImages Inc.) was applied for the terrain modeling in each plot (MicroImages 2013). Terrain model was created in raster format at spatial resolution of 0.5 m. Individual tree height was calculated as the vertical difference between the top canopy position and the estimated terrain model at which the tree top was located. Because of difficulties in matching individual trees on the satellite imagery with the field-measured individual trees,

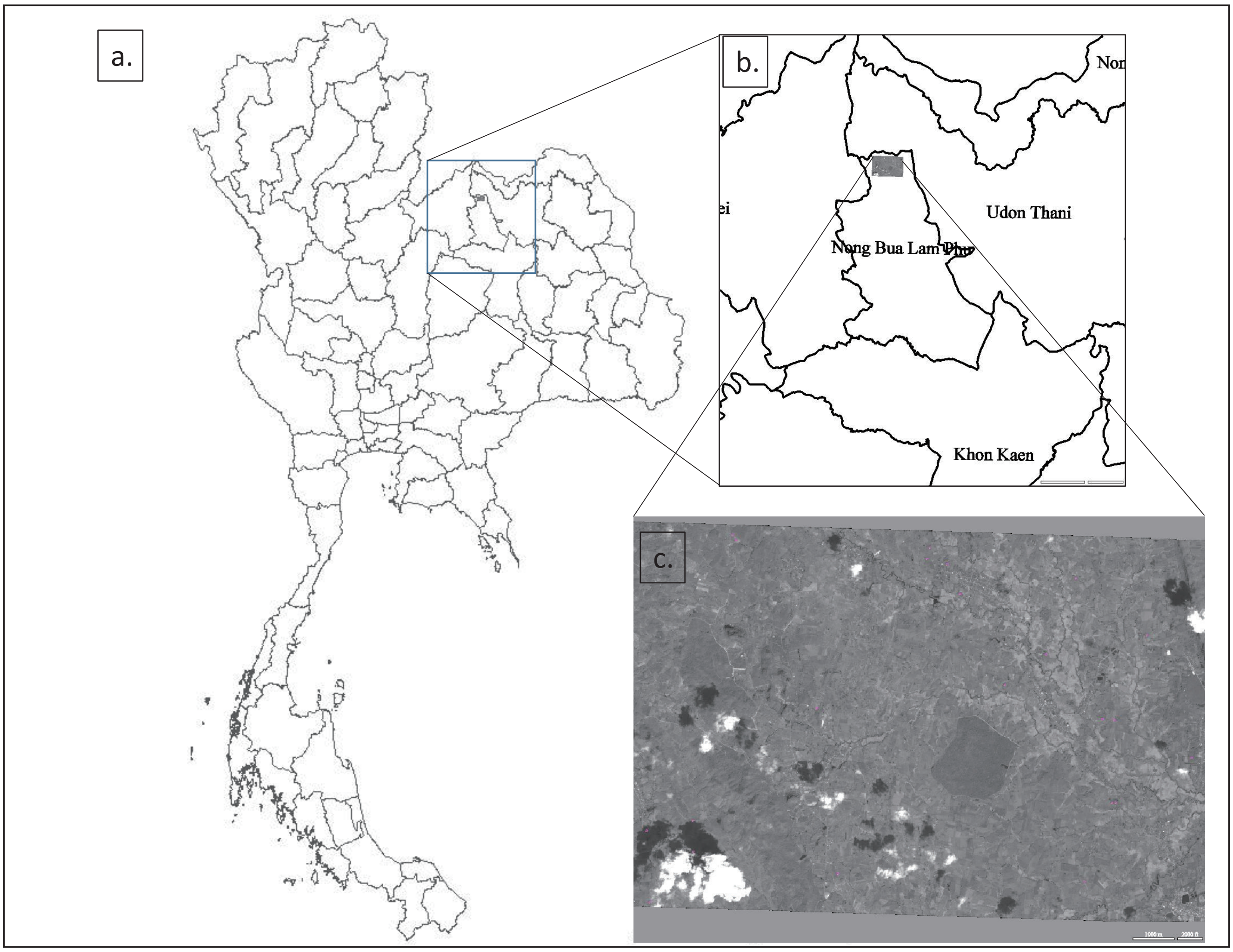

Fig. 1. Location of the study area (a. the Kingdom of Thailand, b. location of Nong Bua Lam Phu province, and c. coverage of Pléiades high-resolution satellite imagery)

Table 1. Description of stereo-paired Pleiades satellite images in triplet mode

Satellite/Sensor	Pléiades 1A	Pléiades 1A
Image ID	Forward	Nadir
Acquisition date	2012/11/14	2012/11/14
Acquisition time	3:54:49	3:55:06
Image size (column × row)	29796 × 18067	30279 × 18976
Global incidence (deg.)	13.1	5.8
Across track incidence (deg.)	−3.0	−5.4
Along the track incidence (deg.)	−12.7	−2.2
Solar azimuth (deg.)	156.3	156.7
Solar elevation (deg.)	51.1	51.2

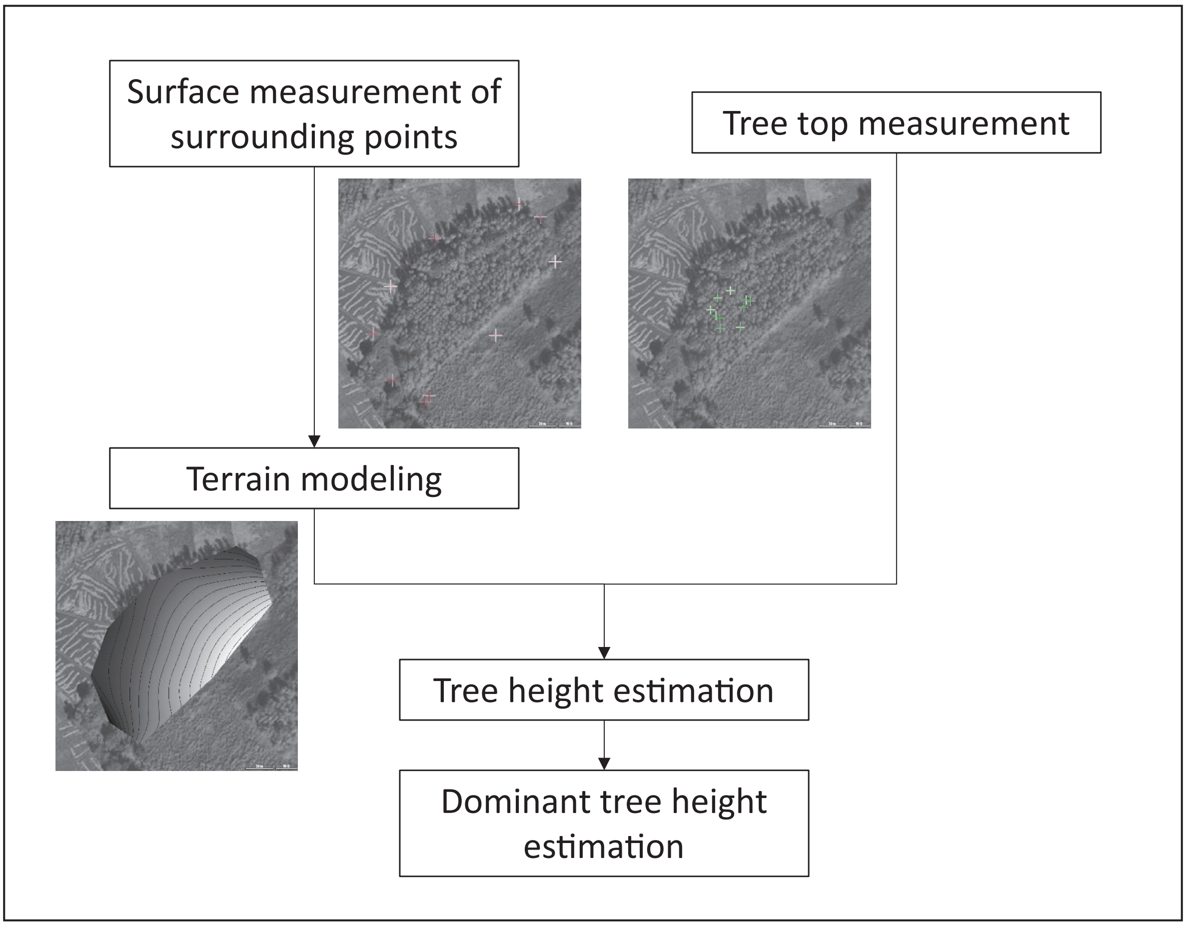

Fig. 2. Flowchart of DTH estimation by stereoscopic measurement of satellite imagery

dominant trees inside the field survey plot were sampled independently on the satellite image and the tree top positions of these dominant trees were identified by visual interpretation. DTH for each plot was calculated as the mean value of the measured tree heights. In this study, DTH was defined as the mean height of the top 100 trees per hectare. The number of dominant trees for calculating DTH were decided individually plot by plot as below,

$$m = 100 \times a$$

where m is number of sampled dominant tree and a is plot size in hectare. Three replicative measurements both of dominant tree top (p = 1 to 3) and terrain (q = 1 to 3) were conducted independently by the same interpreter in a same procedure. In summary, the estimated DTH (eDTH) on satellite imagery was calculated as below,

$$\text{eDTHpq} = \frac{1}{m}\sum_{j=1}^{m}(DSMp(i) - DTMpq(i))$$

where p is number of p th tree top measurement, q is number of q th terrain estimation, m is number of height estimated dominant trees, DSMp(i) is altitude of i th tree top based on the p th tree top measurement, and DTMpq(i) is altitude of estimated ground position of i th tree top based on the p th tree top measurement and the q th terrain estimation.

The field survey was conducted in December 2012. Tree height measurement was conducted using a Vertex ultrasonic hypsometer (Haglöf Sweden) for trees sampled by the planting line. More than half of the trees inside the plot were intended to be sampled in each stand. The field-surveyed DTH (sDTH) was calculated for each plot based on the direct height measurement as below,

$$\text{sDTH} = \frac{1}{m}\sum_{j=1}^{m} h(j)$$

where m is number of sampled dominant trees, and h(j) is tree height of the j th tallest tree of the height measured tree. Although the sampling ratio was different plot by plot, the number of dominant trees of m, same with the satellite analysis, was used for each plot for calculating sDTH in this study.

The eDTHpq were compared with sDTH to discuss the accuracy, and the applicability of the methodology were discussed. A total nine estimates (eDTHpq) calculated as the combinations of three tree top measurements (p = 1 to 3) and three terrain measurements (q = 1 to 3) were examined.

Results and discussion

Error factors of height measurement

Fig. 3 shows the results of estimations of the DSM, DTM, and DTH in each plot. Fig. 3a shows variations in $\overline{DSMp}$ and $\overline{DTMpq}$ for each plot. Relative variations in $\overline{DTMpq}$ was larger than those in $\overline{DSMp}$, although the absolute values of $\overline{DSMp}$ and $\overline{DTMpq}$ varied depending on the altitude of the plots. Fig. 3b shows the distribution of eDTHpq in relation to the sDTH. There was a correlation between eDTH and sDTH for each combination of measurements (R^2 = 0.53 to 0.75 at slope values close to 1 (0.97 to 1.02)). However, overestimation was observed in Plot 13 and Plot 20, and underestimation was observed in Plot 1. Fig. 3c shows the deviations of eDTHpq from sDTH. For each combination of p and q, distribution of the deviation through the plots showed the normal distribution with the mean of close to zero (-0.38 to 0.52). However, as seen above, there was remarkable overestimations in Plot 13 and Plot 20 and remarkable underestimation in Plot 1. The maximum deviation of eDTHpq of each combination of measurement was about 4 m. The deviations were mainly caused by inaccurate and unstable DTM estimations. In Plot 1, the variation in eDTHpq was small but underestimation of DTH by around 3 m was observed.

The reasons for the overestimations and underestimations were examined in some plots. In Plot 20, an overestimated plot, the terrain was rather flat according to the field observation. However, it was located on a slightly hilly area. The area, where the surface of surrounding the teak plantation was measurable, was located at the lower end of a small hill. As a result, estimated DTM obtained from triangle interpolation was lower than actual, and then the resultant DTH was overestimated. The case of Plot 1 was a case of underestimation of DTH. The terrain was concave in contrast to the case of hilly Plot 20. As a result, the terrain might be estimated as being higher than it actually was, and then DTH was underestimated. The variation in estimation was small because the locations of measurable surrounding surfaces were limited and fixed, and the terrain was inevitably modeled constantly.

Studies on building height measurement by space-borne observation has shown height estimation accuracy of root-mean-square error (RMSE) of 0.6 to 1.3 m (Abduelmula et al., 2015). In our study on DTH measurement, it ranged from 1.43 to 1.96 m. The sources of errors can be separated into three factors. Firstly, error in tree top detection by visual interpretation. Secondly, errors can be caused by terrain modeling. The accuracy of terrain modeling based on surrounding point measurements becomes worse if the surrounding land is covered by vegetation. Rugged terrain is easily simplified in the current surface modeling procedure. These factors occasionally cause large estimation errors in tree height estimation. Therefore, precise terrain estimation and the subsequent tree height estimation will be more difficult in rugged terrain than in flat and moderate terrain areas. Thirdly, the sensor model that decides the position and attitude of the sensor. This factor was not evaluated in this study but the height estimation calculated as the relative difference between two measurements of surface and terrain will diminish any influence of this source of error.

Terrain modeling

In this study area, as illustrated in Fig. 4, all the teak plantations were located amongst a mosaic of agricultural lands. Road networks have also developed and tend to stick to the teak plantations. Therefore, the positions of surfaces surrounding the teak plantations were measureable. This enabled the terrain estimation of teak plantations, although the terrain estimation had large variations in some cases. As a result, DTH of all the plots could be estimated. On the other hand, the direct terrain measurement of teak plantations was more difficult using the current leaf-on imagery captured at the beginning of the dry season because there is, in general, no space to enable direct surface measurements inside the teak plantations. Only the surfaces of a small number of large canopy gaps was measurable. Therefore, terrain estimations based on surface measurements in surrounding locations of the teak plantations was needed. The probability of direct terrain measurement inside teak plantations from leaf-off imagery should be checked as a further step.

Future work

This study clarified the potential of stereoscopic tree height measurement using high-resolution satellite imagery targeting small-scale teak plantations in a moderate terrain area. In this study, human interpretation was conducted to search for adequate locations to estimate terrain heights. However, there is potential for automation for large-

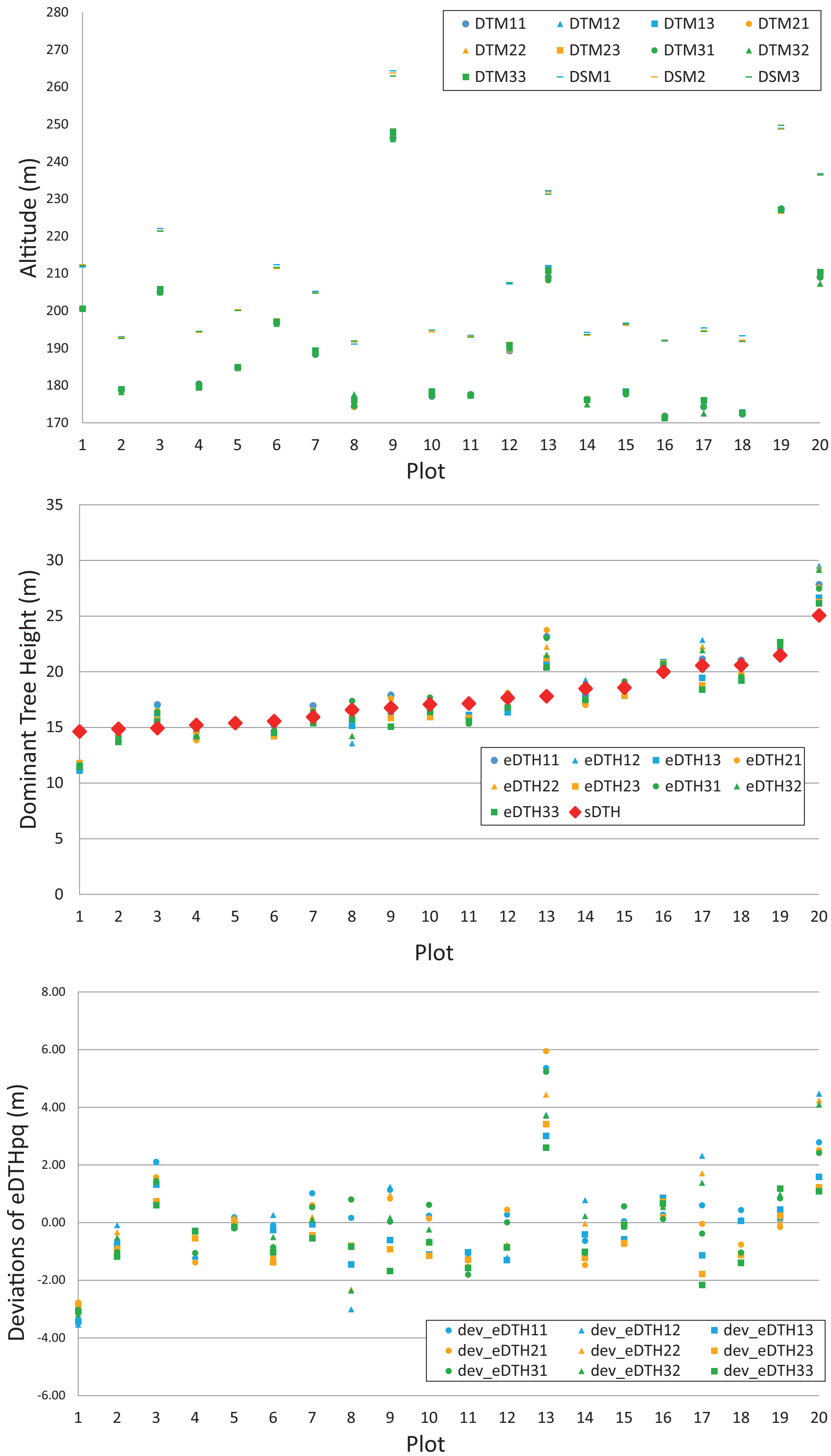

Fig. 3. Distribution of $\overline{DSMp}$, $\overline{DTMpq}$, and eDTHpq and the deviations (Fig. 3a (upper). Variations in the $\overline{DSMp}$ and $\overline{DTMpq}$ in each setting; Fig. 3b (middle). Variations in eDTHpq in each setting; Fig. 3c (lower). Variations in the deviations of DTH estimation (eDTHpq minus sDTH) in each setting) Here, mean DSMp was calculated as $\overline{DSMp} = \frac{1}{m}\sum_{i=1}^{m} DSMp(i)$ and $\overline{DTMpq}$ was defined as $\overline{DTMpq} = \frac{1}{m}\sum_{i=1}^{m} DTMpq(i)$.

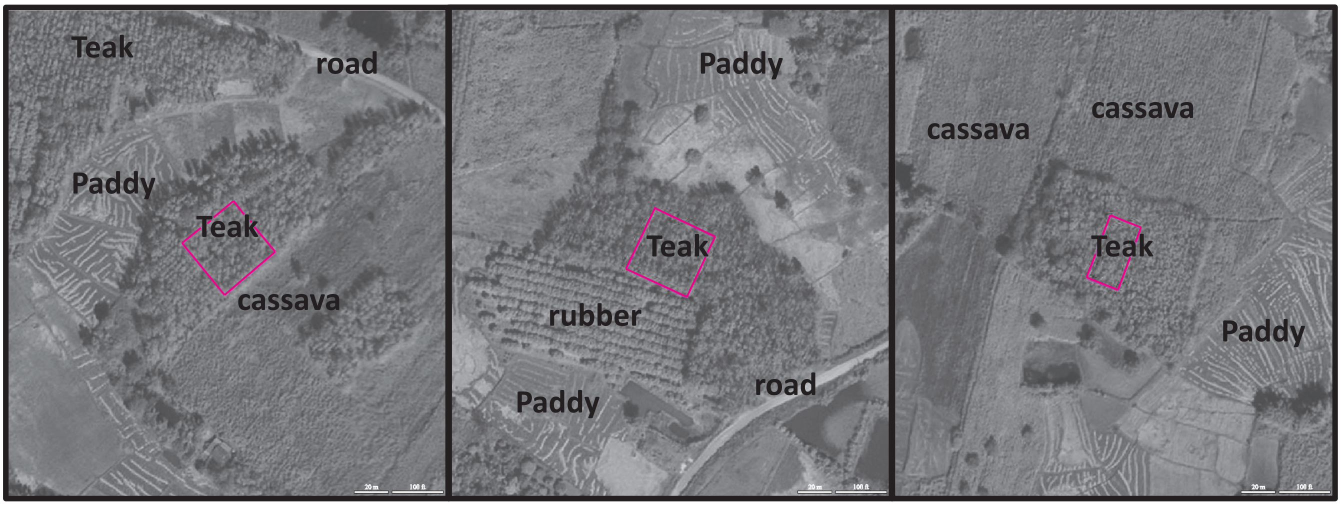

Fig. 4. Examples of teak plantations located amongst an agricultural land mosaic (the rectangular polygon indicates the location of the survey plot).

area monitoring. For building height measurement in urban areas, some studies have reported good results for automatic building height estimation by analyzing an automatically created DSM and DTM (Abduelmula et al. 2015). Simplification of complicated land mosaics and tree canopy surface modeling will be more difficult than city modeling. However, the procedure for automatic extraction of tree height by automatically creating the DSM and DTM should be further developed in future studies. Some studies on DSM extraction using space-derived imagery examined the influences of B/H (base to height) ratio both on the accuracy and on the applicability of height estimation (ex. Jacobsen and Topan 2015). In this study, only a pair of forward and nadir images was used for stereoscopic measurement. However, other combinations of image, such as a backward-nadir and forward-backward image, can also be examined in future studies. For example, short base length will influence the possible vertical accuracy, but it will enable better image matching (Jacobsen and Topan 2015). In any cases, estimated DTH information will contribute to the growth assessment and resource monitoring of teak plantations in large areas.

Acknowledgement

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Effects of First Thinning on Growth and Stem Form of Teak Plantations in Thailand

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Abstract

The effects of first thinning on growth and stem form of teak stands were examined in Uttaradit Province, Northern Thailand. In this study, a randomized complete block design with 3 replications was used, and thinning from below (low thinning) was applied as the first thinning. The thinning treatments were as follows: removal of basal area at the levels of 0% (unthinned), 30% (moderate), and 50% (heavy). The measurement period after thinning was 4 years. The results of the study revealed that heavy thinning provided the largest mean basal area and mean stem volume of individual trees in the stands compared with the other treatments. The total stand volume increase in production per rai (0.16 ha) was largest in moderate thinning plots and differed significantly from unthinned plots, but did not differ significantly from heavy thinning plots. The moderate and heavy thinning intensities reduced the annual stand volume increase by 23% and 64%, respectively, related to the mean stand volume increase of thinned stands before thinning was executed, whereas those in unthinned plots reduced by almost 99%.

Part of the total stand volume production of unthinned plots was lost through natural mortality. In the thinned plots, natural mortality was considerably lower compared with the unthinned plots. The mean diameter at breast height (DBH) increment of all trees as well as the mean DBH increment of the dominant trees was enhanced with increasing thinning intensity, but there was no significant difference among the thinned and unthinned plots. However, the mean DBH increment of all trees in unthinned plots was as much as those in moderate thinning plots. In contrast, total height increment of all trees and the dominant trees were not affected by thinning intensity. Live-crown ratio, slenderness ratio, and absolute form factor of the trees in the stand were affected by different thinning intensities. Live-crown ratio increased with greater thinning intensity. On the other hand, slenderness ratio decreased with greater thinning intensity. The absolute form factor was smallest in unthinned plots, and different thinning intensities had clear effects on the absolute form factor. Thus, thinning intensity resulted in improved growth and yield of stands after thinning as well as individual tree size and tended to have positive effects on stem form.

Keywords: Thinning intensity, Mean volume increment, Stand volume increment, Live-crown ratio, Slenderness ratio, Absolute form factor

Introduction

Teak (*Tectona grandis* L.f.) is the most important indigenous tree species of Thailand. It is considered by forestry industries as a species of high commercial value. The growth rate of teak is greater at sites with annual rainfall between 1,250 mm and 3,750 mm, associated with a 3- to 5-month drought periods, minimum temperatures between 13 °C and 17 °C, and maximum temperatures between 39 °C and 43 °C (Pandey et al. 2000).

Control of stand density by thinning has been the major tool in regulating tree growth and improving timber quality. Although thinning from below may increase the merchantable volume of a stand, usually it does not increase the total volume increment per unit area (e.g. Hasenauer et al. 1997; Zeide 2001). Many studies have revealed that the stand volume increment of various tree species does not decline with decreasing stand density (e.g. Hamilton 1981; Horne et al. 1986). This indicated that thinning from below (or low thinning) redistributes the increment of individual trees from smaller trees to larger ones, and the smaller number of trees is able to produce the same volume increment per unit area.

Thinning practice also affects wood properties such as heartwood proportion, wood density, and stem form. Stem form is defined as the rate of taper of a stem. Taper is the decrease in diameter of a stem of a tree or of a log from the base upwards. The potential change in stem form as a result of thinning is important with regard to volume and the product recovery prediction. Most variation in stem form may be traced to the change in size and distribution of the live crown on the stem and to the length of the branch-free bole (Larson 1963).

The objective of this study was to relate thinning intensity of the first thinning operation with diameter, height, volume increment, and stem form on the basis of permanent long-term experiments with thinning from below in a teak plantation in Thailand. This study provided us with the opportunity to investigate total stem volume production, thinning removal as well as changes in stem form, during the whole rotation.

Materials and methods

Study site

The thinning trial was established in a private teak plantation in Tha Sao District, Mueang Sub-District, Uttaradit Province, on a site with a tropical monsoon climate and mountainous region in Northern Thailand. The average annual temperature was approximately 27.7 °C with minor daily and annual fluctuations. The annual precipitation was 1,432.6 mm, with 6 dry months. The study site was located at an altitude of 105 m a.s.l., at 17° 41’25.5” N, and 100° 17’52.8” E.

In an area originally cleared for agricultural crops, a 47 rai (a rai is the local measurement unit used in Thailand and 1 rai equals 1,600 m^2 or 0.16 ha) *T. grandis* plantation was established in May 2005, with initial spacing of 2×4 m (200 trees per rai). The first thinning was conducted in May 2011, when the teak plantation was 6 years old. The pure teak stand presented canopy closure but severe competition was not evident. The stand basal area was around 1.90 m^2 rai^{-1} (11.88 m^2 ha^{-1}). There was no other silvicultural interventions such as pruning applied to the plantation prior to thinning.

Experimental design and treatments

The experimental design consisted of randomized complete blocks, with three treatments and three replicates. Prior to thinning, each treatment consisted of 200 trees (including dead trees) in square blocks of 1,600 m^2 (20×10 trees under a spacing of 2×4 m) or 1 rai, excluding buffer zones consisting of two lines of trees, each of them thinned according to the corresponding treatment they were bordering (Fig. 1).

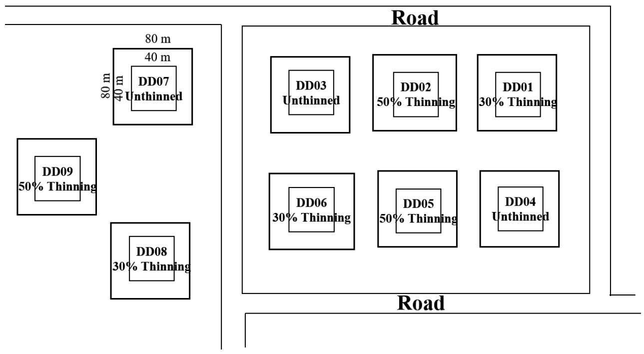

Fig. 1. Layout of experimental plots.

Thinning from below or low thinning (defined as the thinning method that favors the tallest trees in the stand by removal the lower crown classes) with different thinning intensities was applied in each treatment based on the percentage of the stand basal area prior to thinning. The trees removed in each treatment were also selected based on crown class, i.e. dominant, co-dominant, intermediate, and suppressed and also based on characteristics of tree, e.g. no defects, some defects, weak, and standing dead. All trees in each thinned stand was divided into five classes and the trees in the fifth class (or the lowest class, i.e. consisting of weak trees, dead trees, and fallen trees) were selected before the others until the target basal area removal in each treatment was reached. The thinning treatments were removal of initial basal area at rates of 0% (unthinned or control), 30% (moderate), and 50% (heavy).

Measurements

Prior to thinning, the experimental plots were measured, and they were measured again just after thinning was conducted. Following thinning, the tree sizes were measured and the surviving trees were surveyed in each plot every year. The measurement period was 4 years. At the time of the last measurement, the stand age was 10 years. All living trees in each treatment were numbered and marked at 1.3 m stem height for repeated annual measurements of stem diameter at breast height (DBH), total height (H), and height to crown base (Hb), using diameter tape and a measuring pole. A digital hypsometer was used when tree height was more than 15 m.

Two years after thinning, the stem diameter of 10 randomly selected trees per treatment (unthinned, 30% thinning, and 50% thinning) was measured, using an electronic BAF-scope/dendrometer (CRITERION RD 1000). The diameter of a standing tree at target points along the stem and total height of the tree were measured and recorded. The data was used to construct an allometric equation for calculating the individual stem volume of trees in each treatment.

Basal area and volume were calculated for each tree, and stand total basal area and total volume were calculated by summing the values of all trees in the measurement plot, and then these values were converted to 1 rai (1,600 m^2 or 0.16 ha). The stem volume of each tree was calculated at the thinning time, just after thinning, and 1 year after thinning from the stem volume equation for this species presented by Vacharangkura et.al. (2010):

$$V = 0.00009734\ DBH^{1.99583}\ H^{0.64695}$$

Where V is the over bark volume (m^3), DBH is the diameter at breast height over bark (cm) and H is the tree total height (m).

Because thinning affected stem form (shape) of any tree in the stands, different stem volume equations were calculated for each stand with the different treatments. The nonlinear model used to calculate individual stem volume was:

$$V = a\ (DBH^2H)^b$$

Where a and b are constants. Mean basal area and mean stem volume of each treatment were calculated to examine tree size. Annual increment was calculated as the difference between successive measurements divided by the number of years between the measurements. Dominant trees were based on 100 trees by diameter (DBH) of the largest trees per hectare (16 trees per rai). Total volume production and stand volume increment were calculated to examine the effects of the thinning operation.

In order to evaluate the effect of thinning on stem form, the three parameters were applied to investigate the attributes of trees in each treatment at the time before and after thinning was performed. These parameters were:

(1) Live-crown ratio (ratio between crown height and total height (H-Hb)/H)
(2) Slenderness ratio (H/DBH ratio)
(3) Absolute form factor (defined as the ratio of the volume of a tree or its part to the volume of a cylinder having the same length and cross section as the tree).

These parameters were calculated for each tree before and after thinning, and then the average in each treatment was used to examine the effect of thinning on stem form.

Statistical analysis

The effects of thinning intensity on tree size, individual growth rate, and growth rate of stand were analyzed. ANOVA was applied to examine statistical significant of the differences among treatment. The mean difference comparison using Tukey's HSD was performed to compare the means among treatments.

Results

Effects of the thinning on tree size

ANOVA showed that there was no significant difference among treatments in terms of mean DBH, mean height, stand basal area, or stand volume. This means that the plantation had a homogeneous structure even though there were slight differences in stand density in the heavy thinning plots compared with the moderate thinning and unthinned plots (Table 1).

Just after thinning, mean DBH was not significantly different between the thinned plots, but the thinned plots were different from the unthinned plots. There was no significant difference among treatments in term of mean height. Stand basal area differed significantly in all treatments. There was no significant differences in stand volume in the moderate thinning and heavy thinning plots, but the both thinning type plots were significantly different from the unthinned plots. The density of trees differed significantly because of the difference of thinning intensities (Table 1).

By the final measurement, at 4 years after thinning, the differences in stand density among the treatments had changed. There were no significant differences in stand density among treatments because mortality was high in the unthinned plots owing to severe competition. Mean diameters of the residual stands increased significantly in thinned plots and differed significantly from unthinned plots. On the other hand, there was no significant difference in mean height among treatments. Stand basal area was highest in the unthinned plots (2.02 m^2 rai^{-1}) but was not significantly different from plots that had received moderate thinning. There was no significant difference in stand basal area in all thinned plots. Four years after thinning, stand volume had increased in all of the thinned plots but decreased in unthinned plots. There was no significant difference in stand volume among the treatments (Table 1).

The corresponding basal area and stem volume development of trees in the stands from the time of thinning to 4 years after thinning are presented in Fig. 2 and Fig. 3, respectively. The mean basal area in heavy thinning plots was the largest year by year after thinning. At the age of 10 years (4 years after thinning), the mean basal area in heavy thinning plots differed statistically from those in moderate thinning plots and unthinned plots. There was no significant difference in mean basal area between moderate thinning plots and unthinned plots.

This result indicated that thinning promoted larger stem diameter in the stands, and heavier thinning intensity tended to encourage larger stem diameter of trees. The corresponding mean stem volume of the stands was significantly different among treatments by 1 year after thinning. From 2 year after thinning, the mean stem volume in both moderate and heavy thinning plots were not significantly different, but they were significantly different from the unthinned plots. The results clearly demonstrated that thinning promoted larger tree size.

Effects of thinning on tree growth

The arithmetic mean annual DBH increments of all trees in heavy thinning plots were the largest, followed by those in unthinned plots and moderate thinning plots (Fig. 4). The differences among thinning intensities were not statistically significant in all treatments. The mean diameter increment was also calculated for the dominant

Table 1. Stand characteristics of Den Dan plantation before, just after and 4 years after thinning

	Treatment								
Before thinning	Moderate			Heavy			Unthinned		
Stand density (tree ha^{-1})	195	(±1.00)	a	193	(±1.00)	b	196	(±0.58)	a
Mean DBH (cm)	10.15	(±1.06)	a	10.33	(±0.81)	a	9.99	(±1.00)	a
Mean height (m)	10.94	(±1.31)	a	11.01	(±1.00)	a	10.44	(±1.44)	a
Stand BA^2 (m rai^{-1})	1.63	(±0.30)	a	1.68	(±0.23)	a	1.6	(±0.30)	a
Stand volume (m^3 rai^{-1})	9.64	(±2.38)	a	9.94	(±1.79)	a	9.25	(±2.35)	a
Just after thinning									
Stand density (tree ha^{-1})	123	(±8.98)	c	81	(±4.04)	b	196	(±0.58)	a
Mean DBH (cm)	11.58	(±0.58)	a	12.17	(±0.34)	a	10.82	(±0.87)	b
Mean height (m)	12.45	(±0.48)	a	12.54	(±0.24)	a	11.17	(±1.32)	a
Stand BA^2 (m rai^{-1})	1.33	(±0.21)	b	0.93	(±0.12)	c	1.88	(±0.28)	a
Stand volume (m^3 rai^{-1})	8.40	(±1.49)	b	5.95	(±0.78)	b	11.30	(±2.40)	a
4 years after thinning									
Stand density (tree ha^{-1})	120	(±11.01)	a	79	(±6.11)	a	174	(±5.86)	a
Mean DBH (cm)	13.16	(±0.70)	b	14.50	(±0.18)	a	12.49	(±0.45)	b
Mean height (m)	13.42	(±0.89)	a	13.95	(±0.11)	a	12.83	(±0.37)	a
Stand BA^2 (m rai^{-1})	1.62	(±0.26)	ab	1.31	(±0.11)	b	2.02	(±0.17)	a
Stand volume (m^3 rai^{-1})	14.19	(±3.28)	a	8.91	(±0.72)	a	10.15	(±1.01)	a
Thinning ratio									
No. of trees (%)	36.91			58.20			0.00		
BA (%)	30.32			50.77			0.00		

Remarks: BA = basal area

Treatments marked with the different letters are significantly different ($p< 0.05$); standard deviation in parentheses.

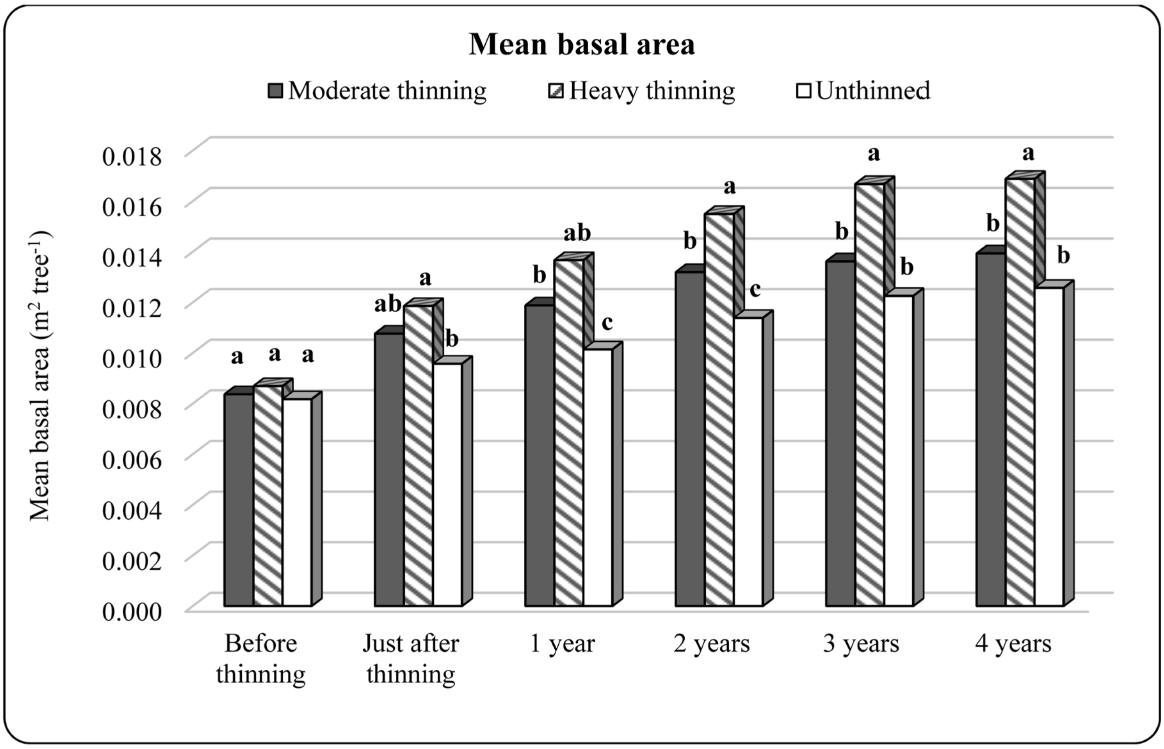

Fig. 2. Mean basal area 4-year after thinning. Letters signify individual statistical differences among treatments in each measurement time, based on the ANOVA test. The treatments marked with the different letters are significantly different ($p < 0.05$).

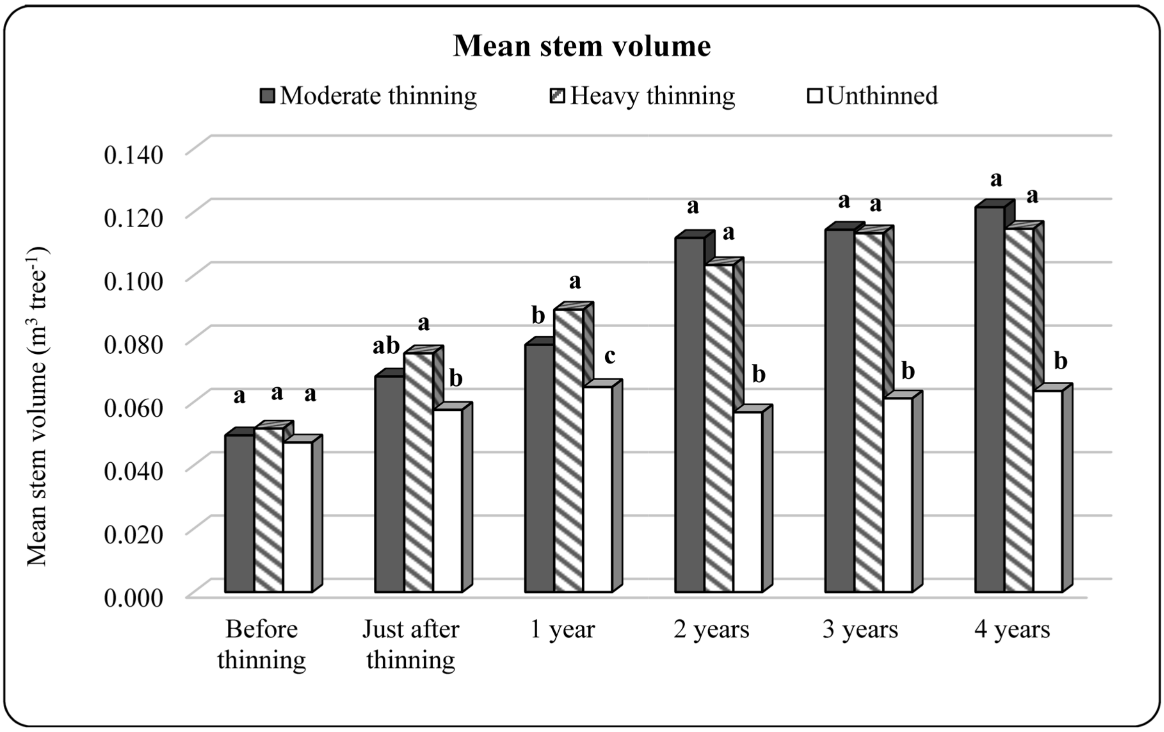

Fig. 3. Mean stem volume 4-year after thinning. Letters signify individual statistical differences among treatments in each measurement time, based on the ANOVA test. The treatments marked with the different letters are significantly different ($p < 0.05$).

trees (defined as 16 largest tree by DBH per rai). The mean annual increment of the dominant trees was the largest in heavy thinning plots, followed by those in moderate thinning plots and unthinned plots. The test of mean annual increment of dominant trees revealed the same result as for all the trees. This result indicated that thinning intensity had no clear effect on annual DBH increment of the dominant trees in the residual stands (Fig. 4).

In case of mean height of all trees and mean annual height increment of the dominant trees, the results were aligned with the results in mean annual DBH increment presented above. The mean annual height increment of all trees and dominant trees were largest in the unthinned plots, followed by the heavy thinning plots and then the moderate thinning plots. The heavy thinning plots seemed to show a greater annual height increment of all trees and the dominant trees, but there was no significant differences (Fig. 5).

Effects of thinning on stand growth

The volume production of the residual stands calculated from the year of thinning was only examined in the fourth year after thinning, and the data are presented in Table 2. Total volume production in each stand consisted of the volume of thinned trees, volume of dead trees, and current volume production. The total volume of production was the summation of these three parts. The total volume of production in moderate thinning plots was the largest (17.95 m^2 rai^{-1}), followed by the heavy thinning plots and then the unthinned plots. The numbers and volume of dead trees in unthinned plots were much larger than those

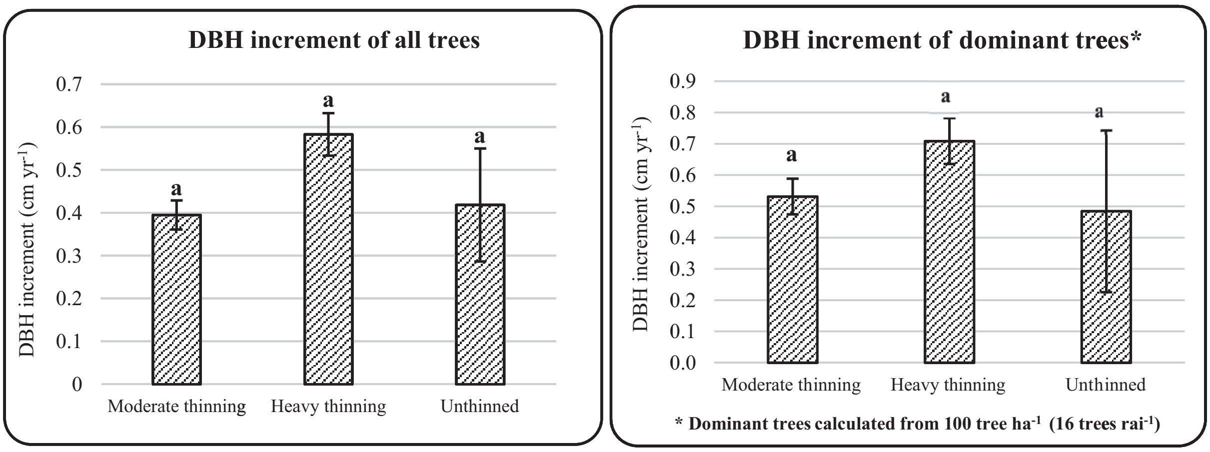

Fig. 4. Mean annual DBH increment of all trees and dominant trees. Letters signify individual statistical differences among treatments in each measurement time, based on the ANOVA test. The treatments marked with the different letters are significantly different ($p< 0.05$).

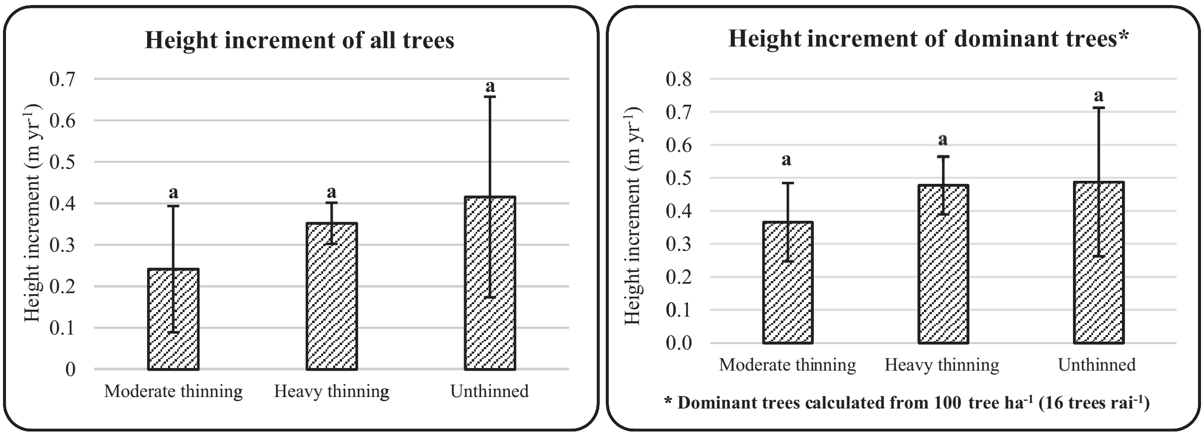

Fig. 5. Mean annual height increment of all trees and dominant trees. Letters signify individual statistical differences among treatments in each measurement time, based on the ANOVA test. The treatments marked with the different letters are significantly different ($p< 0.05$).

in both thinned plots, because of severe competition in unthinned plots. The number and volume of dead trees was smallest in heavy thinning plots. This result may be caused the larger volume of production in heavy thinning plots than in unthinned plots. This result indicated that thinning prevented regular tree mortality.

The annual stand volume increment was larger in moderate thinning plots than those in heavy thinning plots, but there was no significant difference between the two thinning intensities. Compared with the unthinned plots, the annual stand volume increment in moderate thinning plots differed significantly. In contrast, annual stand volume increment in heavy thinning plots was not significantly different from the unthinned plots (Fig. 6).

The total stand volume production was largest in moderate thinning plots, followed by heavy thinning plots and then unthinned plots. The differences between the thinning intensities were not statistically significant. The total stand volume production in heavy thinning plots was not significantly different from that in the unthinned plots. These results were in accordance with the results of annual stand volume increment (Fig. 7).

Annual stand volume increments on the thinned and unthinned plots during the whole measurement period were also examined in relation to the mean volume increment of unthinned plots (Table 2). As expected, annual stand volume increment decreased with increasing thinning intensities. This result was in accordance with the result of current volume production (Table 3). The heavy thinning intensity decreased the annual stand volume increment by 64% compared with the mean volume increment of unthinned plots prior to thinning. The moderate thinning intensity decreased the annual stand volume increment by 23%, whereas unthinned plots showed a decrease in annual stand volume increment of almost 99%.

Effects of thinning on stem form

The effect of thinning on live-crown ratio was observed from the year thinning was performed to 4 years after thinning. The live-crown ratio in thinned stands was larger than those in unthinned plots from 1 year after thinning. Among thinned plots, the live-crown ratio in heavy thinning plots was larger than those in moderate thinning plots by 2 years after thinning and clearly differed from 3 years after thinning (Fig. 8).

On the other hand, the slenderness ratio (slenderness coefficient) in unthinned plots was larger than those in thinned plots from 1 year after thinning. The slenderness ratio in heavy thinning plots clearly showed lower values than those in the moderate thinning plots and unthinned plots, although the differences between the moderate thinning and unthinned plots were not clear (Fig. 8).

Absolute form factor clearly differed among treatments from 3 years after thinning. The form factor in moderate thinned plots yielded more cylindrical trees than those in heavy thinned plots and unthinned plots. The form factor of all thinned plots was larger than those of unthinned plots (Fig. 9).

The effects of thinning on the three parameters contributed to the quality of stem form by 4 years after thinning, and the results are presented in Table 4.

The ANOVA results indicated that there were significant differences in live-crown ratio among treatments. The live-crown ratio in heavy thinning plots was larger than those in moderate thinning and unthinned plots; however, there was no significant difference between heavy thinning plots and moderate thinning plots. Compared with the unthinned plots, but the live-crown ratio in moderate thinning plots was not significantly different.

In contrast, the ANOVA results clearly indicated that there was no significant difference in slenderness ratio among the treatments. The slenderness ratio in heavy thinning plots was markedly different from the others because the value was less than 100%, whereas the corresponding values were higher than 100% in the other treatments.

As shown in Table 4, the absolute form factor in moderate thinning plots was the largest, followed by those in heavy thinning plots and unthinned plots. The ANOVA results clearly showed that there were significant effects of thinning intensity on the absolute form factor.

Discussion

The plantation responded to the first thinning, and the largest diameter increment occurred after heavy thinning (Fig. 4). The results of this study were similar to the results of many other studies, especially in broad-leaved stands (e.g. Hibbs et al. 1995; Rytter 1995; Kerr 1996; Clatterbuck 2002; Meadows and Goelz 2002). The increase in diameter growth in response to thinning was associated with an increase in photosynthetic rate and water and nitrogen use efficiency among thinned trees (Wang et al. 1995).

Height increment was not affected by thinning intensity in moderate thinning or heavy thinning plots (Fig. 5). Similar results were found in young stand of teak in Costa Rica after the first thinning was performed at 4 years (Kanninen et al. 2004). It is well-known that stand

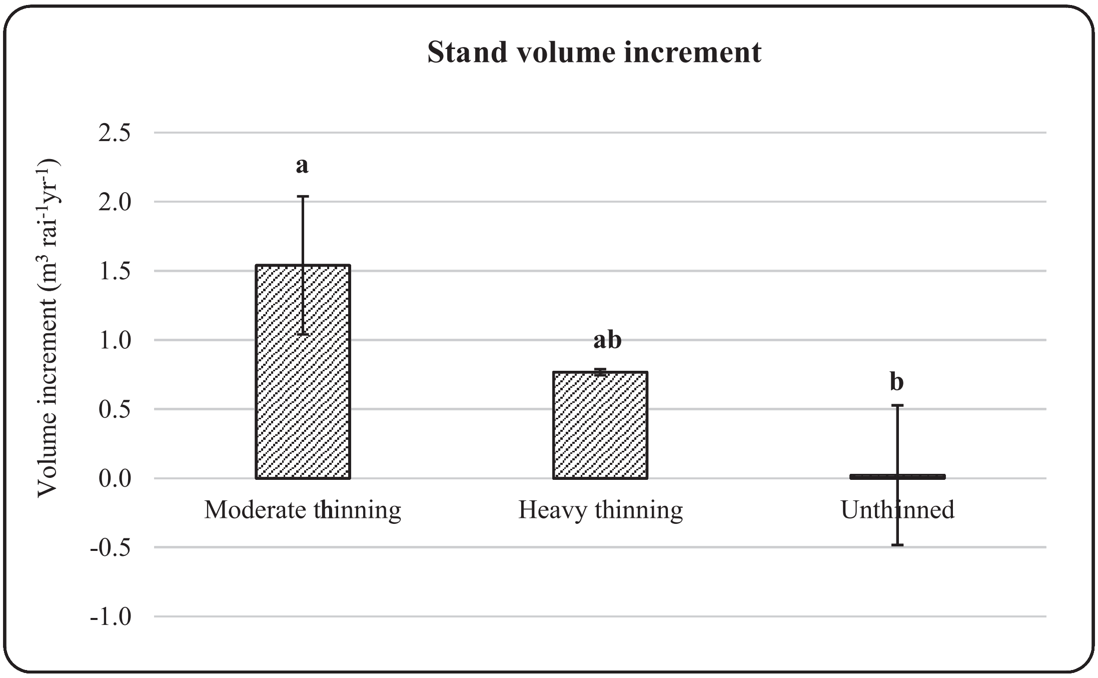

Fig. 6. Mean stand volume increment. Letters signify individual statistical differences among treatments in each measurement time, based on the ANOVA test.

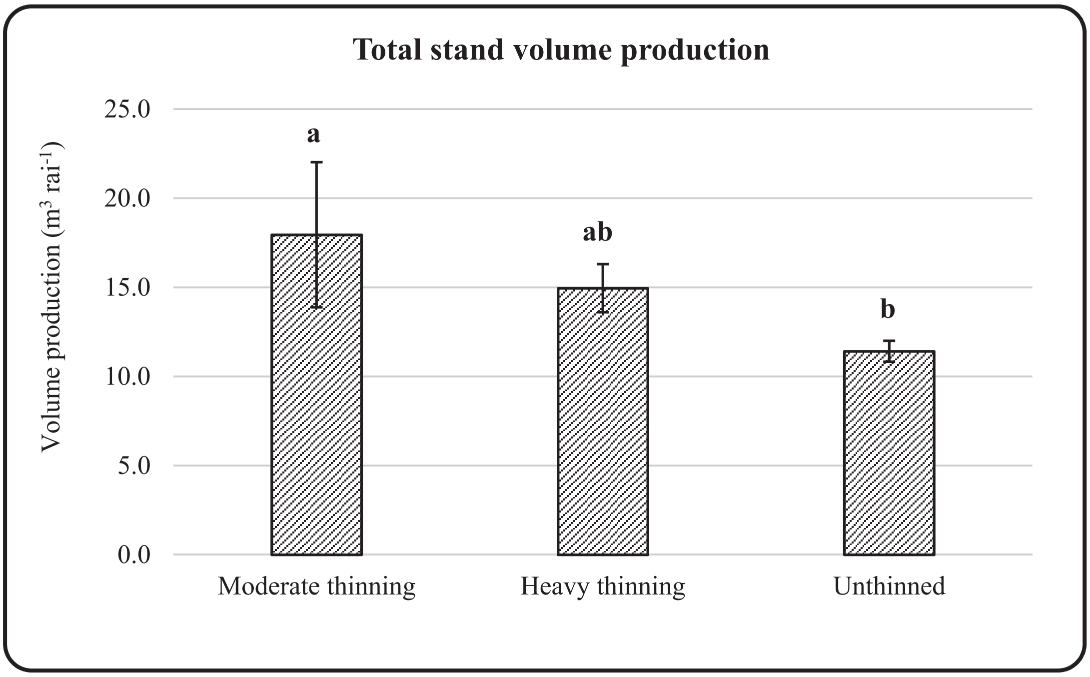

Fig. 7. Total stand volume production. Letters signify individual statistical differences among treatments in each measurement time, based on the ANOVA test. The treatments marked with the different letters are significantly different ($p < 0.05$).

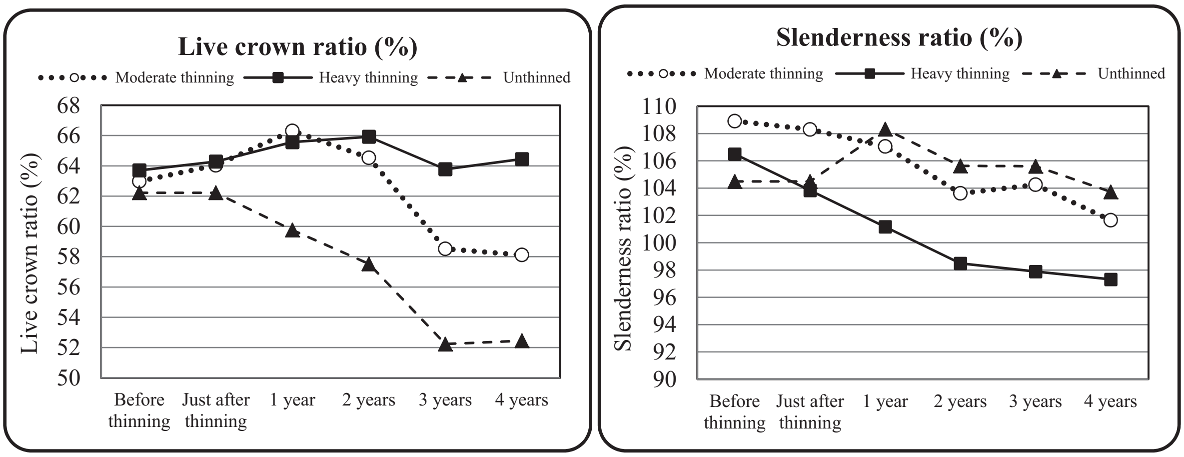

Fig. 8. Live-crown ratio and slenderness before and after thinning.

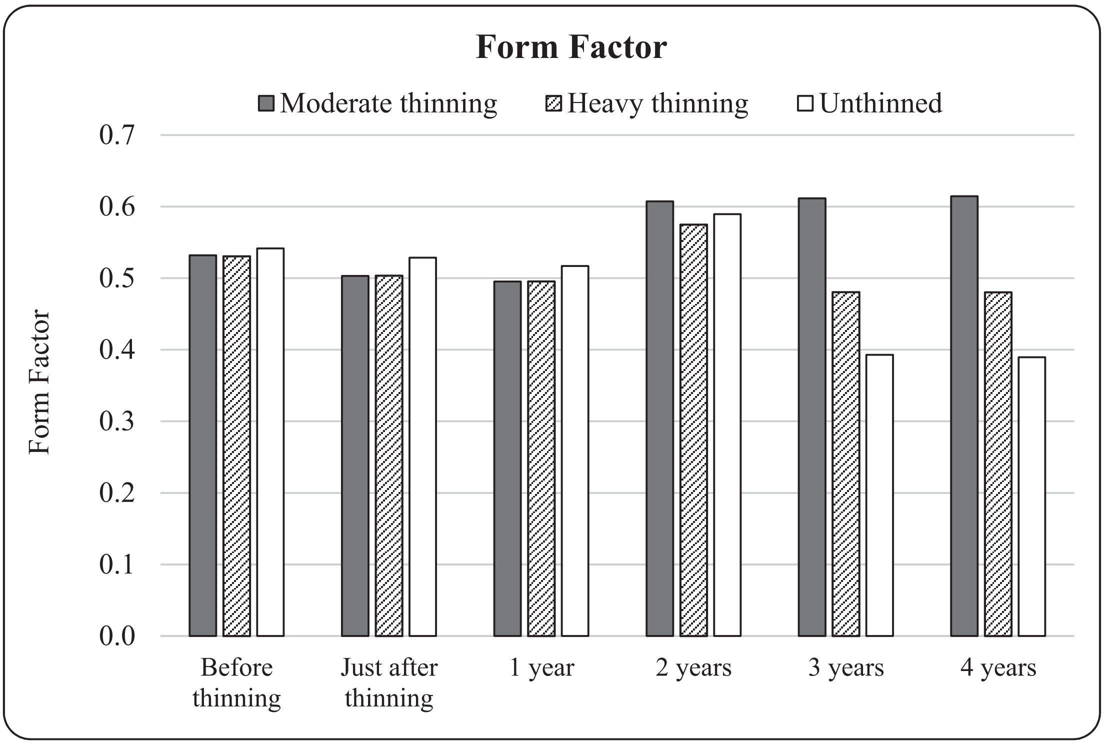

Fig. 9. Absolute form factor before and after thinning.

Table 2. Decrease in annual stand volume increment

Treatment	Annual stand volume increment (m^3 rai^{-1} $year^{-1}$)		
	Just after thinning	4 years after thinning	Decrease in volume increment (%)
Moderate thinning	1.96	1.54	−22.51
Heavy thinning	1.98	0.77	−64.30
Unthinned	1.89	0.02	−98.86

Table 3. Stand volume production (m^3) in stands with different thinning intensities

Treatment	Volume of thinned trees	Volume of dead trees	Current volume production	Total volume production	No. of dead trees
Moderate thinning	3.39	0.36	14.19	17.95	7.33
Heavy thinning	5.88	0.15	8.91	14.95	3.00
Unthinned	0.00	1.26	10.15	11.41	36.00

Table 4. Parameters of tree attributes associated with quality of stem form: 4 years after thinning

Treatment	Live-crown ratio (%)	Slenderness ratio (%)	Absolute form factor
Moderate thinning	58.11 (+3.96) ab	101.65 (+3.56) a	0.61 (+0.02) a
Heavy thinning	64.45 (+2.43) a	97.31 (+1.91) a	0.48 (+0.0005) b
Unthinned	52.45 (+5.60) b	103.73 (+1.71) a	0.39 (+0.005) c

density has significant effects on diameter growth, but not on height growth, except for very high and very low stand densities. Our study results concurred with this finding.

The results clearly demonstrated that the remaining trees can rapidly occupy the growing space released by the thinned trees, especially in the moderate thinning plots. The DBH and height increment of all trees as well as that of dominant trees clearly increased (Hamilton 1976), but there was no significant difference among thinned and unthinned stands. The differences in diameter increment, basal area, and volume in reaction to thinning can be explained by differences among tree species, sites, stand ages, tending practices, and thinning type and intensity. The results from our study support known information about the effects of thinning on stand production.

The total stand volume increment per unit area (per rai) did not vary much between the moderate thinning plots and heavy thinning plots, but there was significant difference from the unthinned plots (Fig. 7). The main reason was the dense unthinned stands consumed more carbon for respiration than thinned stands; thus, net production will be reduced in dense stands (Savill et al. 1997). However, stand volume increment in the heavy thinning plots did not differ significantly from the unthinned plots because a large number of trees were removed. The total stand volume production in the unthinned plots was the smallest compared with the thinned plots (Table 3) because part of the total stand volume production was lost owing to severe competition in the stand. Therefore, thinning prevents natural mortality. The results in this study revealed that increasing thinning intensity resulted in only a small reduction in total stand volume production (from 17.95 m^3 rai^{-1} in moderate thinning plots to 14.95 m^3 rai^{-1} in heavy thinning plots) (Fig. 7). However, the DBH increment of the remaining trees was clearly increased by thinning.

The results in this study revealed that thinning had a positive effect on stem form. Live-crown ratio in heavy thinning plots was largest and differed significantly from the unthinned plots (Fig. 8). It meant that heavy thinning expanded the crown size of trees. Because we know that the crown contains the foliage, which is the photosynthetic structure that provides carbohydrates for the growth and development of the whole tree (Larson 1963; Leites and Robinson 2004). The stem of a tree was strongly influence by its crown size and position (crown length, crown ratio, and crown height). This result was confirmed in our study, whereby the mean stem volume of an individual tree in the unthinned plots was the smallest compared with those in the thinned plots.

The slenderness ratios (or slenderness coefficients) of trees in the heavy thinning plots were larger than those in the moderate thinning and unthinned plots, even though the difference among treatments was not statistically significant (Fig. 8). The slenderness ratio has been widely used as an index of the stability of trees, especially the resistance of a tree to windthrow. The preferred slenderness ratio of a tree was lower than 100%. In this study, the slenderness ratio was lower than 100% (97.31%) only in the heavy thinning plots. It meant that the trees in heavy thinning stands may be at low risk for windthrow compared with the others. However, for teak species Pérez and Kanninan (2005) reported from their study in a young stand of a teak plantation, intensive thinning had a positive effect on the stem form, inducing the development of trees with the desired proportion of DBH and total height. Trees suffering high competition in the unthinned and medium thinning treatments will hardly reach a DBH/total height ratio (slenderness ratio) of 1:1. However, there have been no similar studies in teak plantations for comparison.

The absolute stem form factor was largest in the moderate thinning plots and differed significantly from the heavy thinning and unthinned plots. The unthinned plots had the smallest value (Table 4). The larger stem form factor provided a more cylindrical volume of a tree. The results of this study confirmed this; the mean stem volume of individual trees at 4 years after thinning in the moderate thinning plots was largest compared with the others. Pérez and Kanninen (2005) reported in young teak plantations in Costa Rica that moderate early thinning yielded trees that were more cylindrical in form (average form factor of 0.46) than late thinning and control (unthinned) average form factors (0.43 and 0.44, respectively). The results of our study in the heavy thinning plots provided a similar value of stem form factor found in early moderate thinning stands from their study.

Conclusion

The heavy thinning intensity (50% based on basal area) applied at the age 6 years gave the largest values in terms of mean DBH, mean height, mean basal area, and mean stem volume of individual trees, whereas the unthinned control showed the smallest values. The total height was not statistically different among treatments, although the mean height in the unthinned treatment was smaller than that of the other treatments. The current stand basal area and stand volume at 4 years after thinning was the largest with moderate thinning intensity, whereas those with the heavy thinning intensity were the smallest.

The results from this study indicated that the mean DBH increment of all trees, as well as the mean DBH of the dominant trees, increased with increasing intensity, but there was no significant difference among thinned and unthinned stands. The mean DBH increment of all trees in the unthinned stands was similar those in the moderate thinning stands. On the other hand, the height increment of all trees and of the dominant trees was not affected by thinning intensity.

The mean stand volume increment produced per rai was largest in the moderate thinning stands and differed significantly from the unthinned stands. However, it did not differ significantly from the heavy thinning stands. In the case of total stand volume production at 4 years after thinning, the results were in accordance with the results of the total stand volume increment.

The moderate and heavy thinning intensities reduced the stand volume increment by 23% and 64%, respectively, related to the mean stand volume increment of the unthinned stands, whereas the stand volume increment in the unthinned stand decreased by almost 99%. However, part of the total stand volume production of the unthinned stands was lost because of natural mortality.

Thinning intensity had effects on tree (stem) attributes that contributed to the quality of stem form. Live-crown ratio increased with increasing thinning intensity. On the other hand, the slenderness ratio decreased with increasing thinning intensity. The absolute form factor was clearly affected by thinning intensity. The form factor was significantly different among treatments, and unthinned stands gave the smallest form factor; therefore, thinning practice tended to have a positive effect on stem form even in a young stand of teak.

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The Growth of Coppiced Teak in Northern Thailand

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Abstract

Coppicing is an alternative regeneration method to replanting that reduces reestablishment costs and time. However, whether the growth from coppicing is different from that of the original planted trees is a frequent concern. The growth of teak after coppicing was studied in teak plantations in Uttaradit Province at the Tha Pla Plantation, belonging to Forest Industry Organization (FIO), and the Den Kra Tai and Nam Ang Plantations, belonging to Tha Sao Sawmill Limited Part. The objectives were to compare the growth performance of teak after coppicing and teak from planting, including comparing the growth of teak after coppicing using different management methods.

The results revealed that mean height and diameter at breast height (DBH) of teak from coppicing were significantly higher than teak from planting grown in the same area because of the faster growth of sprouts in the first stage affected the growth of seedling. In contrast, the growth of teak had no significant difference if sprouting occurred in different areas from replanting. The sprouts from a clear cut stump showed better growth than sprouts from thinned stumps. Additionally, the stump diameter was positively correlated with the mean height and DBH of sprouts.

Keywords: Growth, Coppiced teak, Northern Thailand

Introduction

Teak (*Tectona grandis*) is an important indigenous tree species in Thailand, and it is one of the most widely cultivated hardwood timber species in tree plantations. The first teak plantation in Thailand was established in 1906 in Phrae Province, Northern Thailand, with the aim of producing teak to meet increasing demand. At present, teak is widely planted with many forms of planting by several agencies. The main agencies responsible for teak planting in Thailand are the Royal Forest Department (RFD) and the Forest Industry Organization (FIO), including the farmers who have increasingly planted teak for tree farming near their homesteads and mixed with other crops along the boundaries and other planting systems. Teak somehow still remains as a promising economic species across the country.

Teak is one of tree species that has the ability to coppice after it has been cut. Chaweepuk (1999) found that the coppicing ability of teak was 100 percent, whereas the survival rate of sprouts was about 71.40%, which suggests that the sprouting ability of teak may contribute to the rapid restoration of forest cover in gaps after timber extraction or cyclone damage (e.g. Bellingham et al. 1994; Riswan and Kartwawinata 1991). Where sprouts are able to grow into mature trees, sprouting may be a more effective means of re-establishment than slow-growing seedlings (Harcombe and Marks 1983; Ohkubo 1992). Rapid production of sprouts can benefits from the established root system and may enable the species to reestablish in gaps (Rijks et al. 1998), which is also important for wildlife habitats (Solomon and Blum 1967). However, the ability to coppice declines with age, and the ability to coppice may also vary with local environmental conditions and the felling season (Grundwald and Karchon 1974; Jacobs 1955). Vacharangkura and Viriyabuncha (2003) found that 3 years after treatment, two thinning treatments affected neither stand-level volume growth nor total yield. A study on coppicing in a teak plantation indicated that diameter at breast height (DBH) and total height of coppice sprouts in thinning with two alternate rows were higher than those in thinning with an alternate row. However, there was no significantly difference between the two treatments. The advantages of the coppicing system is not only in shortening the rotation but also in the productivity of the plantation (Himmapan and Noda 2012). Coppicing is an alternative regeneration system that has a low cost of establishment because little or no site preparation is required (Thaiutsa et al. 2001), and Akkhaseeworn (2007) recommended that the stumps left after teak had been cut could be allowed to undergo self-coppicing, which in turn would reduce the cost in both new seedlings and site preparation. The decrease in the costs with 4 × 4 m spacing in teak plantation management using coppicing was the cost of land preparation, planting, the first weeding, fertilizing, and seedlings in the first year. In the case of a coppicing rate of 50%, the first year cost of management was reduced from 3,960 Baht rai^{-1} (24,750 Baht ha^{-1}) to 2,028 Baht rai^{-1} (12,675 Baht ha^{-1}), and it reduced to 2,203 Baht rai^{-1} (13,769 Baht ha^{-1}) if the coppicing rate was high at 70% (Himmapan, 2008). Moreover, Noda and Himmapan (2012) established a discounted cash flow model for producing teak timber with a 15-year cutting cycle, and they evaluated the profitability of coppicing using afforestation with genetically improved seedlings with an incremental net present value (NPV). In the first rotation period, seedlings were planted and for reforestation in the second rotation period, separate models with coppicing and seedling reforestation were prepared. The results found that in these two rotation periods lasting 30 years, the introduction of coppicing improved the initial-year balance of payments by 50% or more.

This study was a joint research project between RFD and Japan International Research Center for Agricultural Science (JIRCAS) under the program for the development of combined management techniques for agriculture and forestry to support farmers engaged in planting beneficial indigenous tree species, by focusing on teak. This study aimed to examine the growth of coppiced teak in various patterns to identify low-cost teak plantation management methods.

Materials and methods

This study was conducted at teak plantations in Uttaradit Province, Northern Thailand, at the latitude of 17°8′–18°11′ N and longitude of 99°54–101°11′ E. The elevation was about 64 m above mean sea level. Uttaradit has a tropical savanna climate, and winter is dry and very warm. Temperature rises until April, which is very hot with an average daily maximum of 38.2 °C (100.8 °F). The monsoon season occurs from May through to October with heavy rain and somewhat cooler temperatures during the day, although nights remains warm. Most of the province was once covered with teak forests, and teak is a major product of Uttaradit. The largest teak tree in the world is to be found at the Ton Sak Yai Park in the Luang Prabang Range. This 1,500-year-old tree measures 9.87 m in circumference and 37 m in height, although it was originally 48.5 m high before being damaged in a storm (Wikipedia 2016).

There are teak plantations belonging to FIO and private plantation across Uttaradit Province. Coppice regeneration after clear cutting is used in some areas with various management systems. Three coppicing management systems were selected for examination in this study.

1. The growth of teak from coppicing and from planting within the same area at Tha Pla Plantation belonging to FIO, Uttaradit Province.

This plantation was planted in 1981 with 2 × 8 m spacing for agroforestry, and clear cutting was conducted in 2007 when the teak trees were 26 years old. After clear cutting, sprouting occurred from stumps and new seedlings were planted within the 8 m row widths and in positions where no sprouts had grown. This changed the spacing to 2 × 4 m. Thus, coppices and seedlings grew in the same area. The best sprout (healthiest, best growth rate, and occurring from the lowest position on the stump) was selected for each stump. Three experimental plots of 40 × 40 m were set when the teak trees were 4 years old in 2012 with a completely randomized design. The growth in terms of DBH and height was measured once a year from 2012 to 2016, and mean variables were compared using independent t-tests (5% significance level).

2. The growth of teak from coppicing and from planting in different areas at Den Kra Tai Plantation belonging to Tha Sao Sawmill Limited Part, Uttaradit Province.

This plantation was planted in 1996 with 2 × 4 m initial spacing, and all trees were clear cut in 2006 when the teak trees were 10 years old after being bought from farmers. Sprouts occurred from more than 85% of stumps, and then the best sprout (healthiest, best growth rate, and occurring from the lowest position on the stump) was selected for each stump. Tha Sao Sawmill Limited Part also planted the new seedling with 2 × 4 m spacing in a nearby area in the same year. The three experimental plots of 20 × 40 m were set in 2011 with a completely randomized design in each coppiced plot and planted plot for a total of 6 plots. Because the sprouts grew in different areas, some initial factors may effect to the growth in the first stage, the relative growth rate (RGR) of DBH and height were calculated and compared using independent t-tests (5% significance level).

3. The growth of sprouts coppiced from thinning stumps and clear cutting of stumps at Nam Ang Plantation belonging to Tha Sao Sawmill Limited Part, Uttaradit Province.

This plantation was planted in 1989. The plantation underwent line thinning in 2004, and all tree, including the sprouts that grew from the thinning, were clear cut in 2011. Sprouts occurred from both kinds of stump in 2012, and the most vigorous sprout was selected from each stump. Three experimental plots of 40 × 40 m were set in 2013, with a completely randomized design, when all of the sprouts were 1 year old. The growth in terms of DBH and height was measured once a year from 2012 to 2016. The growth characteristics of sprouts from the two kinds of stump were compared using independent t-tests (5% significance level). The correlation efficient between the diameter of a stump and growth characteristics was also analyzed.

Results and discussion

The growth of teak from coppicing and planting within the same area.

The growth of teak from coppicing and planting was studied in teak from 4 to 9 years old. The average numbers of trees in the study area (1 rai) were 49 coppiced and 51 planted trees. The average values of growth, including the comparison based on t-test results, are shown in Table 1. The DBH of coppiced trees was 9.10 cm when teak was 4 years old, increasing to 15.35 cm at 9 years old, whereas those of planted seedlings increased from 5.79 cm to 11.93 cm over the same time period. The increments of DBH and height of coppiced trees were 1.25 cm $year^{-1}$ and 1.17 m $year^{-1}$, respectively. The height increment of coppiced in this study was higher than the study of Chaweepuk (1999) which showed a height increment of coppiced teak at Lampang Province of 0.99 m $year^{-1}$. Comparisons based on t-test showed that the DBH and height of coppiced teak were significantly higher than planted teak (p<0.05). This result

Table 1. Mean values with standard deviation of growth performance and comparison between teak from coppicing and planting at Tha Pla Plantation, Uttaradit Province.

Age	Treatment	DBH (cm)			Height (m)		
		Mean	Std.	t-test	Mean	Std.	t-test
4-year	Coppicing	9.10	2.62	**	7.90	1.82	**
	Planting	5.79	2.69		5.32	2.31	
5-year	Coppicing	11.45	3.03	*	9.84	1.80	*
	Planting	7.87	3.14		7.26	2.58	
6-year	Coppicing	13.22	3.36	*	11.48	1.75	*
	Planting	9.70	3.45		8.97	2.75	
7-year	Coppicing	14.80	3.71	*	12.44	1.85	*
	Planting	11.22	3.65		10.31	2.82	
8-year	Coppicing	15.45	4.10	*	13.21	2.20	*
	Planting	12.08	3.82		11.43	2.97	
9-year	Coppicing	15.35	3.95	*	13.74	2.31	ns
	Planting	11.93	3.74		11.98	3.31	

ns – non-significant, * - significant at $p < 0.05$, ** - significant at $p < 0.01$

was similar to the study of Akkhaseeworn (2007), which found that the growth of coppiced sprouts in the plantation was higher than those in other teak plantations. Additionally, the study of Himmapan (2008) found that the growth characteristics, including DBH, height, basal area, stem volume, and biomass, of teak coppice sprouts that grew in the same area with the additional seedlings were increasing dramatically at 2–3 years old, and slightly increased in the age of 8 years. Bailey and Harjanto (2005) also reported that diameter growth as well as height of coppiced teak was higher than from teak seedlings, and this was due to stored food reserves in the mother stumps (Troup, 1921). The height at the last measurement showed no significant difference between coppiced teak and planted teak ($p = 0.08$), which was similar to the studies of Thueksathit (2006), who reported that the difference in growth between sprouts and additional seedlings became smaller as teak trees grew older.

The growth of teak from coppicing and from planting in different areas

The growth of coppiced teak and planted teak was studied when teak was 5 to 10 years old. The average number of coppiced teak and planted teak in the study area were 179 coppiced teak rai^{-1} and 190 planted teak rai^{-1}. The DBH of 5 years old coppiced and planted teak were 9.61 cm and 9.19 cm, respectively, and increased to 12.00 cm and 11.13 cm at 10 years old. The growth of both coppiced teak and planted teak in this area was poorer than teak of the same age at the Tha Pla Plantation.

The coppiced teak grew in different areas to a planted teak, and RGR in term of DBH and height were calculated for the comparison of growth between teak from coppicing and planting. The average values of growth including the comparison based on t-test are shown in Table 2. The result showed that the RGR of DBH of teak from coppicing and from planting was not significantly different in every measurement during the study, whereas the RGR of height of planted teak was significant higher than that of coppiced teak. As a result, the growth of teak from planting was not less than from coppicing if they were grown together because the planted teak did not suffer any negative effects from the faster growth of coppices in the initial stage and small difference in growth performances when teak became older.

The growth of sprouts coppiced from thinning stumps and clear cutting stumps

Planted teak and coppice sprouts after thinning in 2004 were clear cut in 2011. Not all stumps produced coppices. The rate of sprouts that occurred from stumps after thinning and from clear cutting were 45.24% and 54.76%, respectively. The DBH and the height of coppiced sprouts from thinning stumps were 2.75±1.10 cm and 0.96±0.93 m, respectively, whereas the DBH and the height of coppiced sprout from clear cutting stumps were 4.08±0.91 cm and 3.42±1.27 m, respectively. Fig. 1 shows the growth of coppiced sprouts from clear cutting stumps, which was significantly different from coppiced sprouts from thinning stumps ($p<0.01$). The results were in agreement with an earlier study by Thaiutsa et al. (2001), which found that teak coppiced well after clear cutting. Additionally, Himmapan and Noda (2012) found that the growth ability

Table 2. Mean values with standard deviation of the relative growth rate of DBH and height, and comparison between teak from coppicing and planting at Den Kra Tai Plantation, Uttaradit Province.

Age	Treatment	RGR DBH (cm cm^{-1}year^{-1})			RGR Height (m m^{-1}year^{-1})		
		Mean	Std.	t-test	Mean	Std.	t-test
6-year	Coppicing	0.118	0.019	ns	0.087	0.022	*
	Planting	0.114	0.016		0.127	0.017	
7-year	Coppicing	0.082	0.005	ns	0.058	0.015	*
	Planting	0.093	0.010		0.092	0.007	
8-year	Coppicing	0.069	0.001	ns	0.053	0.008	*
	Planting	0.072	0.009		0.075	0.011	
9-year	Coppicing	0.058	0.006	ns	0.047	0.008	*
	Planting	0.053	0.007		0.064	0.010	
10-year	Coppicing	0.044	0.012	ns	0.042	0.005	*
	Planting	0.038	0.011		0.060	0.010	

ns – non-significant, * - significant at $p < 0.05$

of coppiced sprouts of teak was affected by the origin of teak with coppiced sprouts from stumps after final cutting being better than from stumps after thinning or additional seedlings, whereas coppiced sprouts from stumps after a second thinning were better than from stumps after the first thinning. The study of Thaiutsa et al. (2001) also found that thinning methods did not affect shoot density, but they affected shoot growth. Modified mechanical thinning such as 2:2 mechanical thinning could be the recommended thinning method for faster growth of new shoots if clear cutting could not be applied.

Correlation of diameter of stump and growth of coppiced teak

Stumps after thinning and clear cutting had different diameters. The study showed that the diameter of thinned stumps was 5.0–34.4 cm, whereas the diameter of clear cut stumps was 7.3–38.8 cm. The average diameter was significantly different between these two stump origins (Table 3). The results also indicated that DBH of sprouts from clear cut stumps was 4.11 cm (1.60–6.10 cm) and height was 3.56 m (0.12–6.29 m). The growth of sprouts from thinned stumps was smaller than that from clear cut stumps; DBH was 2.99 cm (0.93–5.80 cm) and height 1.04 m was (0.10–5.10 m). Furthermore, both DBH and height of sprouts of clear cut stumps were positively correlated with stump diameter (r = 0.4393, $p< 0.0001$ and r = 0.5848, $p< 0.0001$, respectively) (Fig. 2). In cases of thinned stumps, it was only the height of sprouts from thinned stumps that was positively correlated with stump diameter (r = 0.2144, $p = 0.0024$) (Fig. 3). This result was similar to the study of Kwame et al. (2014), who found that stump diameter was positively correlated with leader height as well as the number of sprouts, but conversely the study of Akkhaseeworn (2007) showed that the size of the stump did not affect shoot growth.

Conclusion

In the earlier stages, the growth of teak from coppicing regeneration was faster than when it was raised from seedlings, especially when coppicing occurred in the same area with planting. The difference was decreased as teak trees grew older. The growth ability of coppice sprouts of teaks was affected by the source of the teak stump;

Table 3. Comparison of diameter of stump after thinning and clear cutting at Nam Ang Plantation, Uttaradit Province.

	Clear cutting	Thinning	t value	*p* (>t)
Average	22.26	15.36	13.893	<0.0001
S.D.	5.90	4.35		
Max.	7.30	5.00		
Min.	38.80	34.40		

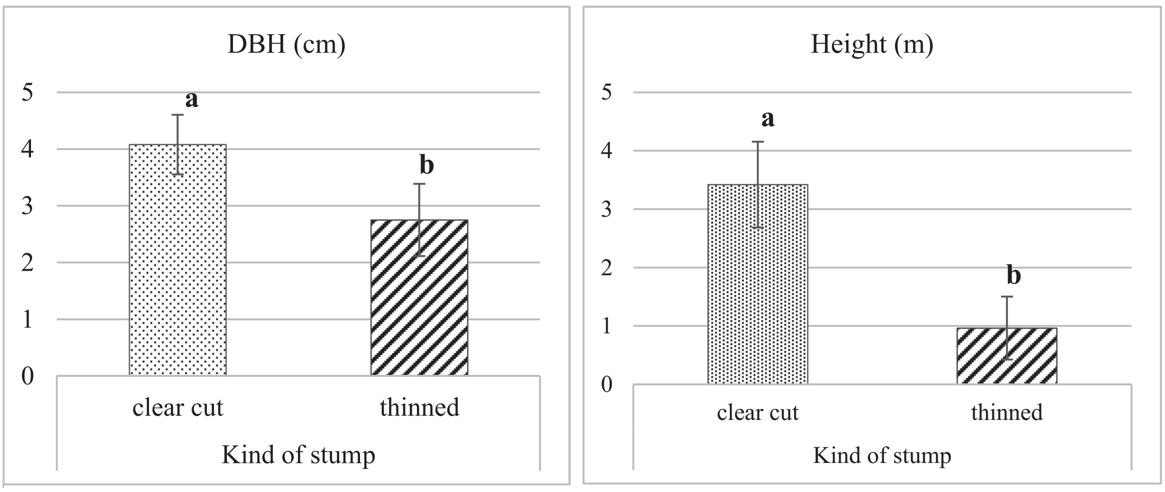

Fig. 1. Average DBH and height of coppiced teak from thinned stumps and clear cut stumps at Nam Ang Plantation, Uttaradit Province; different letters denote significant differences at p<0.05; vertical bars indicated standard error.

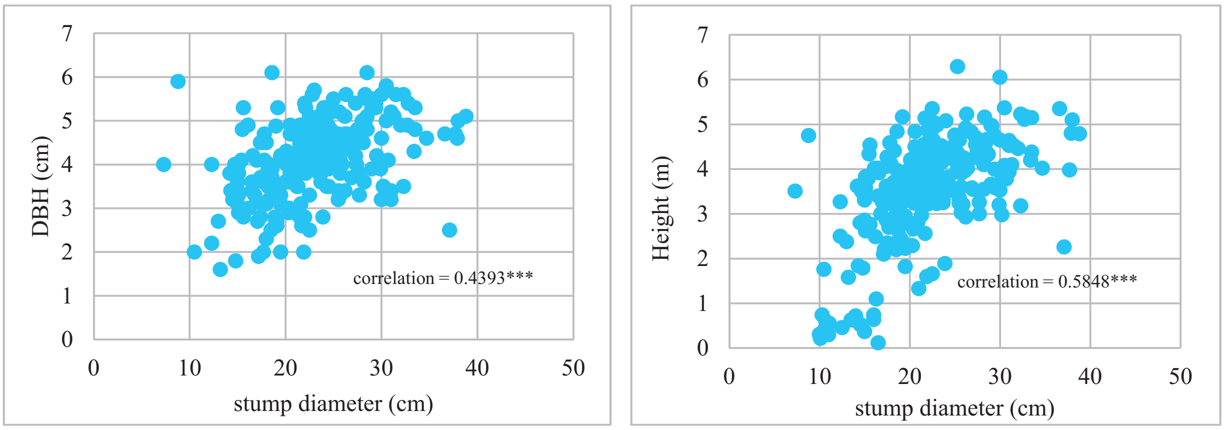

Fig. 2. Relationship between the diameter of clear cut stumps and DBH and height of sprout at Nam Ang Plantation, Uttaradit Province. Correlations with *** are significant at $p<0.001$

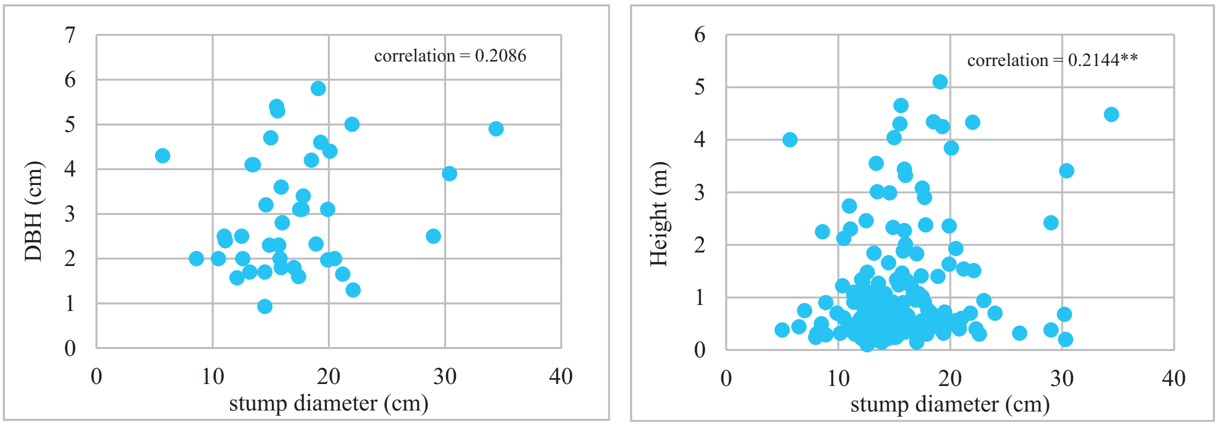

Fig. 3. Relationship between diameter of thinned stumps and DBH and height of sprouts at Nam Ang Plantation, Uttaradit Province. Correlations with ** are significant at $p<0.01$ and *** are significant at $p<0.001$

coppice sprouts from stumps after clear cutting were better than from stumps after thinning. The interaction of stump diameter had a positive impact on the size of coppicing in teak. Coppicing is one of the alternative regeneration systems and has advantages for coppice silviculture, which is very simple in its application, and reproduction from coppicing was usually more reliable and cheaper than reproduction from planting. Furthermore, there were some benefits from minimal soil damage during harvesting, a reduced need for weed management, physical protection of the site, and negligible risk of wind throw. However, management decision are still an important factor.

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Preliminary Results of a Second Clonal Test of Teak (*Tectona grandis* L.f.) in Northeastern Thailand

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Abstract

The objectives of the study were to determine the differences in tree performance among teak clones, to confirm the previous test (first study), and to produce improved genetic materials for teak farmers in Northeastern Thailand. The experiment was undertaken with a randomized complete block design (RCBD) with four replications. Each replication contained three ramets of each clone planted in a row (3 line plot). Twenty-five clones were selected based on the results of the previous field trail (first study), full-sib progeny, teak improvement program, and newly added trees from Navamin teak forest in Mae Hong Son province. In total, 300 seedlings (25 clones × 3 trees/plot × 4 replications) were planted in Khon Kaen province, Thailand.

The preliminary results of height (H), diameter at ground level (DGL), and stem form were evaluated when the seedlings reached 1 year old. In terms of clone performance, statistical analysis showed that there was a significant difference in current annual increment (CAI) of H and DGL of seedlings among clones. The average CAI of H and DGL of each clone were 1.11 m and 1.47 cm ranging from 0.56 to 1.45 m and 0.76 to 1.76 cm, respectively (n = 244). Based on Duncan's multiple range test, clones no. 219, 8c20, MH7 3bb/38, 119, 302, and 300 showed high performance in CAI of H. Among the 25 clones, clone no.3bb/38 showed especially good performance in growth (DGL = 1.69 cm and H = 1.25 m) and stem form. Regarding stem characteristics, we found variations of stem form within and among clones. The forms were classified as four types: straight stem, V shape, branchy, and multi-stem.

Keywords: *Tectona grandis* L.f, Clonal test, Clone, Northeastern Thailand, Khon Kaen

Introduction

Considered as the major clonal test project in Thailand, rooted cuttings were planted in 2000 at three sites (KamphaengPhet, Kanchanaburi, and Songkhla) in order to select teak plus trees and suitable clones to be planted in various sites. Meunpong et al. (2016) evaluated the differences in tree performance among the clones when the trees were 16 years old. It was reported that the site significantly affected tree growth. They found clones significantly affected in DBH in KamphangPhet and Songkhla. The clone performance was ranked based on the growth in diameter. The top clones from KamphaengPhet were 120, 245, 282, 116, 327, 83, 129, 290, 146, and 158. The top clones were totally different from those in Kanchanaburi, which are 336, 335, 265, 324, 273, 160, 271, 267, 89, and 333. At Songkhla, the top clones were 246, 36, 119, 336, 292, 345, 91, 159, 27, and 130. Only clone no. 336 was repeatedly found to be the superior clone at both Kanchnaburi and Songkhla (Meunpong et al. 2016). In brief, the results indicated that the site properties must be taken into consideration in the selection of suitable clones for plantations.

During 2008–2012, we studied the first set of clonal tests of teak in Northeastern Thailand in Udon Thani and Khon Kaen Provinces (Tangmitcharoen et al. 2012: referred to as "the first study" in this report). Unfortunately, the test was not successful because the growth rate of the trees was generally low and there was high variation among individuals. We found no significant difference in the height and diameter of trees among clones at two sites and no interaction effect between the site and clone in terms of height and diameter. The major reasons for clone failure were environment factors (drought and flooding), improper soil conditions for teak (pH, structure, property, porosity, drainage, and moisture holding capacity) including disturbance by *Eucalyptus* rooting systems nearby, and variations in soil in planting site micro-site effects.

For soil suitability, our study relied on the Land Department Development (LDD; 1990) in which the soil suitability was classified into three classes as 1: well suited, 2: moderately suited, and 3: unsuited. We also used the rank of classes and limitation of soil in the same way as Sukchun and Sakai (2009) (a: slightly acid, d: drainage problem or too wet, f: flood problem, gravel mixed in soil or shallow soil, n: nutrient status, s: soil texture is not suited because of being very sandy soil or having low natural fertility). Based on LDD (1990) and Sukchun and Sakai (2009), our planting site for the first test was categorized as 3s, (moderately suited soil with limitation that the soil texture was not suitable because of being very sandy soil or having low natural fertility). In short, for the first study, we concluded that the low rate of growth was primarily related to the unsuitable conditions both non-preferred soil for teak and severe flooding and drought.

Referred to as the second study, this study was set up again to serve the same objectives as the first study, which were to determine the difference in tree performances among clones and to produce improved genetic material of teak for planting in areas of Northeastern Thailand. This study attempted to overcome the reasons of the failure in the first study by: 1) Planting the seedling at a 2n site (well suited soil but slightly low soil pH for teak) instead of the 3s site (moderately suited soil with a limitation that the soil texture was not suited because of being very sandy soil or having low natural fertility). The 2n site was considered as a relatively good site for teak based on Sukchun and Sakai (2012). They classified 2n conditions as "2–3" for teak growth class, whereas the 3s was classified as "3–4". 2) Planting far away from Eucalyptus plantations. 3) Planting in the early rainy season.

Materials and methods

Experimental plots were planted on 17 July 2014 at Tambon Noonsomboom, Banhaad district, Khon Kaen province near to the Northeast Forest Seed Center. The planting site was classified as 2n.

The 25 tested clones, including unselected clones used as control treatments, were selected based on superior performance and from plus tree selection. The higher performing clones were from the first study (7), full-sib progeny (4); and from a new selection with high-elevation provenance in Mae Hong Son province (3).

Experimental design was a randomized complete block design (RCBD) with four replications. Each replication contained 3 ramets of each clone planted in a row (Fig. 1).

For statistical analysis, means and standard deviation were calculated for diameter at ground level and height. Analysis of variance (ANOVA) was used to determine variation in growth among clones. The Duncan new multiple range test at P<0.05 was used to compare the

245	219	28C28	302	37	MH7	271	245	3/27	38
5/79	Control	8C20	11C26	119	302	5C18	Control	119	331
271	V335	14/105	MH17	39	300	MH9	14/105	219	39
300	331	MH9	3/27	5C18	8C20	28C28	MH17	V335	22C50
2AA/15	22C50	38	3BB/38	MH7	37	11C26	3BB/38	5/79	2AA/15
271	Control	2AA/15	22C50	MH9	MH17	5C18	302	22C50	331
V335	8C20	5/79	245	39	V335	119	37	MH7	8C20
119	MH7	37	5C18	3/27	control	11C26	14/105	271	3BB/38
MH17	38	14/105	300	331	5/79	39	MH9	300	3/27
3BB/38	11C26	219	302	28C28	2AA/15	245	28C28	38	219

Remark:		
	Rep. 4	Rep. 3
	Rep. 2	Rep. 1

Fig. 1. Planting design (latinized low-column design) of teak clonal test of 25 clones (4 replications × 3 tree plots)

means for a significant differences among the variables.

We monitored the growth in terms of survival rate, height (H), and diameter at ground level (DGL). The preliminary results were monitored when the trees reached 1 year old. Survival rate and current annual increment (CAI) of H and DGL were measured and analyzed statistically in August 2016.

Results

The major findings of this second study were as follow:

1. The average survival rate of the seedlings was 81.33% ranging from 50% to 100% in each clone.
2. The average CAI of H and DGL of each clone were 1.11 m (SD=0.26) and 1.47 cm (SD=0.26), ranging from 0.56 to 1.45 m and 0.76 to 1.76 cm respectively (n=244).
3. Statistical analysis showed that there was a significant difference in CAI of H and CAI of DGL of seedlings among clones (p<0.01) (Table 2).
4. The group of clones that showed high performance in H included clone no. 219, 8c20, MH7 3bb/38, 119, 302, 300, as determined using Duncan's multiple range test.
5. Stem characteristics were classified as four types: straight stem, V shape, branchy, and multi-stem. There were some variations in stem characteristic within and among clones (Fig. 2).
6. Among 25 clones, clone no.3bb/38 showed good performance in growth (DGL = 1.69 cm and H = 1.25 m) and stem form (8 out of 11 with straight stems) (Fig. 3).

Discussion

Teak performs better on deep, well-drained alluvial soils derived from limestone, schist, gneiss, shale and some volcanic rocks. The optimum pH range for better growth and quality was between pH 6.5 and pH 7.5. In contrast, this species performs very poorly, in terms of growth and stem form, on dry sandy soil, shallow soil (hard pan soil or lower water table soil), acidic soil (pH < 6.0) derived from laterite or peatbog, and on compacted or waterlogged soil (Kaosa-ard 1981; Tewari 1992). The growth rate in terms of H and DGL of the seedlings reported in the present study was better than in the first study (Tangmitcharoen *et*

Fig. 2. Examples of stem characteristics categorized as straight stem, v shape, branch, and multi-stem (from left to right).

H (m)	DGL (cm)	CAI of H (m)	CAI of DGL (cm)	No. of ramets	% survival
1.67 (0.73)	3.99 (0.79)	1.25	1.69	11	91.67

Fig. 3. Clone no. 3bb/38 showed outstanding performance in terms of growth and stem form. Numbers in brackets represented the standard deviation.

Table 1. Average of diameter at ground level (DGL), height (H), and current annual increment (CAI) of 1-year-old teak seedlings.

No.	Clone no.	DGL mean (mm)	DGL SD (mm)	H mean (cm)	H SD (cm)	CAI Height (cm)	CAI DGL (mm)	n	% survival
1	119	40.08	10.18	193.67	48.24	131.08	14.58	12	100.00
2	271	31.17	8.63	96.50	45.09	55.56	13.21	8	66.67
3	300	39.33	12.19	197.91	65.89	122.50	12.63	11	91.67
4	11C26	36.20	42.45	128.50	53.47	73.92	13.73	6	50.00
5	14/105	33.71	19.71	117.42	68.81	69.75	13.06	12	100.00
6	219	37.93	11.49	200.13	75.90	145.00	12.78	8	66.67
7	22C50	36.62	11.89	135.00	64.27	82.17	11.71	6	50.00
8	245	28.51	8.66	100.67	54.62	63.72	8.64	9	75.00
9	28C28	38.39	8.88	174.00	60.86	116.55	17.45	11	91.67
10	2AA/15	36.40	14.31	132.00	69.49	91.13	12.67	12	100.00
11	3/27	33.42	13.50	121.20	63.54	72.40	13.95	10	83.33
12	302	45.74	14.99	188.58	60.13	120.33	16.38	12	100.00
13	331	40.78	13.60	152.80	64.95	99.60	15.97	10	83.33
14	37	28.92	7.79	105.89	51.43	63.94	7.70	9	75.00
15	38	38.20	15.03	141.67	55.80	79.33	11.82	9	75.00
16	39	33.63	8.62	130.90	51.85	91.15	11.25	10	83.33
17	3BB/38	39.88	7.86	167.14	73.13	125.68	16.93	11	91.67
18	5/79	38.52	13.49	165.63	77.17	99.38	9.21	8	66.67
19	5C18	31.58	8.34	114.78	44.34	64.28	7.62	9	75.00
20	8C20	39.33	10.61	193.89	71.29	124.83	13.30	9	75.00
21	MH17	44.73	12.42	200.20	78.23	136.55	15.68	10	83.33
22	MH7	37.00	9.92	146.80	66.96	91.05	13.20	10	83.33
23	MH9	38.42	13.89	133.00	58.77	79.63	16.21	8	66.67
24	V335	37.41	7.70	165.83	52.77	114.96	11.85	12	100.00
25	Control	40.12	7.31	149.08	57.85	90.58	14.43	12	100.00
	Average	37.04	12.54	150.13	61.39	96.20	13.04		81.33
	SD	4.25	6.94	33.00	9.86	26.12	2.72		15.08

Table 2. Statistics for current annual increment (CAI) of height (H) and diameter at ground level (DGL) of 1year-old seedlings.

CAI	Source	DF	Type I SS	Mean square	F value	Pr>F
H	Block	3	19875.005	6625.002	4.48	0.0047
	Clone	24	150412.998	6267.208	4.24	0.0001
DGL	Block	3	430.539	143.513	3.19	0.0251
	Clone	24	2243.623	93.484	2.08	0.0039

al., 2012). This was probably due to better environmental factors (no severe climate conditions after planting and also planting in more suitable soil conditions for teak [2n instead of 3s]).

It was interesting to find one outstanding clone (no. 3bb/38) that performed the best in terms of growth and stem form. This clone originated from the full-sib progeny where both paternal and maternal clones were selected from the plus trees. Further monitoring of this specific clone should be performed.

As for stem characteristics, it seemed that there were variations that could categorized into four types (straight stem, V shape, branchy, and multi-stem). The different characteristics of the stems were not the result of clonal effects, and instead were probably caused by nursery effects or damage during transportation before planting. To obtain more homogeneous measurements, implementation of cutting all seedlings at ground level was probably necessary at an early stage (1–2 years old).

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Growth characteristics of teak seedling planted on different types of sandy soil in Northeast Thailand

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Abstract

In Northeast Thailand, sandy soil is prevalent, in which the growth of teak (Tectona grandis L. f.) is suppressed. Sandy soil is characterized by low pH, poor fertility, and low water holding capacity. To determine the factors that suppress teak growth, we planted teak seedlings in sandy soil at two sites. One of the sites exhibited suppressed teak growth but the other did not. We compared growth, photosynthetic rate, leaf water potential, and the concentrations of elements in plant organs between the two sites.

The site where teak growth was suppressed showed low concentrations of nutrients in the soil, especially Ca. The average tree height at this site was only 40 cm after 16 months, whereas tree height at the other site was over 300 cm at same time point. The site with low teak growth was characterized by low uptake of nutrients, and especially Ca deficiency. The low growth rates correlated with decreases photosynthetic rate and drought stress in the dry season. Moreover, Mg accumulated in the leaves of teak with low growth, and this accumulation was considered as a factor in the decreased photosynthetic rate and drought stress. We concluded that the concentration of Ca in soil was important for teak growth, and the site with low Ca showed drastic suppression of teak growth and Mg toxicity caused by Ca deficiency.

Keywords: Acrisols, Photosynthesis, Leaf water potential, Nutrients

Introduction

In Northeast Thailand, teak (*Tectona grandis* L. f) plantations have increased as a result of a tree plantation promotion project since 1994 (Furuya et al. 2012). However, there was an area in which the growth of teak was very poor (Tangmitcharoen et al. 2012). In contrast, in an experimental plot only 10 m from that studied by Tangmitcharoen et al. (2012), teak growth was much better (Wichiennopparat et al. 2012). Wichiennopparat et al. (2012) examined the effects of fertilizer on the growth of teak. These experiments showed favorable growth even without fertilization. The representative soil from Northeast Thailand is described as a “light textured sandy soil” (abbreviated to sandy soil) that is categorized in the acrisols (ultisols in USDA soil taxonomy) (Kyuma 2003; Suzuki et al. 2007). The plots of Tangmitcharoen et al. (2012) and Wichiennopparat et al. (2012) had acidic sandy soil (pH <5.5); however, teak growth differed between the two sites. From these previous studies, we could not elucidate the factors that affected teak growth. We predicted that other soil parameters may affect teak growth and caused the observed differences.

The difference in soil texture affected growth of teak, with growth of teak showing a negative correlation with the content of sand, and a plantation with a high content of sand in the soil showed low growth of teak (Tanaka et al. 1998; Salifu 2001). With regard to nutrients, the growth of teak is restricted by nutrient deficiency, especially nitrogen (N), calcium (Ca), and phosphorous (P) (Tewari 1992; Tanaka et al. 1998, Barroso et al. 2005; Zhou et al. 2012). In addition, the concentrations of nutrients in plant organs are important indicators to estimate the effect of any nutrient deficiency (Zech and Drechsel 1991; Gopikumar and Varghese 2004; Barroso et al. 2005). However, little information exists to analyze the concentrations of nutrients in the organs of teak in Thailand (ex. Kayama et al. 2016). Moreover, teak consumes large amounts of water for its growth, and the leaves of teak are sensitive to drought stress (Rao et al. 2008; Cernusak et al. 2009; Kunert et al. 2010). There is a possibility that the plots examined by Tangmitcharoen et al. (2012) and Wichiennopparat et al. (2012) may have differed in their soil texture, nutrients, and water soil content, and as a result the growth levels were different.

The aim of our research was to determine the factors that affect teak growth. We conducted a planting test of teak seedlings in sandy soil in two plots with different sandy soils. We analyzed soil properties and water in soil in the two plots. In addition, we examined the ecophysiological traits of teak seedlings, specifically (1) the growth characteristics of seedlings, (2) leaf water potential, (3) photosynthetic rate, and (4) concentrations of elements in plant organs. Based on these results, we identified factors to affected teak growth in sandy soil in Northeast Thailand.

Materials and methods

Study site

Our experiment was conducted at the Northeast Forest Seed Center located in Khon Kaen Province in northeastern Thailand (16°16′ N, 102°47′ E, 191 m a.s.l.). This center conducts measurements of meteorological data: mean annual precipitation was 1,104 mm, and annual mean, maximum, and minimum temperatures were 28.3 °C, 40° C, and 13 °C, respectively (from 2008 to 2012, Northeast Forest Seed Centre, unpublished data). Precipitation is concentrated from May to October (Northeast Forest Seed Center, unpublished data).

In Khon Kaen Province, we previously published a soil suitability map of teak plantation for farmers (Wichiennopparat et al. 2015). Sandy soil in Khon Kaen Province is distributed over a large area (13.5%). These areas are categorized as moderately suitable for teak planting (“3s” site in a soil suitability map).

Selection of experimental plots and preparations of land and teak seedling

For the selection of experimental plots with sandy soil, we selected two sites at the Northeast Forest Seed Centre based on differences in the herbaceous plant species present. At the more suitable site, grasses were widely distributed over the area, whereas the moderately suitable site was covered with dwarf herbaceous legumes. The moderately suitable plot was the same research site as examined by Tangmitcharoen et al. (2012, “3s” site). The more suitable plot neighbored the research site examined by Wichiennopparat et al. (2012, “2n” site in a soil suitability map). We abbreviated to “moderate” for the moderately suitable site and to “suitable” for the more suitable site, which are used hereafter.

We secured 432 m^2 of land at the moderate and suitable sites for our experiment. The distance between the two sites was ca. 100 m. In the neighborhood of each plot, there were plantations of eucalypt. We made ditches at the border of the plantations of eucalypt in December 2013 to prevent root invasion. The width and depth of the ditch were 2 m and 1 m, respectively. In April 2014, we conducted land preparation. All of trees growing in the two plots were cut down and their roots were removed. In addition, we weeded the two plots. After this work, we ploughed the two plots three times to a depth of 30 cm.

The teak seedlings were prepared by a tissue culture technique. The teak clone was from Mae Hong Son Province (clone number 21), and this clone has been planted in various places (Royal Forest Department, unpublished data). Teak seedlings were raised from March to June 2014 at the Teak Improvement Center, Lampang, Thailand. In July 2014, 252 teak seedlings were transported to the Northeast Forest Seed Center, Khon Kaen.

Establishment of the experiment

We established three blocks each in the moderate and suitable plots. The size of each block was 12 m × 10 m, and there was 4 m between the blocks. On the border between the blocks, teak seedlings were planted for the buffer. After establishment, we buried a concrete pole in the center of two blocks at the two sites. In July 2014, we planted 42 teak seedlings in each block at the two sites. The interval between seedlings was 2 m × 2 m. Twenty-two teak seedlings were planted outside of the blocks and were considered as the buffer trees. We measured various growth characteristics for 20 teak seedlings per block planted within the buffer trees.

After planting, we inserted soil moisture sensors (SM150, Delta-T Devices Ltd., Cambridge, UK) in two blocks at the two sites. The sensors were set near a seedling.

Soil analysis

We measured soil texture, cation exchange capacity (CEC), and chemical properties including pH and concentrations of carbon (C), N, exchangeable P, and base cations. Three soil samples from each block at the two sites were collected in July 2014. To determine the pH of the soil, 25 ml of distilled water was added to 10 g fresh soil to make a homogenized mixture (van Reeuwijk 2002). This mixture was then shaken for 1 h and the pH was measured using a pH meter (SG2, Mettler Toledo, Zürich, Switzerland). Prior to chemical analysis, we conducted the air-drying of soil samples.

The soil texture was determined by the hydrometer method (Klute 1986). In the analysis of CEC, we used a method based on that of Chapman (1965), and developed a rapid method by Fujihira Industry Co. (http://www.fujihira.co.jp/english/soi/Field%20Soil%20Doctor.html). The concentrations of C and N in dried soils were determined using a nitrogen and carbon analyzer (Flash 2000, Thermo Fisher Scientific, Waltham, MA). Exchangeable P was separated using dilute acid fluoride (Sparks et al. 1996) by shaking for 1 minute. P in the extracted solution was determined by the molybdenum blue method (American Public Health Association et al. 1998) using a spectrophotometer (U-1800, Shimadzu, Kyoto, Japan). Exchangeable base cations (Ca, magnesium [Mg], potassium [K], and sodium [Na]) was quantified by mixing 4 g of dry soil with 100 ml of 1 M ammonium acetate solution, and shaking for 1 h (Sparks et al. 1996). Base cations in the extracted solutions were analyzed using an atomic absorption spectrophotometer (AAnalyst 300, Perkin-Elmer, Norwalk, CT).

Measurement of teak seedlings

For the measurement of teak seedlings, 20 seedlings for each block at two sites were used for growth measurements. Total numbers of seedlings were 60 for each site. We measured tree height and basal diameter at six time points (July 2014, October 2014, February 2015, May 2015, July 2015, and November 2015). At these times, we also confirmed the number of dead teak seedlings.

Measurement of photosynthetic rate

We measured area-based photosynthetic rate at light saturation (P_{sat}) and stomatal conductance (gs) for teak leaves located second from the top. For the measurement of photosynthetic rate and leaf water potential, six teak seedlings (two individuals each from three blocks) were used for the measurements. When we measured photosynthetic rate, the leaves of some seedlings were immature or senescent. In addition, the leaves of two-thirds of the seedlings were damaged by worms. To provide uniformly mature and healthy teak leaves, we selected six teak leaves from 60 seedlings. On the maturation of teak leaves, we used them that passed one month after foliation. We measured P_{sat} seven times (October 2014, December 2014, February 2015, May 2015, July 2015, October 2015, and November 2015), and the measurement were always performed between 09:00 and 11:00.

Measurements were made using a portable gas analyzer (LI-6400, LiCor, Lincoln, NE, USA) in steady-state conditions, at an ambient temperature of 28 °C and ambient CO_2 concentration of 38.0 Pa. The LED light source was adjusted to a saturation light level of 1,800 μmol $m^{-2}s^{-1}$ PPF.

Measurement of leaf water potential, concentration of nitrogen, and leaf mass per area

After measurement of photosynthetic rate, we measured the leaf water potential of teak leaves at seven time points (October 2014, December 2014, February 2015, May 2015, July 2015, October 2015, and November 2015). The leaf used to measure water potential was the same as that used to measure photosynthetic rate. In general, leaf water potential was lowest in the afternoon because of transpiration and highest during the night after recovery of water (Larcher 2003). We measured leaf water potential in the afternoon and predawn. Six teak leaves for each treatment were sampled at 13:00–14:00 and 05:30–06:00 the next day. Sampled shoots were placed in a plastic bag that contained a wet filter paper and then kept in a refrigerator. We measured leaf water potential using a pressure chamber (Model 600, PMS Instrument Co., Albany, OR, USA).

After measuring leaf water potential, we analyzed the concentration of nitrogen and leaf mass per area (LMA). Photosynthetic rate is closely related to the concentration of N (Evans 1989; Larcher 2003; Kayama et al. 2007) and leaf thickness (Niinemets 1999; Terashima et al. 2001).

The leaf samples were oven-dried at 70 °C for 3 days. After drying, we samples 3 cm^2 of teak leaf samples and weighed them. LMA (g m^{-2}) was calculated by the method of Larcher (2003). Leaf samples were ground to a fine powder using a sample mill (WB-1; Osaka Chemical Co., Osaka, Japan). The concentration of N was determined using an NC analyzer (Sumigraph NC-220F, Sumika Chemical Analysis Service, Tokyo, Japan). The concentration of N was calculated from the area based on N (N_{area}) from the LMA data.

Analysis of biomass and element concentrations of teak seedlings

To determine the aboveground biomass of teak seedlings, we measured the dry masses of leaves and stems. At the end of November 2015, we collected the aboveground organs of four teak seedlings from each of the three blocks at the two sites. The organs were divided into leaves and stems, and the fresh masses were measured. We collected the largest leaf from the leaf samples and measured its length and width. Leaf area was calculated using equation of the Tondjo et al. (2015). In addition, about 100 g (fresh mass) of leaf and stem samples were collected and their fresh mass measured. Moreover, we collected the leaf located second from the top for analysis. These leaf and stem samples were each placed into separate envelopes and oven-dried at 70 °C for 3 days. When the sample that fresh mass was below 100 g, all of samples were placed into a single envelope. After drying, the dry mass of each component was determined and the water content calculated. We calculated the dry mass of total leaves and stems from this water content data.

We also collected parts of the roots of teak seedling from the same seedlings as used for the aboveground organs. We collected four root samples from each of the three blocks at the two sites. The roots weighed approximately 10 g (fresh mass) and their diameter was less than 2.0 mm. The roots were washed twice with tap water to remove soil and air-dried. The root samples were transport to our laboratory in Japan and washed again with distilled water. Each root sample was placed into a separate envelope and oven-dried at 70 °C for 3 days.

For the analysis of elements in the plant organs, we measured the concentrations of N, P, K, Ca, Mg, and Na in leaves (located second from the top) and roots. Dried samples were ground to a fine powder, and N concentration was determined using the NC analyzer. The remaining samples were digested by the HNO_3-HCl-H_2O_2 method (Goto 1990). Concentrations of K, Ca, Mg, and Na were analyzed using an ICP analyzer (ICPE-9000, Shimadzu, Kyoto, Japan), and the concentration of P was determined by the molybdenum blue method using a spectrophotometer (UV-2500PC, Shimadzu, Kyoto, Japan).

Statistical analysis

Significant pairwise differences for each variable were tested by t-test using Stat View 5.0 (SAS Institute Inc.). Comparisons were made between the moderate and suitable sites. For the data of soil water content, times and sites were examined repeated measures of ANOVA.

Results

Water contents in soil

Average soil water content values at two blocks of two sites were shown in Fig. 1. The water content was low from January to May 2015, but in the rainy season (June to September 2014, and June to August 2015) water content was high. Soil water content was significant difference among months (P<0.001).

Comparing with the data of two sites, soil water content of suitable a showed high values in every months compared with other data. In contrast, the value of soil water content of suitable b was similar with those of moderate a and b. The margin between the suitable and moderate sites was low from December 2014 to May 2015. Soil water content was significant difference between moderate and suitable sites (P<0.001). However, there was no significant interaction between months and sites.

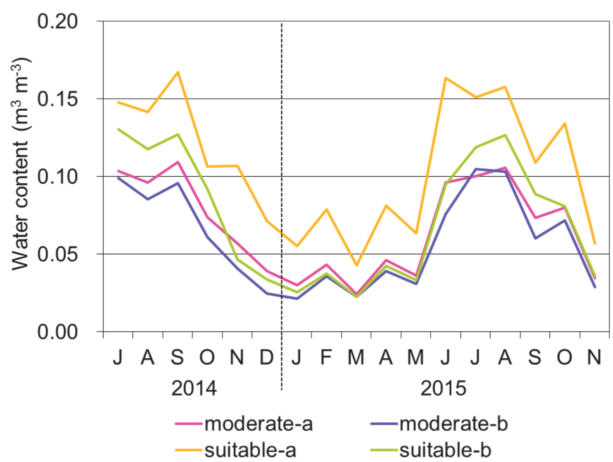

Fig. 1. Average soil water content at the moderate and suitable sites with sandy soil. (from July 2014 to November 2015). There were two data (a and b) at different blocks of two sites.

Soil properties

Regarding soil texture, the content of sand was over 80% for each site (Table 1). Compared the two sites, there was no significance of sand, silt, and clay contents between suitable and moderate sites ($P>0.05$).

The pH and CEC values were significantly higher for the suitable site than for the moderate site ($P<0.001$). The concentrations of C, N, Ca, Mg, and K at the suitable site were also significantly higher than those at the moderate site ($P<0.01$). There was no significant difference in the concentrations of P and Na between the two sites

Growth characteristics

From October 2014, tree height and diameter were significantly larger for the suitable site than for the moderate site (Fig. 2, $P<0.001$), and differences in teak growth between the moderate and suitable sites were clear (Fig. 3). At the suitable site, the increase in tree height and diameter accelerated from July 2015. In contrast, teak seedlings at the moderate site did not show obvious growth. During the experimental period, the increase in tree height and diameter was 12 cm and 4.6 mm at the suitable and moderate sites, respectively.

Dead seedlings were observed at the moderate site from February 2015. At the end of experiment, 47% of seedlings at the moderate site had died. In contrast, only one seedling died at the suitable site.

Photosynthetic rate

P_{sat} values were significantly higher for the suitable site than that for the moderate site ($P<0.05$) except for in February 2015 (Fig. 4). P_{sat} was high in October 2014, then the values decreased until May 2015 at each site. In July 2015, P_{sat} increased at both sites, but it then decreased from October 2015 at the moderate site.

gs was also significantly higher at the suitable site than the moderate site ($P<0.05$) except for in February 2015. The decrease in gs from October 2014 to May 2015 showed a similar trend to P_{sat}. In July 2015, gs increased drastically at the suitable site.

Leaf water potential

Leaf water potential in the afternoon was highest in July 2015 (Fig. 5) for each site. In contrast, leaf water potential was lowest in November 2015 for the suitable site, but at the moderate site it was lowest in February 2015. Comparing the two sites, leaf water potential was significantly higher for the suitable site than that for the moderate site in February 2014, July 2015, and October 2015 ($P<0.05$).

Table 1. Texture and chemical properties of soils from the moderate and suitable sites with sandy soil (Mean ± SE, n=9). Mean values of each parameter were analyzed by t-test. ** $P<0.01$, *** $P<0.001$, and n.s. not significant.

Treatment	Texture (%)			pH
	Sand	Silt	Clay	
moderate	80.2±0.5	14.1±0.7	5.7±0.9	4.53±0.08
suitable	81.5±0.6	13.8±0.4	4.7±0.4	5.95±0.05
Statistical test	n.s.	n.s.	n.s.	***
	CEC ($cmol\ kg^{-1}$)	C ($mol\ kg^{-1}$)	N ($mmol\ kg^{-1}$)	P ($mmol\ kg^{-1}$)
moderate	1.30±0.10	0.58±0.19	21.6±2.5	0.278±0.065
suitable	2.50±0.14	1.35±0.09	6.9±1.1	0.341±0.070
Statistical test	***	**	***	n.s.
	Ca ($mmol\ kg^{-1}$)	Mg ($mmol\ kg^{-1}$)	K ($mmol\ kg^{-1}$)	Na ($mmol\ kg^{-1}$)
moderate	1.31±0.21	0.94±0.12	0.58±0.07	0.103±0.026
suitable	8.37±0.79	2.93±0.20	2.62±0.27	0.184±0.046
Statistical test	***	***	***	n.s.

For the predawn leaf water potential, the value at the moderate site in February 2015 was quite low. In contrast, leaf water potential at the suitable site was not particularly low. Comparing the two sites, leaf water potential was significantly higher for the suitable site than for the moderate site except for in October and November February 2015 ($P<0.05$).

Concentration of nitrogen and LMA

N_{area} values were highest in December 2014 at the suitable site and in February 2015 at the moderate site (Fig. 6). Comparing the two sites, N_{area} was significantly higher for the suitable site than the moderate site in October 2014, December 2014, and October 2015 ($P<0.05$). At other time points, there were no significant differences between the two sites.

The trend for LMA at the suitable site showed an increase from October at the start of the dry season. By contrast, this trend was not clear at the moderate site. In May 2015 when new leaves extended, LMA decreased. Comparing the two sites, LMA was significantly higher for the suitable site in December 2014, February 2015, and November 2015 than for the moderate site ($P<0.01$). In contrast, LMA in October 2014 was significantly higher for the moderate site than that for the suitable site ($P<0.05$).

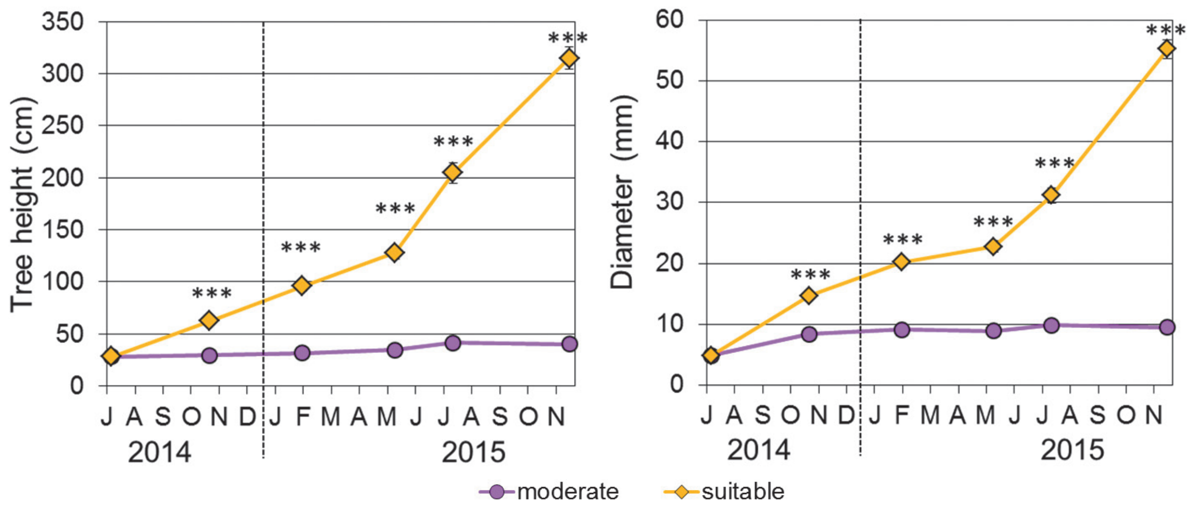

Fig. 2. Tree height and basal diameter of teak seedlings grown at the moderate and suitable sites with sandy soil (mean ± SE, n=60). Mean values of each parameter were analyzed by t-test. *** $P<0.01$.

Note. Divisions on the horizontal axis over the letters are the first day of each month. The same format is used in subsequent figures.

Fig. 3. Pictures of teak seedling grown at the moderate (left) and suitable (right) sites with sandy soil (October 2015). Teak growth showed obvious differences between the two sites.

Biomass of teak seedling

For the dry masses of aboveground organs in July 2014, leaf and stem dry masses were significantly larger for the suitable site than for the moderate site (Fig. 7, $P<0.001$). In the moderate site, leaf and stem dry masses were only 5.1 g and 26 g, respectively.

In addition, the area of the largest leaf was significantly larger for the suitable site than for the moderate site ($P<0.001$). Comparing the two sites, leaves from the suitable site were 29 times larger than from the moderate site.

Concentration of elements in plant organs

For nutrients in roots, the concentrations were significantly higher for the suitable site than for the moderate site (Table 2, $P<0.01$). Moreover, the concentrations of Ca and P in leaves were also significantly higher for the suitable site than for the moderate site ($P<0.05$). In contrast, the concentration of Mg in leaves was significantly higher for the moderate site than for the suitable site ($P<0.05$). The concentrations of N and K in leaves showed no significant differences between the two sites. In addition, the concentrations of Na in leaves and root did not show any significant difference.

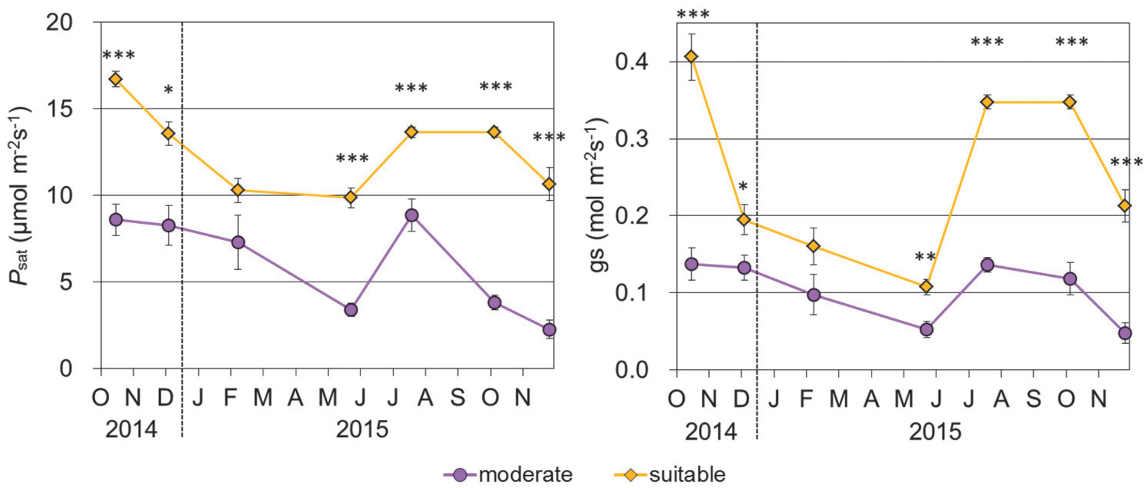

Fig. 4. Photosynthetic rate at light saturation (P_{sat}) and stomatal conductance (gs) for teak seedlings grown at the moderate and suitable sites with sandy soil (9:00-11:00, mean ± SE, n=6). Mean values of each parameter were analyzed by t-test. * $P<0.05$, ** $P<0.01$, *** $P<0.001$.

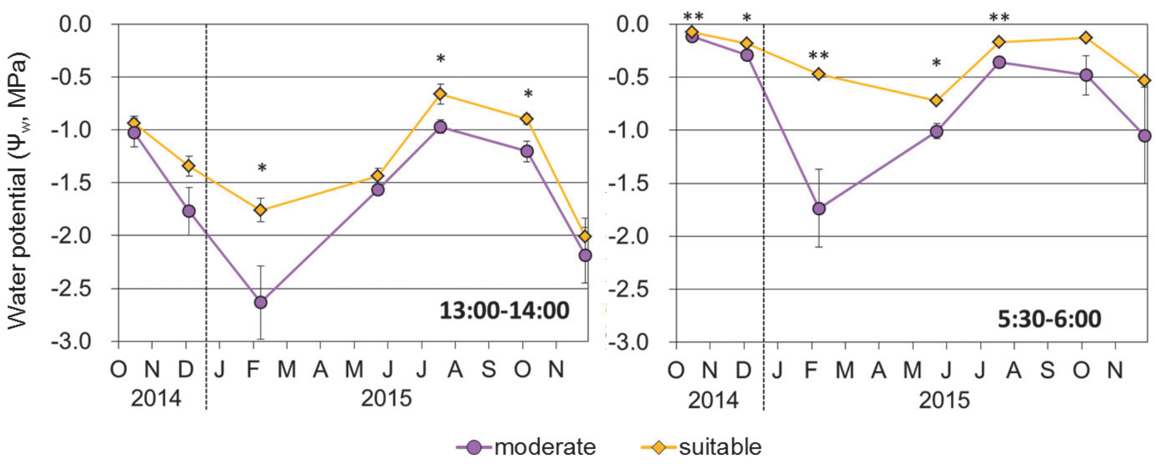

Fig. 5. Leaf water potential in the afternoon (13:00–14:00) and predawn (05:30–06:00) for teak seedlings grown at the moderate and suitable sites with sandy soil (mean ± SE, n=6). Mean values of each parameter were analyzed by t-test. * $P<0.05$, ** $P<0.01$.

Discussion

Based on these results, teak growth was substantially different between the moderate and suitable sites (Fig. 2, 3, 7). At the moderate site, teak growth was suppressed drastically and 47% of seedlings died. With regard to factors that affected teak growth, we predicted that differences of soil texture, nutrients, and water in soil may be contributory factors. The content of sand at the two sites was the same (Table 1); therefore, a difference in soil texture was not the main factor affecting teak growth. Soil water levels were higher at the suitable site; however, the range of its value was wide, and a block of suitable site was similar value of soil water with that of moderate site (Fig. 1). Suitable site showed large growth of teak seedlings for every block compared with moderate site. Thus, differences in soil water were also not a major factor that affected teak growth.

In terms of soil nutrients, various nutrients except for P showed low concentrations at the moderate site (Table 1). In addition, all nutrients in roots and Ca and P in leaves were lower in concentration at the moderate site (Table 2). Thus, teak seedlings grown at the moderate site suffered from the suppression of nutrient uptake, especially of Ca and P.

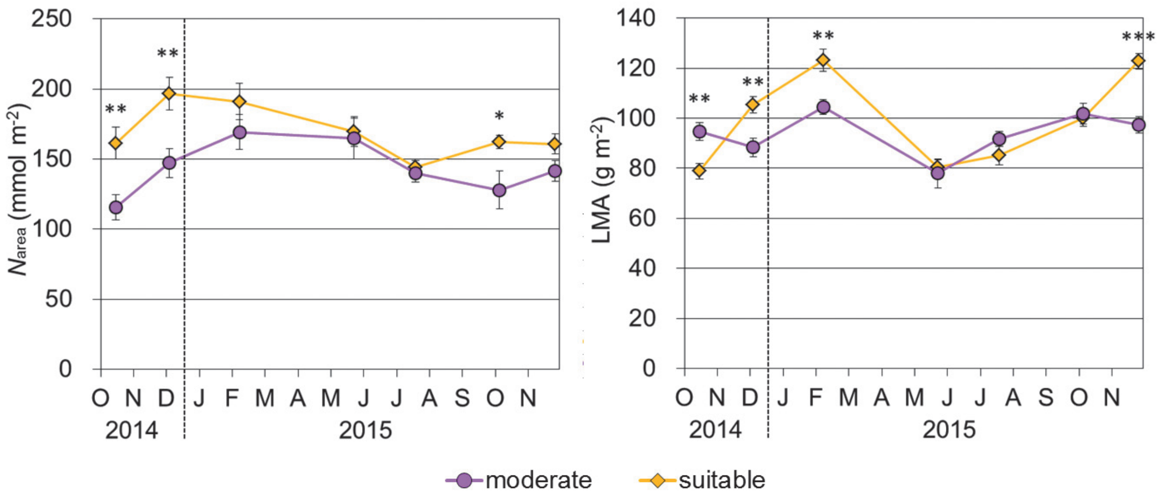

Fig. 6. Concentration of area-based nitrogen (N_{area}) and leaf mass per area (LMA) for teak seedlings grown at the moderate and suitable sites with sandy soil (mean ± SE, n=6).

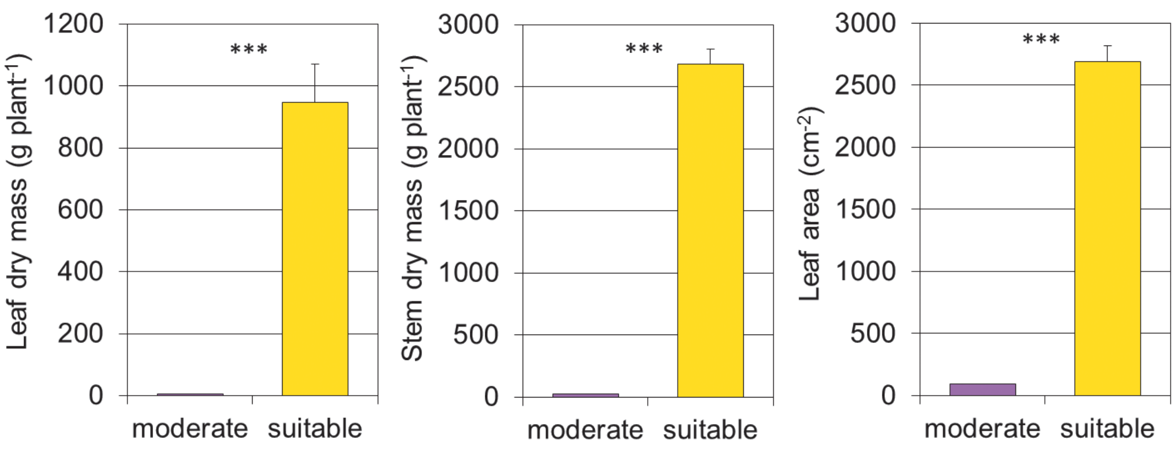

Fig. 7. Leaf and stem dry mass, and the area of the largest leaf for teak seedlings at the end of the experiment (November 2015) at the moderate and suitable sites with sandy soil (mean ± SE, n=12). Mean values of each parameter were analyzed by t-test. *** P<0.001.

Table 2. Concentrations of elements (N, P, K, Ca, Mg, and Na; µmol g^{-1} dry mass) in leaves and roots of teak seedlings grown at the moderate and suitable site with sandy soil (November 2015, mean ± SE, n=12). Mean values of each parameter were analyzed by t-test. * *P*<0.05, ** *P*<0.01, *** *P*<0.001, and n.s. not significant.

Element		Leaf	Root
N	moderate	1423±65	539±22
	suitable	1312±51	705±30
	Statistical test	n.s.	***
P	moderate	165±13	72± 6
	suitable	208±36	109± 7
	Statistical test	*	***
K	moderate	132±15	102± 6
	suitable	101± 8	272±12
	Statistical test	n.s.	***
Ca	moderate	101±20	81± 5
	suitable	249±23	112± 7
	Statistical test	***	**
Mg	moderate	208±15	42± 2
	suitable	157±09	78± 4
	Statistical test	**	***
Na	moderate	26.3±1.4	31.0±2.7
	suitable	25.2±0.9	32.6±1.6
	Statistical test	n.s.	n.s.

In teak, Ca is an important nutrient for growth (Zech and Drechsel 1991; Tanaka et al. 1998; Zhou et al. 2012). When teak seedlings were raised in culture medium excluding Ca, growth was suppressed drastically (Barroso et al. 2005). Comparing with other studies, the nutrient deficiency levels for teak was <138 µmol g^{-1} for Ca and <32 µmol g^{-1} for P (Zech and Drechsel 1991). Based on these data, the concentration of Ca in the leaves of teak at the moderate site (101 µmol g^{-1}) was lower than the deficiency level, and seedlings at this site suffered from Ca deficiency. In contrast, the concentration of P in the leaves at the moderate site (165 µmol g^{-1}) was much higher than the deficiency level. Thus, restriction in the uptake of P was probably not responsible growth suppression of teak compared with Ca. We also calculated the ratio of the moderate site per suitable site for the concentration of each nutrient in soil. The ratio was lowest for Ca, and concentration of Ca in soil at the moderate site was only 16% compared with the suitable site (Table 1). Thus, the main factor affecting teak growth at the moderate site was Ca deficiency.

Moreover, teak seedlings grown at the moderate site suffered from a decrease in photosynthetic rate at many times points (Fig. 4). One of the causes of this decrease in photosynthetic rate was decreased gs (Fig. 4), and low gs decreased the absorption of CO_2 because of stomatal closure. This trend was clear in February and May 2015 (Fig. 4) when the soil water content was low (Fig. 1). Meanwhile, the difference in water content in soil between the moderate and suitable sites was not clear except for in June and October 2014 (Fig. 1). Thus, the difference in gs between the moderate and suitable sites was caused by other factors.

Ca deficiency is not reported to be directly related to decreases in gs (Suárez 2010). However, a low Ca environment decreased N uptake, and lower N levels were associated with decreased photosynthetic rate (Suárez 2010). N_{area} was significantly lower at the moderate site in October 2014, December 2014, and October 2015 (Fig. 6). In these months, photosynthetic rate at the moderate site was probably decreased by the low N_{area}. However, P_{sat} at the moderate site was significantly lower in May, July, and November 2015 when the N_{area} did not differ significantly between the moderate and suitable sites (Fig 4, 6). Thus, there were other causes of the decreases in photosynthetic rate and gs.

In teak leaves at the moderate site, the concentration of Mg was significantly higher than at the suitable site (Table 2). This concentration was quite high and similar to level in woody species grown on high Mg environments such as serpentine (Alexander et al. 2007). Barroso et al. (2005) also confirmed that teak seedlings were raised in culture medium excluding Ca, Mg accumulated in the leaves. In general, when we examine the effects of Mg, we calculated the Ca:Mg ratio in plant organ because Mg toxicity can occur when there is an imbalance between Ca and Mg (Alexander et al. 2007). When this ratio decreases below 0.5, plants can suffer from Mg toxicity (Mizuno 1979; Kayama and Koike 2015). The Ca:Mg ratio for leaves of teak at the moderate site was 0.49, and this level was considered to indicate the plants were suffering from Mg toxicity. In plant species not adapted for Mg tolerance, the accumulation of Mg can readily decrease photosynthetic rate and gs (Palm et al. 2012; Kayama and Koike 2015). Thus, the main cause of the decreased photosynthetic rate and gs in teak seedlings at the moderate site was probably the accumulation of Mg in leaves. Barroso et al. (2005) also indicated negative effects on teak growth from the accumulation of Mg.

Furthermore, teak seedlings grown at the moderate site suffered from drought stress. Leaf water potential was lowest in February 2015, and this value did not increase in the predawn period (Fig. 5). These results were considered to indicate that teak seedlings grown at the moderate site could not recover water during the night time, and as a result they suffered from serious drought stress in February 2015. In addition, the accumulation of Mg is associated with decreased leaf water potential (Rao et al. 1987). Teak seedlings grown at the moderate site may readily suffer from drought stress from the accumulation of Mg.

Finally, we concluded that differences in soil chemical properties affected teak growth. The main factor affecting growth of teak was Ca, with a low concentration of Ca in soil being associated with the suppressed growth of teak. In addition, we confirmed that when teak suffered from Ca deficiency, Mg accumulated in the leaves and various physiological traits were suppressed. To accelerate teak growth at the moderate site, the addition of Ca was essential.

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Growth Performance of 6-year-old Teak Plantation under Different Soil Improvement Methods in Khon Kaen Province, Thailand

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Abstract

In general, the soils in Northeast Thailand are moderately to very strongly acidic with low organic content and low fertility. Improvements in soil quality are needed to promote better teak growth in the northeast of Thailand. This study aimed to investigate the growth performance of a 6-year-old teak plantation under various soil improvement methods at the Northeastern Forest Seed Center, Ban Had District, Khon Kaen Province, Thailand. Five different soil improvement treatments were applied as follows: control (no treatment); 2) dolomite application (400 kg/rai; 6.25 rai equals 1 ha); 3) dolomite (400 kg/rai) and organic fertilizer (1 kg/tree); 4) dolomite (400 kg/rai) and chemical fertilizer (15:15:15, 200 g/tree); and 5) mixed fertilizer (dolomite + organic fertilizer + chemical fertilizer at (15:15:15, 200 g/tree). The trees were planted 2 m × 4 m apart. The height and diameter at breast height (DBH) of the trees were recorded. The results showed that there were statistically significant differences in height but not in DBH among the different treatment groups at 6 years after planting. The plots with both dolomite and chemical fertilizer had the greatest height and DBH with averages of 12.3 m and 11.94 cm, respectively.

Keywords: Teak, Soil improvement, Tree growth, Soil properties

Introduction

Teak (*Tectona grandis* Linn.f.) is an important economic tree species in Thailand. Its wood is used for general-purpose timber and its properties make it suitable for a wide range of uses. Teak was, for many decades, the most important exported timber species in Thailand until logging was banned in 1989. There is still high demand from both local and international markets for teak timber. However, owing to the ban and the decrease in natural stands, there is not sufficient teak to meet demand. Thus, there is a great need for improving the growth of teak in plantations in Thailand.

Teak's natural distribution range in Thailand covers mainly areas of the northern and eastern part of the country. Although teak can grow over a wide range of edaphic conditions, the quality and distribution of natural teak is related to the nature of the underlying rock, which is reflected in the soil characteristics. The physical and chemical properties of soil such as texture, depth, porosity, drainage, pH and calcium content determine the growth quality of teak. Teak requires deep, moist, fertile and well-drained sandy loam soils (Kadambi 1951; Kaikini 1956). Teak usually occurs on soils within a pH range of 6.5 to 7.5, rarely grows in soils below 6.0, and suffers poor growth in soils with pH higher than 8.5. However, some studies have shown that teak grows well even in acidic soils (Puri 1951; Pande and Sharma 1986; Banerjee et al. 1986). Teak particularly dislikes laterite soils and is invariably stunted when found on such sites. On limestone, teak flourishes where the rock has disintegrated to form a deep loam layer. Teak requires good subsoil drainage and dislikes stiff clayey soils because its root system is very sensitive to oxygen deficiency (Beumea and Beckman 1956; Kotwal 1959; Yadav and Sharma 1967). Several soil characteristics, including soil moisture, cation exchange capacity, base saturation, phosphorus and calcium content, have been found to affect teak growth (Jungsuksuntigool and Wichiennopparat 1994).

Owing to continuous high demand and short supply from natural stands, teak plantations are an important source for providing a constant supply of teak. However, regions that have both favorable sites and good soil conditions for teak growth are limited. JIRCAS and the Royal Forest Department have established a collaborative project "Development of Techniques for Nurturing Beneficial Indigenous Tree Species and Integrated Management of Agriculture and Forestry in Northeast Thailand, Tropical Monsoon Regions" to carry out studies to develop appropriate techniques for promoting economic tree species in the country.

Under the same collaborative project, a study was carried out to produce a map showing soil suitability for teak growth in several provinces in the northeast of Thailand. The results revealed that approximately half of the total area in several provinces (including Chaiyaphum, Khon Kaen, Buri Ram and Ubon Ratchathani) were identified as being potentially suitable for growing teak. (RFD-JIRCAS Joint Research Project 2015a; RFD-JIRCAS Joint Research Project 2015b).

This study is a part of two subprojects aimed at identifying appropriate soil improvement techniques to promote better teak growth in the northeast of Thailand, where soils are generally acidic and sandy and have low amounts of nutrients required for teak growth, particularly phosphorus and calcium (Keerati–Kasikorn 1984). The know-how regarding soil improvement techniques gained from this study will be further extended to the farmers in these regions.

To improve soil conditions for teak growth in the northeast of Thailand, dolomite, $CaMg(CO_3)_2$, was applied to adjust soil pH and increase calcium content. Organic fertilizer was applied to improve soil physical characteristics and moisture content. Chemical fertilizer was applied to provide additional, major nutrients for teak.

Materials and Methods

The study site was located at the Northeastern Forest Tree Seed Center, Ban Nonesomboon, Nonesomboon Sub-District, Ban Had District, Khon Kaen Province, northeastern Thailand (Fig. 1).

Fig. 1. Location of the study site

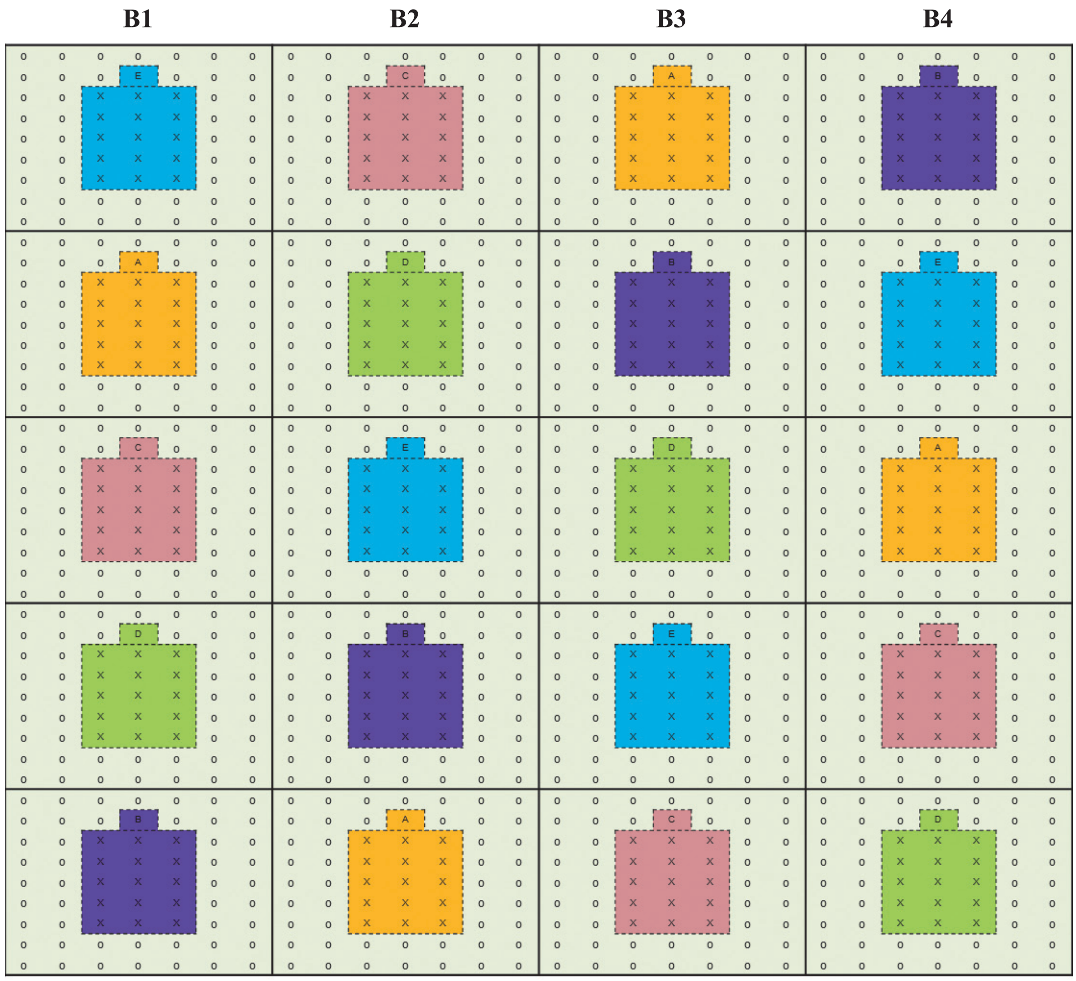
Table 1. Soil characteristics in the study area (Wichiennopparat et al. 2012)

Horizon	Depth (cm)	Organic matter (%)	pH	Avail. P (ppm)
A	0 - 21/35	0.72 - 0.94	4.9 - 5.5	2-5
B1	21/35 - 55/100	0.07 - 0.12	4.9 - 5.8	nil - 3
B2	55/100 - 120+	0.04 - 0.28	4.9 - 5.1	nil - 3

Horizon	Exchangeable Cations (ppm)				Texture
	K	Ca	Mg	Na	
A	51 -59	212 - 364	47 - 50	5 - 9	Sandy
B1	8 - 20	50 - 98	10 - 40	2 - 7	Sandy
B2	12 - 94	34 - 600	15 - 307	7 - 9	Sandy/ Sandy clay loam

Three soil pits were dug at the study area prior to site preparation to investigate the underlying soil conditions. The results regarding some of the chemical and physical properties of the soil in the study area were published in a previous work and are reproduced here in in Table 1 (Wichiennopparat et al. 2012). The experimental area was ploughed using a farm tractor. Teak seedlings were prepared using a tissue culture technique. Clone number 38 was used, which is adapted for the habitat of Ban Dong Sa-ngat, Mae Saleang District, Mae Hong Son Province.

The experimental design was a randomized complete block design with three replicates of 12 trees each. Five soil improvement treatments were tested: A) control (no treatment); B) dolomite (400 kg/rai); C) dolomite (400 kg/rai) and organic fertilizer (1 kg/tree); D) dolomite (400 kg/rai) and chemical fertilizer (15:15:15, 200 g/tree); and E) mixed fertilizer (dolomite + organic fertilizer + chemical fertilizer (15:15:15, 200 g/tree). The treatments were randomly assigned to each subplot. A buffer of non-treated trees surrounded each 18 m × 28 m subplot (Fig. 2). Dolomite was applied to the assigned plots and mixed prior to staking. Organic fertilizer and mixed fertilizer were applied with the planting soil and placed at the bottom of the planting pit (about 30 cm × 30 cm × 30 cm). The seedlings were planted 2 m × 4 m apart in August 2009. Chemical fertilizer was applied evenly around the assigned seedlings 1 month after



Remark: A = Control

B = Dolomite (400 kg/rai)

C = Dolomite (400 kg/rai) + Organic fertilizer (1 kg/tree)

D = Dolomite (400 kg/rai) + Chemical fertilizer (15:15:15, 200 g/tree)

E = Mixed Fertilizer (Dolomite+Organic fertilizer +Chemical fertilizer (200 g/tree)

Fig. 2. Lay out of experimental plots

planting. Total height and DBH of all trees were recorded at 2, 3, 4, 5 and 6 years after planting.

Results

The growth performance of teak in the study area at 2, 3, 4, 5 and 6 years is shown in Table 2. Clearly, the growth of teak in the plots with dolomite and chemical fertilizer, those with dolomite and organic fertilizer and those with mixed fertilizer performed better than in the plots with dolomite alone or controls. A statistically significant difference was found in height but not in DBH of teak at 6 years after planting (P<0.05). The plots with dolomite and chemical fertilizer demonstrated the greatest average height and DBH at 12.3 m and 11.94 cm, respectively. The height and DBH of teak clone no. 38 under the different treatments over time are shown in Figures 3 and 4.

Table 2. Height and diameter at breast height (DBH) of teak clone no. 38 under different soil treatments over time. Different letters indicate significant differences among the five treatments as calculated by Fisher's PLSD test (*P*<0.05).

Treatment	Height (m)					DBH (cm)				
	2 Years	3 Years	4 Years	5 Years	6 Years	2 Years	3 Years	4 Years	5 Years	6 Years
A	4.1	4.8	7.2	8.3^{b}	9.6^{bc}	3.78	5.55	6.72	8.42	9.71
B	3.9	4.3	7.2	8.3^{b}	9.4^{c}	3.54	5.21	6.74	8.52	9.84
C	4.7	6.0	8.3	9.7^{ab}	11.1^{ab}	4.63	6.64	7.70	9.58	10.91
D	4.8	6.2	9.0	11.0^{a}	12.3^{a}	4.85	7.06	8.54	10.71	11.94
E	5.0	5.9	8.3	9.7^{b}	10.5^{bc}	4.91	7.19	8.09	9.76	10.75

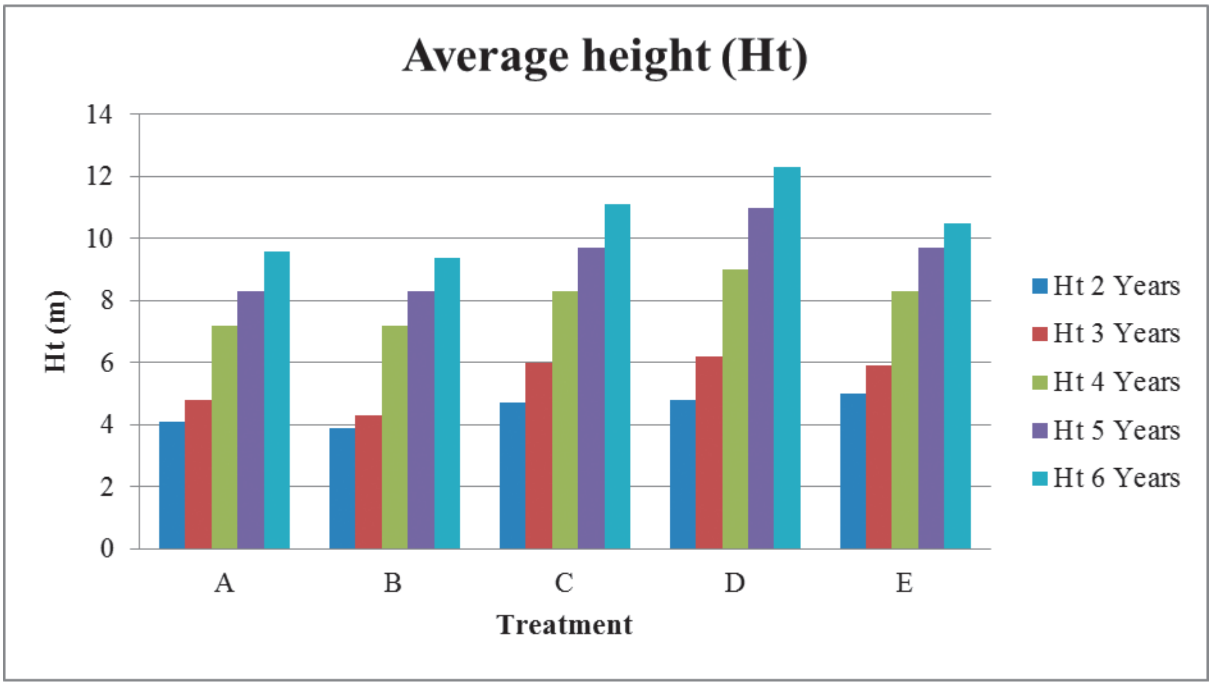


Fig. 3. Height of teak clone no. 38 under different soil treatments over time

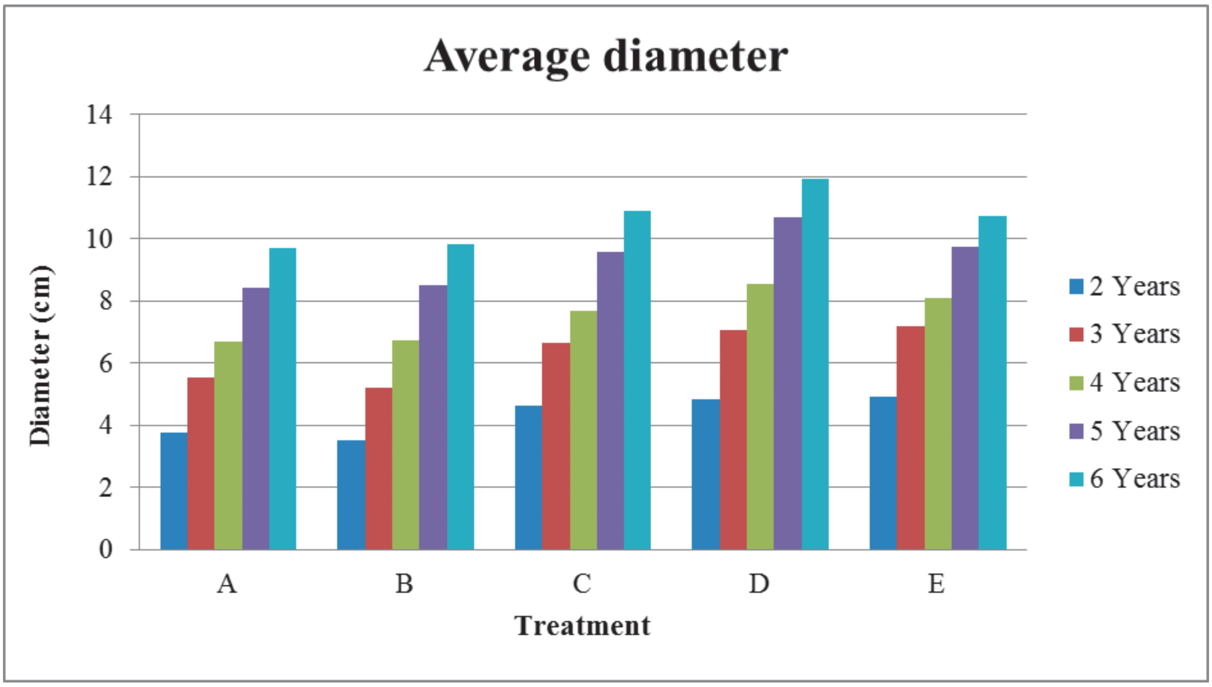


Fig. 4. Diameter at base height of teak clone no. 38 under different soil treatments over time

Discussion and Conclusion

Based on this study, we suggest that application of dolomite is essential for adjusting soil pH and for increasing calcium content in soils for successful teak production in the study area. However, adding dolomite alone, as in treatment B, was not sufficient to improve teak growth. Treatment D, which also included chemical fertilizer, showed the best overall growth. Furthermore, application of organic fertilizer was demonstrated to be helpful for improving growth conditions for teak. The results of this study indicated that various soil treatments could be used to improve teak growth in Northeast Thailand, where soils are acidic, sandy and have low fertility.

In the future, we need to conduct further experiments on teak plantation of different clones. We should also conduct additional experiments in plots with different soil types and in different locations to obtain more information. The spacing for the current study was 2 m × 4 m. There is a possibility that high planting density may inhibit or slow teak growth. To increase growth, it is necessary to thin plantations.

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Effect of perlite for soil improvement and on growth characteristics of teak seedling planted in sandy soil in Northeast Thailand

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Abstract

When teak (*Tectona grandis* L. f.) is planted in sandy soil in Northeast Thailand, its growth is suppressed by low pH, poor fertility, and low water holding capacity. To examine materials capable of increasing water holding capacity and nutrients in the soil in order to improve teak growth, we conducted an experiment with teak seedlings. We used perlite and added at a rate of 4% to sandy soil from northeast Thailand. Teak seedlings were potted in these soils and raised from July 2013 to July 2014. We compared growth, photosynthetic rate, leaf water potential, and concentrations of elements in plant organs between the perlite and no addition (control) treatments.

Water content in the soils was increased with the perlite treatment from December 2013; however, this effect decreased after March 2014. Comparing the growth traits of the teak seedlings, perlite treatment produced larger growth and promoted the uptake of phosphorus, calcium, and magnesium. These trends originated from the presence of these nutrients in perlite. We concluded that perlite had a role as a fertilizer, and was a useful material to improve teak growth in sandy soil.

Keywords: Acrisols, Photosynthesis, Nutrients, Soil improvement

Introduction

Teak (*Tectona grandis* L. f) is one of the most valuable timber species in Thailand (Tewari 1992). Since 1994, a tree plantation promotion project has been conducted and teak had been planted in throughout Thailand (Furuya et al. 2012). However, teak planted in Northeast Thailand showed suppressed growth (Tangmitcharoen et al. 2012). Farmers living in this district are interested in the farming of teak (Himmapan et al. 2010). Thus, we sought to develop methods to accelerate the growth of teak in Northeast Thailand.

The representative soil in Northeast Thailand is described as a "light textured sandy soil" (abbreviated to sandy soil) that is categorized in the acrisols (ultisols in USDA soil taxonomy) (Kyuma 2003; Suzuki et al. 2007). This sandy soil is characterized by a low content of clay, low pH, poor fertility, and low water holding capacity (Suzuki et al. 2007). The growth of teak is restricted by nutrient limitation, and deficiency of nutrients, especially nitrogen (N), calcium (Ca), and phosphorus (P), affects its growth drastically (Tanaka et al. 1998, Barroso et al. 2005; Zhou et al. 2012). Moreover, the growth of teak showed a negative correlation with the content of sand, and a teak plantation in soil with a high content of sand showed poor growth (Tanaka et al. 1998; Salifu 2001).

To improve this sandy soil, the correction of acidity, fertilization, and improvement water holding capacity is essential for the acceleration of teak growth. Kayama et al. (2016) reported that charcoal and bentonite had an ability to increase the soil water content. In addition, charcoal contained nutrients, such as N, Ca, and magnesium (Mg), and the root growth of teak was accelerated with this treatment (Kayama et al. 2016). However, charcoal treatment did not show obvious growth acceleration for other organs. By contrast, bentonite did not contain nutrients, and the growth of teak was not enhanced. Thus, growth acceleration of teak needs not only improvement of low water holding capacity but also increases in nutrient concentrations. As another potentially useful material to improve sandy soil, perlite has also been shown to increase water holding capacity (Özenç 2003; Samadi 2011). Moreover, perlite is produced in Thailand, and large amount of various nutrients are contained within it (Saisuttichai and Manning 2007). We hypothesized that the use of perlite could improve the low water holding capacity and poor fertility of sandy soil. However, research has not yet been carried out to examine the effects of perlite on the growth of teak.

The aim of our research was to examine the ability of perlite to improve water holding capacity and increase teak growth. We conducted a pot experiment with teak seedlings in sandy soil with the addition of perlite. To verify the effects of perlite, we examined ecophysiological traits of the teak seedlings. These parameters were compared with seedlings potted in sandy soil without perlite.

Materials and methods

Study site

Our experiment was conducted at the Northeast Forest Seed Center located in Khon Kaen Province in northeastern Thailand (16°16′ N, 102°47′ E, 191 m a.s.l.). This centre conducts measurements of meteorological data: mean annual precipitation was 1,104 mm, and annual mean, maximum, and minimum temperatures were 28.3°C, 40°C, and 13°C, respectively (from 2008 to 2012, Northeast Forest Seed Center, unpublished data). Precipitation is concentrated from May to October (Northeast Forest Seed Centre, unpublished data). During the experimental period, monthly precipitation and average maximum and minimum temperatures were as report by Kayama et al. (2016).

In Khon Kaen Province, we previously published a soil suitability map of teak plantation for farmers (Wichiennopparat et al. 2015). Sandy soil in Khon Kaen Province is distributed over a large area (13.5%). These areas are categorized as moderately suitable for teak planting.

Preparation of materials, soil, and teak seedlings

For the ratio of perlite, a previous study showed that 8% was effective in increasing water holding capacity (Özenç 2003). However, when we analysed the nutrients in perlite, a large amount of nutrients, especially Ca, was detected. There was a possibility that excess use of perlite may result in fertilizer spoilage of teak. Thus, we decided to decrease the use of ratio of perlite to 4%. In July 2013, we prepared 7 kg of perlite from a market in Lopburi province, Thailand. We also collected 300 kg of sandy soil from the Northeast Forest Seed Center. Our experiment was conducted without fertilization because we had to examine the effects of nutrients in perlite.

The teak seedlings were prepared by a tissue culture technique. The teak clone was from Mae Hong Son Province (clone number 21), and this clone has been planted in various places (Royal Forest Department, unpublished data). Teak seedlings were raised from March to June 2013 at the Teak Improvement Center, Lampang, Thailand. In July 2013, 74 teak seedlings were transported to the Northeast Forest Seed Centre, Khon Kaen. In addition, we prepared eight tables for raising the teak seedlings.

Establishment of the pot experiment

We established the perlite treatment by adding it at a rate of 4% into the sandy soil. We mixed the components, and the total weight of the mixed soil was 153 kg per treatment. These mixed soils were put into 17 pots (depth: 22.5 cm, diameter: 27 cm, volume: 8.5 L), and the soil weight per pot was 9 kg. We also prepared 17 pots filled with 9 kg of sandy soil alone as the control treatment. Before transplantation, 50 g of soil samples were collected from 4 pots for each treatment.

We potted 32 teak seedlings into 32 pots in July 2013. We also set a soil sensor (ML2, Delta-T Devices Ltd., Cambridge, UK) into one pot per treatment. The water content of the soil was measured continuously. Each pot was put onto the tables, and these tables were established in the field in sunny conditions. The two pots containing the soil sensors were also put onto the tables. The logger connected to the soil sensor was fixed to a pole made of concrete.

After being set up, all pots (including pots with soil sensors) were irrigated with 1 L of water in the morning of every day. On rainy days, irrigation was not conducted. Irrigation was carried out until the end of the experiment (July 2014).

Soil analysis

We measured soil texture and chemical properties including pH and concentrations of carbon (C), N, exchangeable P, and base cations. Four soils samples for each treatment from before transplantation were used. To determine the pH of the soil, 25 ml of distilled water was added to 10 g fresh soil to make a homogenized mixture (van Reeuwijk 2002). This mixture was then shaken for 1 h and the pH was measured using a pH meter (SG2, Mettler Toledo, Zürich, Switzerland). Prior to chemical analysis, we conducted air-drying of the soil samples.

The soil texture was determined by the hydrometer method (Klute 1986). The concentrations of C and N in dried soils were determined using a nitrogen and carbon analyzer (Flash 2000, Thermo Fisher Scientific, Waltham, MA). Exchangeable P was separated using dilute acid fluoride (Sparks et al. 1996) by shaking for 1 minute. P in the extracted solution was determined by the molybdenum blue method (American Public Health Association et al. 1998) using a spectrophotometer (U-1800, Shimadzu, Kyoto, Japan). Exchangeable base cations (Ca, Mg, potassium [K], and sodium [Na]) were quantified by mixing 4 g of dry soil with 100 ml of 1 M ammonium acetate solution, and shaking for 1 h (Sparks et al. 1996). Base cations in the extracted solutions were analyzed using an atomic absorption spectrophotometer (AAnalyst 300, Perkin-Elmer, Norwalk, CT).

Measurement of teak seedlings

For the measurement of teak seedlings, eight seedlings for each treatment were used for growth measurements. We measured tree height and basal diameter at six time points (July 2013, October 2013, December 2013, February 2014, April 2014, and July 2014). We also measured length and width for all leaves of the teak seedlings. The leaf area of teak seedling was calculated using the equation of Tondjo et al. (2015), as follows:

$A = 0.60 \times L \times \mathrm{Wi}$

where A is the leaf area, L is the leaf length, and Wi is the leaf width.

Measurement of photosynthetic rate and nitrogen

We measured the area-based photosynthetic rate at light saturation (P_{sat}) and stomatal conductance (gs) for teak leaves located second from the top. From our observations, leaves of teak seedlings had been foliating in response to continuous irrigation, and the average of longevity of teak leaves was 99 days (Kayama et al. 2016). We observed foliation of teak seedlings in every week. Based on these observations, we selected teak leaves for measurement of photosynthetic rate that passed one month after foliation.

For the measurement of photosynthetic rate and leaf water potential, eight teak seedlings not used for the measurement of growth parameters were used per treatment. There was no irrigation to eliminate the effects of water in the pot on the day when the measurements were conducted.

When we measured photosynthetic rates, the leaves of some seedlings were immature or senescent. To provide uniformly mature teak leaves, we selected four teak leaves from among eight seedlings. We measured P_{sat} five times (October 2013, December 2013, February 2014, April 2014, and July 2014), and the measurements were always performed between 09:00 and 11:00.

Measurements were made using a portable gas analyzer (LI-6400, LiCor, Lincoln, NE, USA) in steady-state conditions, at an ambient temperature of 27°C and ambient CO_2 concentration of 38.0 Pa. The LED light source was adjusted to a saturation light level of 1,800 μmol $m^{-2}s^{-1}$ PPF.

Measurement of leaf water potential and concentration of nitrogen

After measurement of photosynthetic rate, we measured the leaf water potential of teak leaves at five times (October 2013, December 2013, February 2014, April 2014, and July 2014). The leaf used to measure water potential was the same as that used to measure photosynthetic rate. In general, leaf water potential showed the lowest value in the afternoon by transpiration, and showed the highest value by recovery of water during the night (Larcher 2003). We measured leaf water potential in the afternoon and predawn. Four teak leaves for each treatment were sampled at 13:00–14:00 and 5:30–6:00 the next day. Sampled shoots were put in a plastic bag that contained a wet filter paper, and kept in a refrigerator. We measured leaf water potential using a pressure chamber (Model 600, PMS Instrument Co., Albany, OR, USA).

After measuring leaf water potential, we analyzed the concentration of nitrogen. Photosynthetic rate is closely related to concentrations of nitrogen (Evans 1989; Larcher 2003; Kayama et al. 2007). Leaf samples were oven-dried at 70°C for 3 days, and LMA (g m^{-2}) measured by the method of Larcher (2003). Leaf samples were ground to a fine powder using a sample mill (WB-1; Osaka Chemical Co., Osaka, Japan). The concentration of N was determined using an NC analyzer (Sumigraph NC-220F, Sumika Chemical Analysis Service, Tokyo, Japan). The results of the concentration of N were calculated from the area based on N (N_{area}) from the data of LMA.

Analysis of biomass and element concentrations of teak seedlings

To determine the biomass of teak seedlings, we measured the dry mass of leaves, stems and branches, and roots. In July 2014, eight teak seedlings from each treatment used for growth measurements were sampled. Roots of seedlings were washed twice with water to remove soil. The washed seedlings were divided into leaves, stems and branches, and roots. Each component was put into its own envelope and oven-dried at 70°C for 3 days. After drying, the dry mass of each component was determined. We also examined the root/shoot ratio as an indicator of teak growth (Gopikumar and Varghese 2004; Rao et al. 2008, Zhou et al. 2012).

Of the elements in the plant organs, we measured the mass base of concentrations of N, P, K, Ca, and Mg in leaves and roots. Dried samples were ground to a fine powder, and N concentration was determined using an NC analyzer. The remaining samples were digested by the HNO_3-HCl-H_2O_2 method (Goto 1990). Concentrations of K, Ca, and Mg, were analyzed using an ICP analyzer (ICPE-9000, Shimadzu, Kyoto, Japan), and the concentration of P was determined by the molybdenum blue method using a spectrophotometer (UV-2500PC, Shimadzu, Kyoto, Japan).

Statistical analysis

Significant pairwise differences for each variable were tested by t-test using Stat View 5.0 (SAS Institute Inc.). Comparisons were made between the perlite and control treatments.

Results

Water contents in soil

To examine the minimum water content in soil for each season, we collected the lowest water contents before irrigation and rainfall. Averages of these values for each month are shown in Fig. 1. The water content was low for the perlite treatment until October 2013. From December 2013 to February 2014, water content increased for the perlite treatment compared with the control treatment. From March 2016, water content showed a similar trend between the two treatments.

Water contents of the perlite and control treatments were increased by rainfall in September 2013. The value of maximum water content in this month was 0.62 m^3 m^{-3} for perlite treatment, and 0.28 m^3 m^{-3} for control treatment.

Soil properties

For soil texture, the content of sand was over 90.0% for each treatment (Table 1). The contents of silt and clay were low for each treatment. Comparing with two treatments, there was no significant difference.

The pH value was significantly higher for the perlite treatment than that for the control treatment (P<0.01). The concentrations of P, Ca, Mg, and K for the perlite treatment were also significantly higher than those for the control treatment (P<0.01). There was no significant difference in the concentrations of C, N, and Na between the two treatments.

Growth characteristics

Tree height and diameter did not show significant differences between the two treatments (Fig. 2, P>0.05). The growth pattern of teak seedlings was similar between the two treatments (Fig. 3). Tree height and diameter showed remarkable increases, but these increases weakened from February 2014.

Total leaf area showed a seasonal increase from April 2014 (Fig. 4). Comparing the two treatments, leaf area in April 2014 was significantly larger for the perlite treatment than for the control treatments (P<0.01). The average of total number of leaves in July 2014 was 9.5 for perlite treatment, and 6.5 for control treatment. The total number of leaves showed significantly difference between two treatments (P<0.01).

Photosynthetic rate, leaf water potential, and concentration of nitrogen

The P_{sat} was not significantly different between the two treatments (Fig. 5, P>0.05). The P_{sat} in each treatment was highest in February 2014; however, P_{sat} decreased drastically from April 2014.

gs in the perlite treatment was significantly higher than in the control treatments in February 2014. The gs value decreased in December 2013 and July 2014.

Leaf water potential in the afternoon and predawn was highest in December 2013 (Fig. 6). In contrast, these values were decreased from February 2014. The predawn leaf water potential in July 2014 showed significantly difference between perlite and control treatments ($P<0.05$).

N_{area} showed the highest value in February 2014; however, N_{area} decreased from April 2014 (Fig. 7). Comparing with treatments, N_{area} did not show the significantly difference. The average of LMA for teak leaves showed 93 g m^{-2}. The value of LMA did not change during the experimental period, and there was no significantly difference between two treatments.

Biomass of teak seedling

In July 2014 the dry mass of roots was significantly higher for the perlite treatment than for the control treatment (Fig. 8, $P<0.01$). Total dry mass of teak seedlings was also significantly higher for the perlite treatment than for the control treatment ($P<0.05$). For the dry masses of leaves and stems and branches, there were no significant differences between the two treatments. The root:shoot ratio was 1.37±0.09 for the perlite treatment and 1.29±0.09 for the control treatment. There was no significant difference in the root:shoot ratio between the two treatments.

Concentration of elements in plant organs

The concentrations of P in the leaves and roots of teak seedlings were significantly higher for the perlite treatments than for the control treatment (Table 2, $P<0.05$). In the perlite treatment, the concentration of Mg in leaves and Ca in roots was also significantly higher compared with the control treatment ($P< 0.05$). By contrast, the concentration of K in roots was significantly higher for the control treatment than that for the perlite treatment ($P<0.05$). In terms of the concentration of N, there were no significant differences between the two treatments.

Discussion

Based on the results of the water content before irrigation, perlite treatment showed high values from December 2013 to February 2014 (Fig. 1). These materials probably have the ability to increase water holding capacity temporarily. In contrast, the water content of perlite treatment did not show high value until October 2013 (Fig. 1). The perlite used for our experiment was granule (2-4 mm), and easy to break. On the water holding substances, increase of water holding capacity was less for granule than that for powder (Yabashi and Konko 1989). There is a possibility that granule of perlite may be low capacity to increase soil water. We also confirmed that granule of perlite was broken from December 2013. Thus, water holding capacity of perlite may be increased after break of granule. Meanwhile, leaf water potential is little difference between perlite and control treatments (Fig. 6). Low value of water content is little effect for the trait of water availability of teak seedlings.

Moreover, gs was high in February 2014 (Fig. 5). This trend showed that stomata in the perlite treatment were harder to close with abundant water in the soil. However, water content was not high from March 2014 (Fig. 1). Thus, the ability of perlite to increase water holding capacity did not last for prolonged period. Compared with other experiments, the period of the experiment was 4 month in Özenç (2003) and 8 weeks in Samadi (2011). Perlite has a capacity to increase water holding capacity for a short period; however, this capacity was probably decreased from 8 months.

Comparing growth between the two treatments, growth of aboveground organs did not show obvious growth acceleration from the perlite treatment (Fig. 2, 8). In contrast, root growth with the perlite treatment was accelerated, as a result, total dry mass for the perlite treatment showed large growth compared with control treatment (Fig. 8). Thus, the use of perlite contributed to root development. A similar trend was confirmed with the use of charcoal (Kayama et al. 2016). Compared with total dry mass, use of perlite (ave. 73.5 g) was larger than that of charcoal (ave. 53.9 g), bentonite (ave. 46.8 g) and corncob (ave. 36.5 g; Kayama et al. 2016). Thus, use of perlite affect obvious growth acceleration of teak seedlings compared with other materials.

Moreover, the concentrations of P, Ca, and Mg were increased in all organs of teak with the perlite treatment (Table 2). These nutrients showed high concentrations in the soil with the perlite treatment (Table 1). Thus, the increased uptake of P, Ca, and Mg originated from these nutrients in perlite. In addition, the observed enhanced root development may be related to the uptake of these nutrients.

Comparing our results with previous reports, when the growth of teak seedlings was suppressed drastically, the value of the root:shoot ratio increased over 1.0 (Gopikumar and Varghese 2004; Rao et al. 2008, Zhou et al. 2012). In the present study, the root:shoot ratios were over 1.0 for both treatments. We considered that teak seedlings showed suppressed growth, and one of the causes of this was N deficiency. The concentration of N in leaves at the end of the experiment (average 683 µmol g^{-1}) indicated N deficiency (<857 µmol g^{-1}, Zech and Drechsel 1991). In contrast, the concentration of P in leaves at this time (average 401 μmol g^{-1}) was much higher and did not indicate any deficiency (<32 μmol g^{-1}, Zech and Drechsel 1991). Thus, sandy soil was considered as a rather infertile environment and especially for N. In addition, P_{sat} was also lower from April 2014 (Fig. 5). Photosynthetic rate shows a positive correlation with the concentration of N (Gopikumar and Varghese 2004; Evans 1989; Kayama et al. 2007), and these decreases were related to decreased N in leaves (Fig. 7). In terms of gs, a leaf suffering from N deficiency can readily suffer from a decrease in leaf water potential (Radin and Ackerson 1981). Thus, N deficiency negatively affects physiological parameters in teak seedlings. These trends were also confirmed by Kayama et al. (2016).

Despite the N deficiency, we confirmed that leaf area of teak seedlings were increased from April to July 2014 (Fig. 4). In particular, the perlite treatment showed obvious increases in leaf area in April 2014 (Fig. 4). In teak, various nutrients are important for leaf production (Barroso et al. 2005; Zhou et al. 2012). Our results showed that the concentration of P and Mg in leaves were significantly higher for perlite treatment that those for control treatment (Table 2). In the perlite treatment, the abundant supply of P and Mg may contribute to develop leaves in April 2014.

In addition, P_{sat} and gs in December 2013 were low (Fig. 5). The date of measurement of P_{sat} showed that the minimum temperature was 11°C in the morning (Kayama et al. 2016). There is a possibility that the leaves of the teak seedlings in December 2013 were suffering from low temperature in the morning, and as a result P_{sat} and gs could not recover in the morning.

Finally, we concluded previously that charcoal was a useful material to improve seedling growth of teak in sandy soils in northeast Thailand. Teak seedlings grown with perlite exhibited accelerated root growth. Perlite produced in Thailand contained P, Ca, and Mg, and we confirmed the effects of fertilizer of these nutrients. In particular, Ca was an essential nutrient for growth acceleration in teak (Barroso et al. 2005; Zhou et al. 2012), and perlite showed a role as a Ca fertilizer. However, this experiment also showed N deficiency in this treatment. Our experiment did not use fertilizer to examine nutrients in perlite. We confirmed that perlite did not contain N (Table 1). If we apply perlite in the raising of teak, we should also use another N-containing fertilizer.

Acknowledgments

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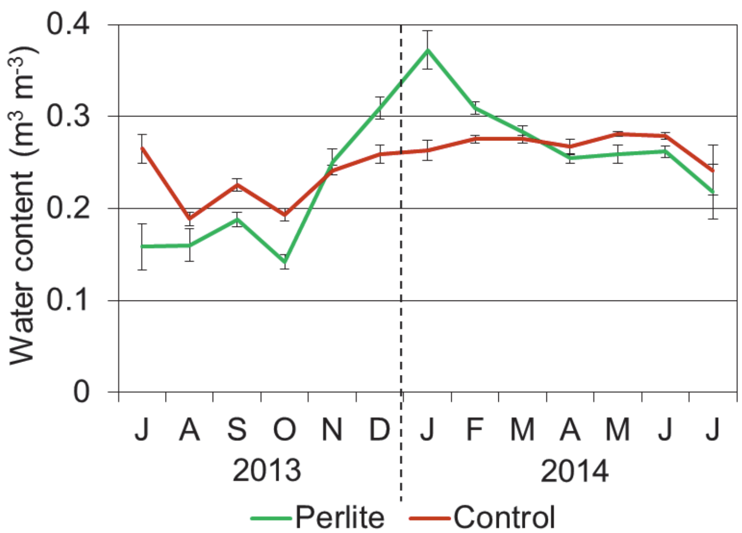

Fig. 1. Average soil water content in the two treatments before irrigation or rainfall (from July 2013 to July 2014, mean ± SE). Note. The values of water content were averaged among several dates with low values before irrigation.

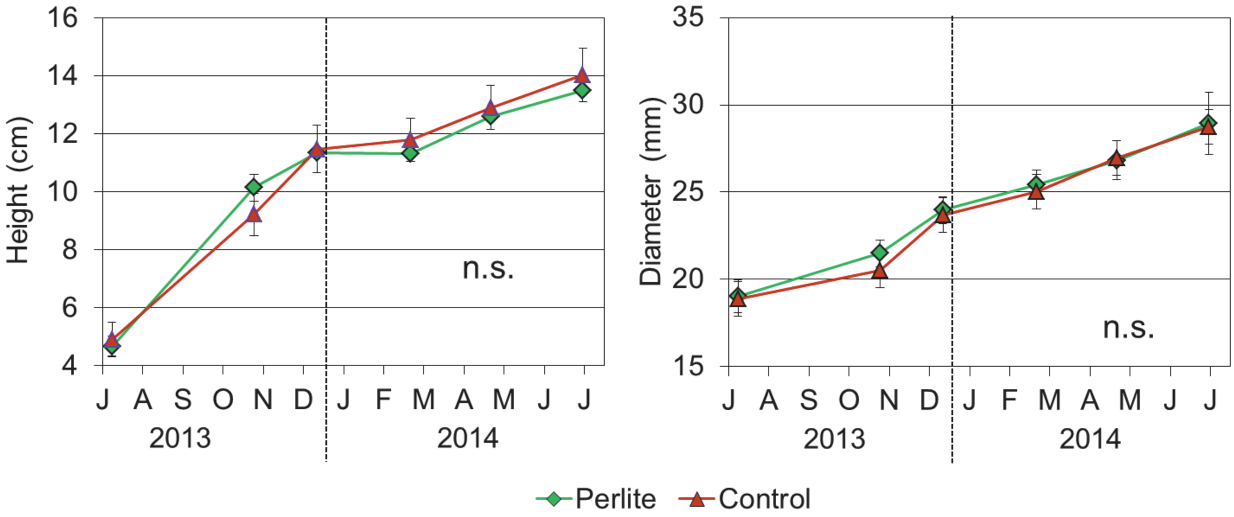

Fig. 2. Tree height and basal diameter of teak seedlings grown in the two treatments (mean ± SE, n=8). Mean values of each parameter were analyzed by t-test (not significant).

Note. Divisions on the horizontal axis over the letters are the first day of each month. The same format is used in subsequent figures.

Fig. 3. Pictures of teak seedlings grown in the perlite (left) and control (right) treatments (April 2014). Tree height and basal diameter did not show obvious difference between the two seedlings. However, total leaf area was larger for the seedling in the perlite treatment (1,369 cm^2) than in the control treatment (1,188 cm^2).

Note. Yellow bars the pictures showed the scale (10 cm).

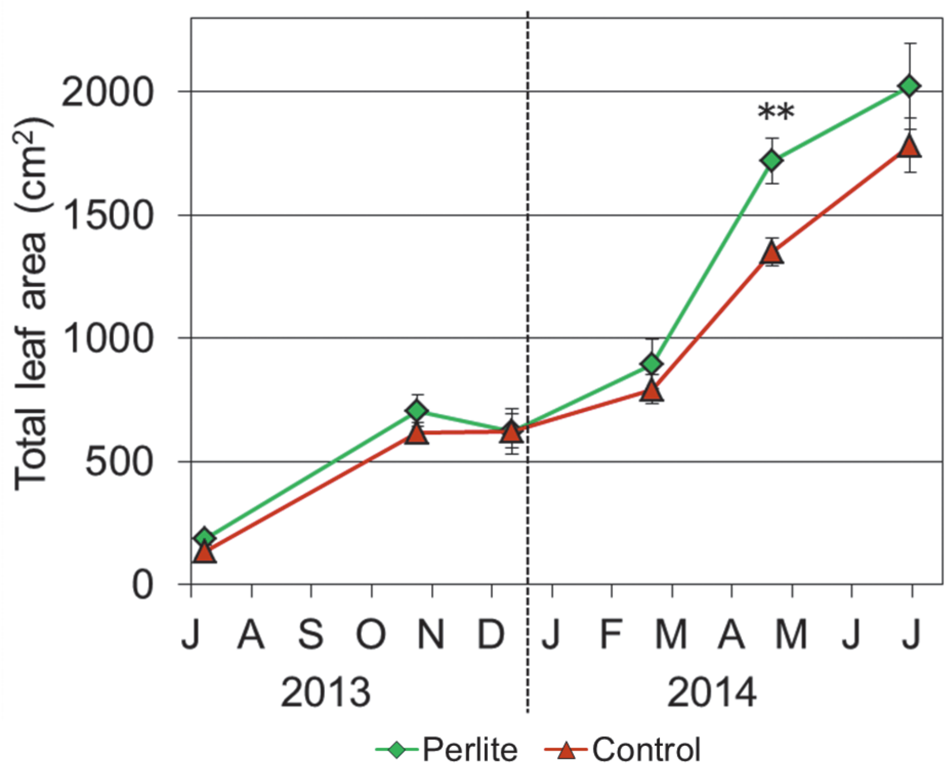

Fig. 4. Total leaf areas for teak seedlings grown in the two treatments (mean ± SE, n=8). Mean values of each parameter were analyzed by t-test. ** *P*<0.01.

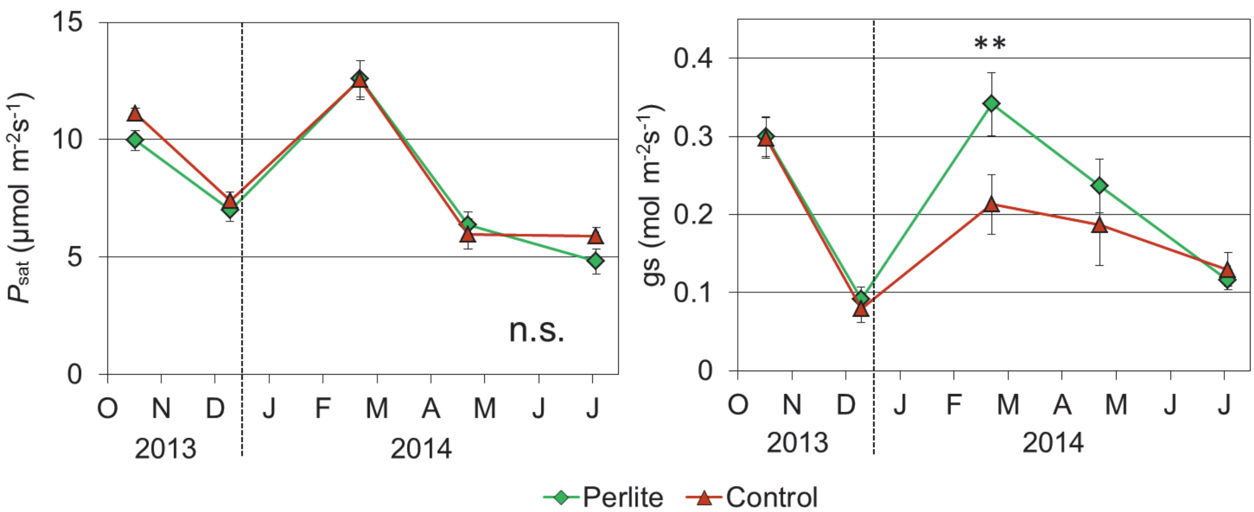

Fig. 5. Photosynthetic rate at light saturation (Psat) and stomatal conductance (gs) for teak seedlings grown in the two treatments (9:00–11:00, mean ± SE, n=4). Mean values of each parameter were analyzed by t-test (not significant).

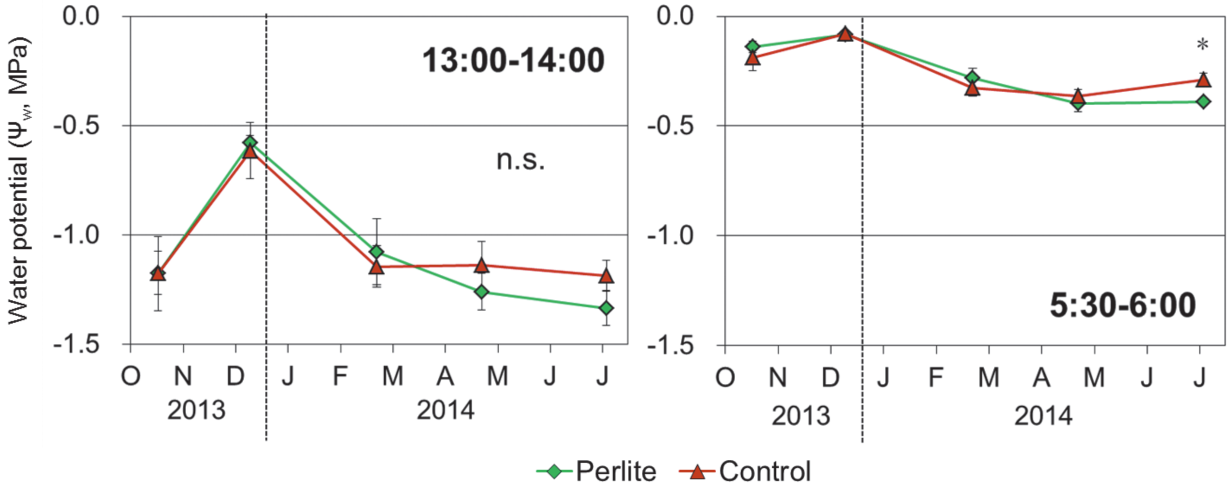

Fig. 6. Leaf water potential in the afternoon (13:00–14:00) and predawn (5:30–6:00) for teak seedlings grown in the two treatments (Mean ± SE, n=4). * P<0.05.

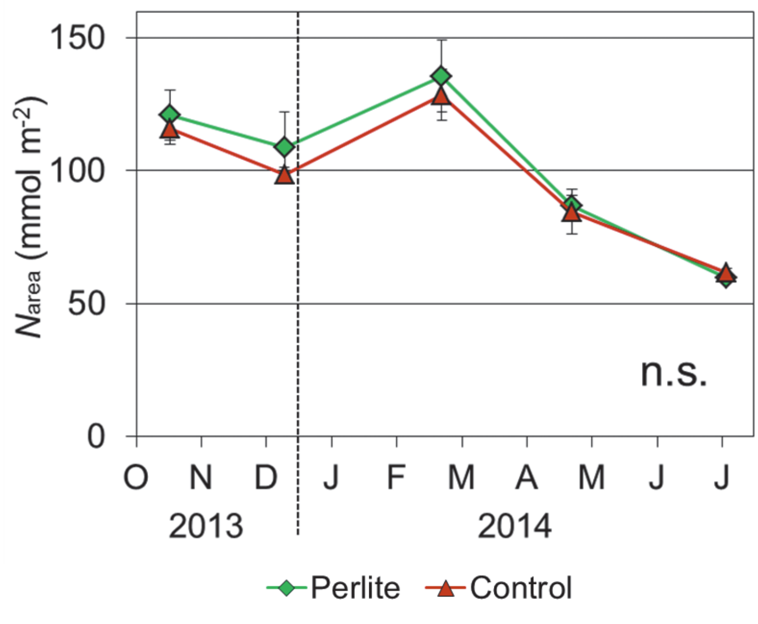

Fig. 7. Concentrations of area-based nitrogen (Narea) and for teak seedlings grown in the two treatments (Mean ± SE, n=4). Mean values of each parameter were analyzed by t-test (not significant).

Table 1. Texture and chemical properties of soils in the two treatments (mean ± SE, n=4). Mean values of each parameter were analyzed by t-test. ** *P*<0.01, *** *P*<0.001, and n.s. not significant

Treatment	Texture (%)			pH
	Sand	Silt	Clay	
Perlite	92.0±0.0	4.0±0.0	4.0±0.0	5.89±0.11
Control	92.0±0.0	4.0±0.0	4.0±0.0	5.31±0.04
Statistical test	n.s.	n.s.	n.s.	**
	C (mol kg^{-1})	N (mmol kg^{-1})	P (mmol kg^{-1})	Ca (mmol kg^{-1})
Perlite	0.62±0.24	12.5±1.8	2.21±0.22	32.6±1.4
Control	0.73±0.26	8.9±3.0	0.29±0.10	2.7±0.3
Statistical test	n.s.	n.s.	***	***
	Mg (mmol kg^{-1})	K (mmol kg^{-1})	Na (mmol kg^{-1})	
Perlite	5.16±0.33	2.79±0.88	0.012±0.012	
Control	1.46±0.16	1.14±0.06	0.083±0.064	
Statistical test	***	**	n.s.	

Table 2. Concentrations of elements (N, P, K, Ca, and Mg; μmol g^{-1} dry mass) in leaves and roots of teak seedlings grown in four treatments (mean ± SE, n=8). Mean values of each parameter were analyzed by t-test. * *P*<0.05, ** *P*<0.01, *** *P*<0.001, and n.s. not significant.

Element		Leaf	Root
N	Perlite	713±40	633±18
	Control	653±11	649±19
	Statistical test	n.s.	n.s.
P	Perlite	484±61	580±18
	Control	318±39	224±08
	Statistical test	*	***
K	Perlite	194±29	187±13
	Control	194±22	222±05
	Statistical test	n.s.	*
Ca	Perlite	226±22	427±60
	Control	196±10	290±18
	Statistical test	n.s.	*
Mg	Perlite	90±03	171±07
	Control	75±03	175±06
	Statistical test	**	n.s.

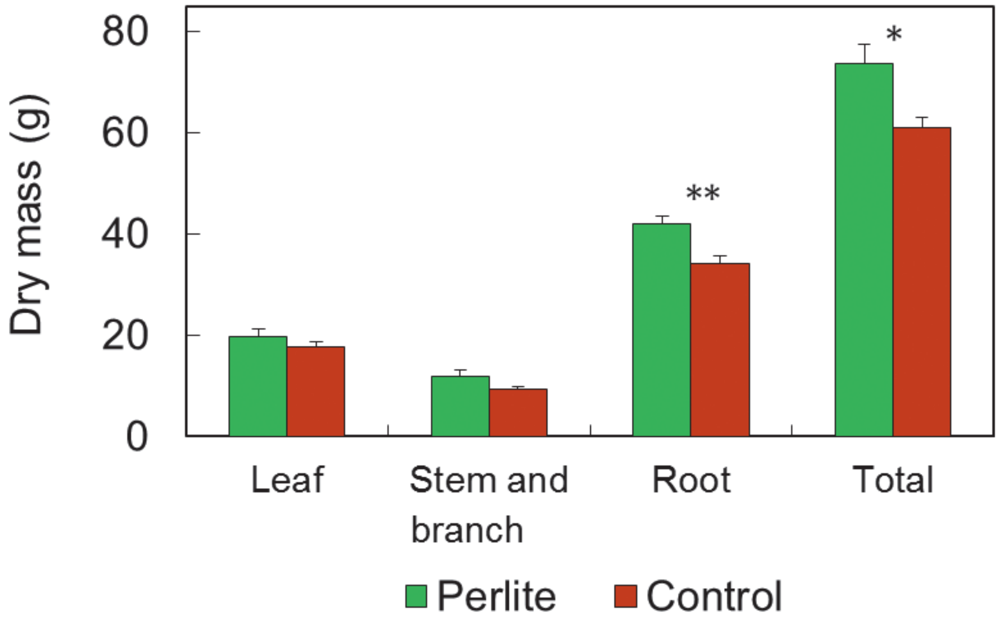

Fig. 8. Dry mass of each organ (leaf, stem and branch, and root) and total dry mass for teak seedlings at the end of the experiment (July 2014) grown in the two treatments (Mean ± SE, n=8). Mean values of each parameter were analyzed by t-test.

* P<0.05, ** P<0.01.

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Improved Yield Prediction Model for Teak Plantations in Northeastern Thailand

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Abstract

To predict the yield of teak plantations in Northeastern Thailand, the new site index function was developed for predicting dominant tree height in teak stands. The Gompertz function was applied as the site index curve to improve the existing yield model. From the model, we computed the stem volume, stand basal area, stand volume, and stand density of the test plots were using site index values derived using the new site index function. These stand aggregates were compared to the previous model. The results revealed that the statistical indicators used to evaluate the performance of the two models provided smaller values in the present model than in the previous model. This confirmed that the improved yield model had greater accuracy and precision than the previous model. The improved yield model could be applied to generate a new yield prediction table for teak plantations in Northeastern Thailand.

Keywords: Non-linear regression model, Dominant tree height, Site index, Stand volume, Stem volume, Stand density, Stand age

Introduction

The Royal Forest Department launched the Economic Forest Plantation Extension Project to promote forest plantation areas in 1994. The goal was to cover 800,000 hectares (5 million rai) and was designed to encourage rural households to plant trees on their land. Farmers were granted subsidies of 3,000 baht per rai, over 5 years to plant trees, and they were allowed to harvest trees after a certain period. The project emphasized the planting of indigenous forest tree species. Teak has been the most popular because its high durability, good dimension stability, and aesthetic quality make it a very valuable species for forest plantations. Additionally, the price of teak wood is relatively high due to increasing demand. Teak was planted all over under this project covering 88,000 hectares during 1994–1996, even in Northeastern Thailand where this species is not naturally distributed. To reach the target of providing highly valuable timber to the owners of teak plantations, understanding growth and yield was essential to develop long-term plans for sustainable forest management. Thus, it was of high priority to distribute information on growth and yield.

The site index is commonly used as a measure of site productivity or site quality that is relatively independent of stand density (Vanclay 1994; West 2004), and it had been used extensively in forestry (West 2004). The site index is the top height at a prescribed age and has commonly been used in models that correlate site and soil characteristics with growth and yield predictions (Mailly et al. 2004; West 2004). The point in the life cycle of a forest when limiting factors may present themselves can significantly alter the shape of the growth curve (Fisher and Binkley 2000). Additionally, sites with a higher growth rate at a given point in the plantation life cycle compared with other sites do not necessarily mean that the same relationship will be the same subsequently.

In July 1992, a yield prediction table was constructed as part of the RFD-JICA REX II Project in order to predict the yield of teak plantations in Northeastern Thailand, and then the table was revised in the RFD-JIRCAS Program during 2009–2010 after more data from this region were obtained. This type of yield table was identified as an empirical yield table that shows average growth and yield data of forest stands. Because of the limitation that empirical yield tables may not provide reliable data, especially for data on old stands, a variable density yield table was constructed in 2011 to obtain more reliable data on growth and yield.

The existing variable yield density model was considered to be improved as a result of additional data from various teak stands in northeastern regions collected from 2012 to 2016. The new site index equation was constructed in order to cover a wider range of dominant height-age relationships of teak stands in this region.

The objective of this study was to improve the efficiency of the variable yield density model by developing a new site index equation for use in this model. The improved yield model will provide more reliable results for predicting the growth and yield of teak plantations located in Northeastern Thailand.

Materials and methods

Site index equation

The data was measured in 279 sample plots that were established from 1972 to 1997. Most of the sample plots were private plantations owned by farmer and the rest were owned by The Royal Forest Department and Forest Industrial Organization. The plots were located in the 10 provinces of Nakhon Ratchasima, Khon Kaen, Sakon Nakhon, Loei, Si Sa Ket, Ubon Ratchathani, Yasothon, Chaiyaphum, Udon Thani, and Nong Bua Lam Phu. Most of the sample plots were temporary plots, but 77 plots were semi-permanent plots that were measured annually for 2–3 years in order to estimate stand growth. The last measurement was conducted during the year 2015–2016 and there was an average of two measurements per plot. At each measurement, tree diameter at 1.3 m aboveground (diameter at breast height [DBH]), total tree height, and number of survival trees in each sample plot were recorded. The total stem volume of individual trees was computed using the formula developed by Ishibashi *et al*. (2002):

$$V = 0.00100712\, DBH^{1.89445042} H^{0.7163796917} \quad (1)$$

Where: V = individual stem volume (m^3); DBH = diameter at 1.3 m aboveground (m); H = total height (m).

Stand growth parameters (number of trees, average height, average DBH, dominant tree height [DTH; defined as the 100 largest trees by DBH per hectare], volume per tree and volume per hectare) for each measurement plot were calculated.

A total of 357 dominant tree height-age measurements for teak stands were recorded and computed and were separated into two data sets based on a random selection procedure. The first dataset consisted of 322 observations for constructing the site index model (equation), and the second data sets consisted of 35 observations (around 10% of the first data sets) used for model validation. Both data sets covered approximately the same ranges of DTH and age of the sample plots (Fig. 1).

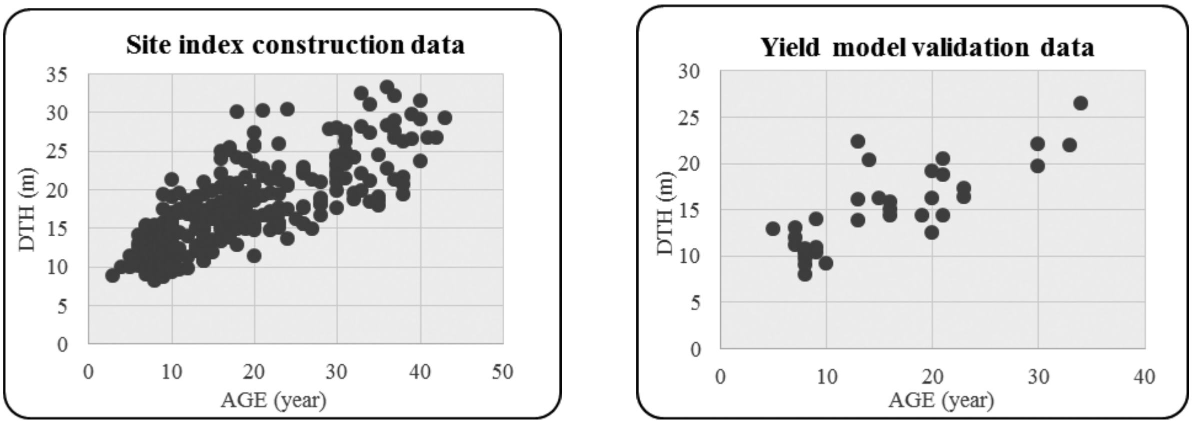

Fig. 1. Scatter plot of dominant tree height (DTH) against stand age for the two data sets used in the study.

A wide variety of non-linear regression models were employed to fit the site index model (for example, Philip (1994); Draper and Smith (1981); Phillips and Campbell (1968); Nelder (1961); Oliver (1964)). The non-linear estimation procedure in the statistical analysis was used to fit the models. Models where all parameters provided significant values (p<0.05) and provided higher coefficient of determination than the others were selected as candidate models. Multiple measurements of performance for the non-linear model were applied as various criteria in order to select the best model for constructing the site index equation. The various criteria were adjusted coefficient of determination ($\bar{R}^2$), root mean square error (RMSE), Akaike information criterion (AIC), mean residuals (MRES), absolute mean residual (AMRES), and mean square error (MSE). They were estimated as:

$$\bar{R}^2 = 1-(1-R^2)\frac{[n-1]}{[n-p-1]} \quad (2)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(Hi-\hat{Hi})^2}{(n-1)}} \quad (3)$$

$$AIC = n.\ln(RMSE)+2p \quad (4)$$

$$MRES = \frac{\sum_{i=1}^{n}(Hi-\hat{Hi})}{n} \quad (5)$$

$$AMRES = \frac{\sum_{i=1}^{n}|Hi-\hat{Hi}|}{n} \quad (6)$$

$$MSE = MRES^2 + v \quad (7)$$

In the above equations: Hi = observed (actual) DTH; $\hat{H}$ = predicted DTH; p = number of parameters used in the model; n = number of observations; v = variance of the residuals; R = coefficient of determination; $\bar{R}$= adjusted coefficient of determination.

System of yield prediction equations

The mean height of each sample plot (Hm) was estimated by DTH at measurable time, and its relationship was fitted using the non-linear regression model. The mean DBH of each sample plot was estimated using a multiple linear regression model that used initial stand density, inverse age, and mean height growth as independent variables of the model.

In the present study, the yield prediction sub-models were the same pattern of sub-model as used in the previous study (Vacharangkura 2012). The sub-model was the natural logarithm of initial stand density, inverse age, and site index value, and the dependent variables were the natural logarithm of the stand aggregates;

$$\text{Ln } Y = \alpha + \beta_0 \text{ Ln } I + \beta_1 \text{Ln} 1/A + \beta_2 \text{ Ln } SI \quad (8)$$

Where: Y = volume/tree (m^3/tree) or volume per hectare (m^3/ha) or basal area per hectare (m^2/ha) or number of trees per hectare (trees/ha) at measurable time (survival); I = initial stand density (trees/hectare); $1/A$ = inverse age (1/years); SI = site index value (m); Ln = natural logarithm.

The following equations derived from multiple linear regression model (n=157) were:

Vt (volume per tree) =
-11.1761– 0.4421 Ln*I*–1.3977 Ln *1/A*+2.7502 Ln*SI* (9)

V (volume per hectare) =
-7.3040+0.3123Ln*I*+0.9543Ln*1/A*+2.2898Ln*SI* (10)

Ba (basal area per hectare) =
-6.4560+0.3353Ln*I*-0.6860Ln*1/A*+1.5440Ln*SI* (11)

N (number of tree per hectare) =
3.8722+0.7544Ln*I*+0.4434Ln*1/A*-0.4603Ln*SI* (12)

To estimate the stand aggregates of the sample plots used in the present study, the site index values derived from the site index function of the present study were employed in the yield model instead of the site index equation presented by Ishibashi et al. (2010). The site index values from this study will calibrate the stand aggregates predictions, thus the yield model will be improved in order to provide more reliable predictions.

Model validation and comparison

Using datasets from 35 independent sample units (observations) the goodness-of-fit of all sub-models was conducted using a bilateral paired t-test. It was used to perform a pair-wise comparison between the observed value and the predicted value computed by the sub-models. The null hypothesis was that there was no significant difference between the actual (observed) values and the predicted values. The difference between these values was evaluated to show whether there was a statistically significant different or not.

The performances of the improved yield model in the present study were compared with that of the model presented by Vacharangkura (2012). A quantitative evaluation involving the characterization of model error (bias) and precision was performed. In addition, residuals were examined to detect any obvious pattern and systematic discrepancies. Model bias and precision were evaluated by computing the MRES, RMSE, AMRES, and MSE. These were presented in Eq. (3), Eq. (5)-(7). MRES, RMSE, and AMRES were also expressed in relative terms as percentages of the predicted mean value for more obvious results.

$$\text{MRES\%} = 100\,\frac{[\sum_{i=1}^{n}(y_i-\widehat{y_i})/n]}{\sum_{i=1}^{n}\hat{y}_i/n} \quad (13)$$

$$\text{RMSE\%} = 100\,\sqrt{\frac{[\sum_{i=1}^{n}(y_i-\hat{y}_i)^2/(n-1)]}{(n-1)}} \quad (14)$$

$$\text{AMRES\%} = 100\,\frac{[\sum_{i=1}^{n}|y_i-\hat{y}_i|/n]}{(\sum_{i=1}^{n}\hat{y}_i/n)} \quad (15)$$

Where: n = number of observations; y and ŷ = observed and predicted values, respectively.

Thereby determining the accuracy and precision of the two models.

Results

Stand characteristics

The characteristics of 322 observations derived from the measurement plots were employed to construct the site index equation in this study, as shown in Table 1.

The stand characteristics were given for the measurement time of all plots used to construct the site index equation. All of the observations covered various initial densities; however, most of them existed on 1,250 trees/ha (2×4 m spacing) and 625 trees/ha (4×4 m spacing). Most of stand ages ranged from 6 to 20 years, and old stands accounted for 69% of all datasets (Fig. 2). The limitations of our data included having only a small number of observations for stands over 40 years old and stands less than 5 years old. The number of measurement plots for which the initial stand densities were not 625, 1111, 1167, 1250, or 2500 trees/ha was very low and accounted for 3.4% of our dataset.

Table 1. Summary of characteristics of the sample plots, as computed from 322 observations used for constructing the site index function in this study.

Variable	Average (min, max)		S.D.
Stand age (year)	17.69	(3.00, 43.00)	9.29
Stand basal area (m^2/ha)	12.94	(3.02, 43.00)	7.87
Stand density (tree/ha)	797.67	(118.75, 2380.95)	420.62
Mean diameter (DBH, cm)	16.46	(5.95, 39.11)	7.61
Mean total height (m)	14.45	(5.13, 29.84)	5.33
Dominant tree height (m)	33.21	(8.21, 17.34)	5.31
Stand volume (m^3/ha)	124.51	(16.85, 483.28)	83.44

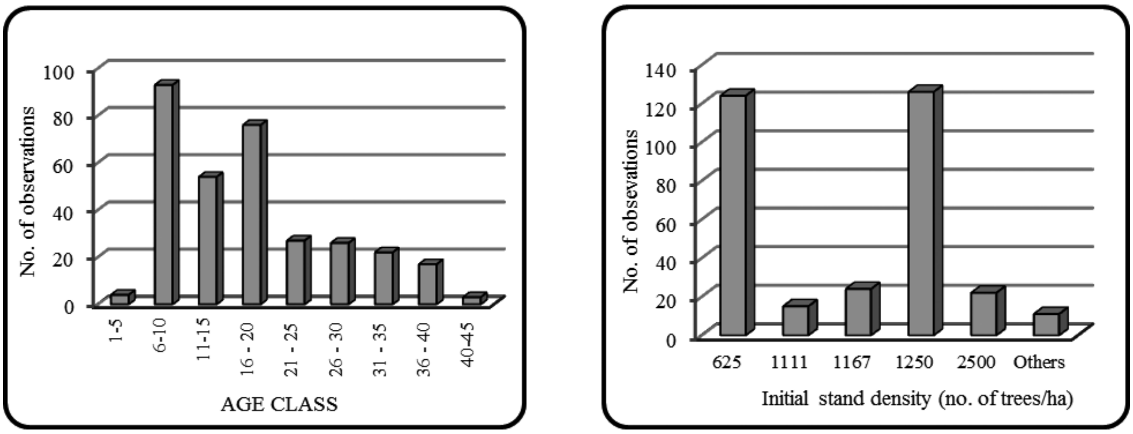

Fig. 2. The characteristics of the measurement plots.

Site index equation

A wide variety of non-linear models were employed for modeling the relationships between stand age and dominant tree height of teak stands. Based on the procedure of non-linear estimation, four non-linear height-growth functions were selected as candidate site index models. These four non-linear growth functions have been widely used because of their appropriate mathematical properties and promising predictive performances for height–age relationships. The datasets from the site index construction data (n=322) were used to perform the non-linear functions. The four candidate non-linear models are presented in Table 2.

The results of the four non-linear dominant height growth functions for teak stands in Northeastern Thailand are presented in Table 3.

The coefficients of all the models were highly statistically significant at $p<0.001$. The differences in R^2 values among the Gompertz, Hossfeld, and Logistic models were negligible, but those of the three models were rather higher than the Negative exponential model.

Table 4 shows the measures of performance for all four candidates site index functions modeled in this study. The models with the lowest RMSE and AIC values and the R^2 and adjusted R^2 closest to unity are known to perform best (Aertsen et al. 2010). The adjusted R^2 values indicated that all models, except for the Negative exponential model produced nearly identical fits explaining approximately 34% of the total variation in dominant height. The MRESs ranged from -0.0019 to 0.0900, whereas AMRESs ranged from 1.9606 to 2.875. In general mean residuals were small for all four candidate non-linear models.

Table 2. Non-linear mathematical models considered the candidate models.

Model	Standard form	Sources
Gompertz	$DTH = a \exp(-b_1 \exp(-b_2 AGE))$	Draper & Smith (1981)
Hossfeld	$DTH = (a AGE^{b1})/(b_2 + AGE^{b1})$	Kimberly & Ledgard (1998)
Logistic	$DTH = a/(1+ b_1 \exp(-b_2 AGE))$	Nelder (1961), Oliver (1964)
Negative exponential	$DTH = a(1-\exp(-b\, AGE))$	Phillip (1994)

Table 3. Parameter estimates for the non-linear dominant height–age model.

Model	Parameter	Estimate	S.E.	R^2
Gompertz	a	31.4788	3.8654	0.5877
	b	1.3173	0.0685	
	c	0.0471	0.0118	
Hossfeld	a	0.1568	0.0101	0.5872
	b	-0.0039	0.0003	
	c	-0.9800	0.0010	
Logistic	a	29.1193	2.3333	0.5859
	b	2.5703	0.1725	
	c	0.0703	0.0128	
Negative exponential	a	24.9841	0.7463	0.5572
	b	0.0785	0.0053	

Table 4. Performance criteria of the four non-linear dominant height-age model for constructing site index equation.

Model	Adj. R^2	RMSE	AMRES	MRES	AIC	$\sqrt{v}$	MSE
Gompertz	0.3393	3.4098	1.9606	-0.0019	796.96	3.4098	11.6264
Hossfeld	0.3387	3.4118	2.6751	0.0415	797.35	3.4119	11.6430
Logistic	0.3371	3.4173	2.7009	-0.0043	798.38	3.4173	11.6780
Negative exponential	0.3062	3.5338	2.8752	0.0810	817.96	3.5326	12.4874

Fig. 3 shows the curved shapes of all four candidate models. The Gompertz and Logistic models showed similar predictions of dominant tree height; however, for older stands the Gompertz model tended to provide a greater height growth than the logistic model. This was confirmed by the larger asymptotic coefficient of the Gompertz model (Table 3). The Negative exponential model gave a smaller value than the others for younger stands (less than 10 years old) and older stands (more than 30 years old). The Hossfeld model showed larger height growth prediction than the others when the stand age was more than approximately 35 years.

Referring to Table 4, it is evident that the Negative exponential model gave poorer performance criteria values more than the others. Therefore, the Negative exponential model was omitted in the first step of this approach. The differences in values among the other three models were small; however, the Gompertz model gave the smallest values, especially for the AIC value. AIC value is considered as one of the most reliable criteria for comparing models with a range of parameters (Burnham et al. 2002; Sharma 2009). The model with the smallest AIC is considered optimal. Therefore, the Gompertz model was the best to use as a guide curve for site index construction.

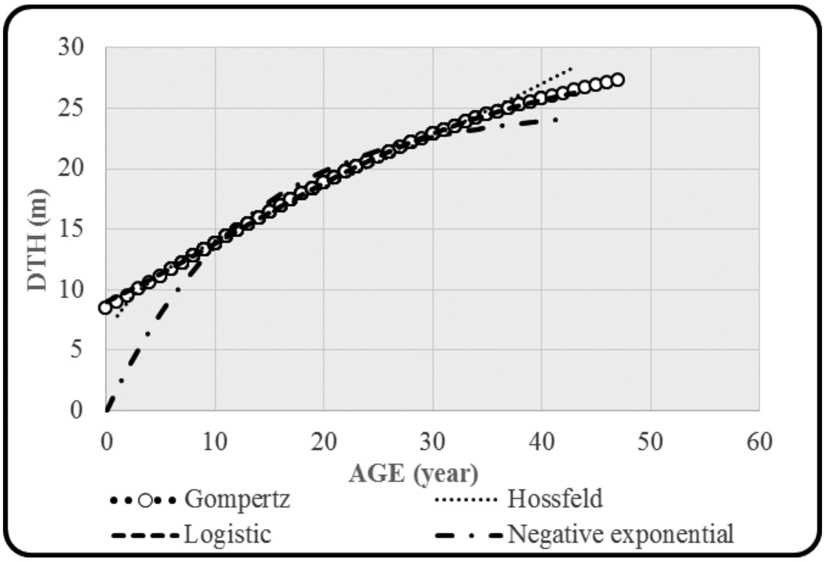

Fig. 3. Dominant height-growth curves derived from the four candidate non-linear models.

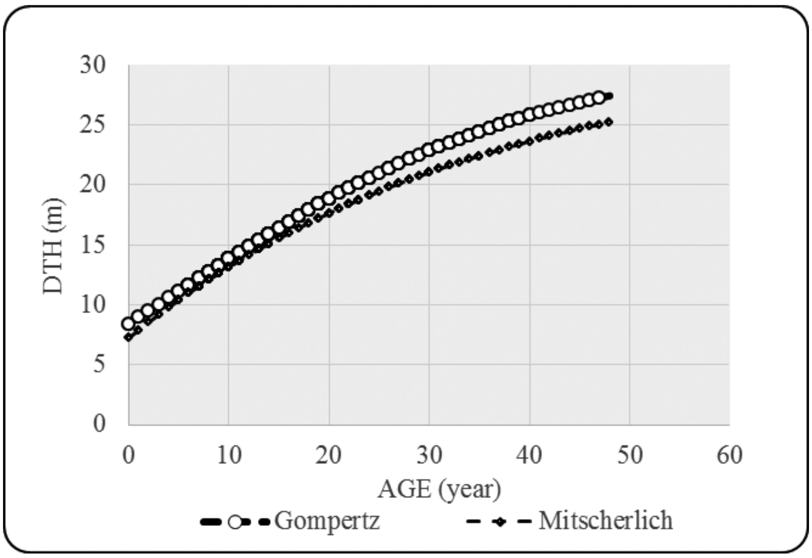

Fig. 4. SI curve (Gompertz model) constructed in this study versus the SI curve (Mitschelich model) from theprevious study

Fig. 4 shows the comparison between site index guide curves in the present study (Gompertz model) and the guide curves (Mitschelich model) used in the previous study (Ishibashi et al. 2010). The curved shapes of the two guide curves looks similar. These two guide curves showed similar prediction, and the difference was small when the stand was young. The convergence of the two guide curves clearly occurred when the stand age was approximately 15 years. The guide curve used in this study gave a larger dominant height prediction than the previous study. The site index function developed in this study was used to produce a guide curve for constructing site index curve were:

$$DTHgt = 31.4788[\exp(-1.3728(\exp(-0.047126t)))] \quad (16)$$

Where: t = stand age (year); $DTHgt$ = dominant tree height at age t on the guide curve (m).

The site index was defined as DTH at the base age. The rotation age is often used as the base age; therefore, 30 years was adopted as the base age. Because the use of the system of equations required the estimation of DTH of each plot at the measurement time, the estimated DTH was computed using the following equation:

$$DTHt = SI \frac{DTH\,gt}{DTHg30} \quad (17)$$

Where: SI = site index value (m); $DTHt$ = estimated dominant tree height at age t (m); $DTHgt$ = dominant tree height at age t on guide curve (m); DTHg30 = dominant tree height at age 30 years old on the guide curve.

When $DTHgt$ and DTHg30 were substituted in Eq. 17, $DTHt$ could be estimated using Eq. 18:

$$DTHt = SI \frac{31.4788[\exp(-1.3728 (\exp (-0.047126Xt)))]}{31.4788[\exp(-1.3728 (\exp (-0.047126X30)))]} \quad (18)$$

The site index curves were then produced for an SI of 14 to 30, and the results are presented in Fig. 5. Stand growth and yield parameters (stand density, stand basal area, stem volume, and stand volume) were computed for each sample plot using SI values derived from the site index function developed in this study instead of SI values derived from the site index function used in the previous study.

Average DBH and total height estimation

The average total height of each sample plot was computed using a non-linear regression model and used the same datasets as for construction of the site index function. The relationship between total height and DTH was:

$$Hm = 0.4776\, DTH^{1.1922} \quad (R^2 = 0.9439) \quad (19)$$

Where: DTH = dominant tree height (m); Hm = average height (m).

The average DBH of each stand was computed using a multiple linear regression model:

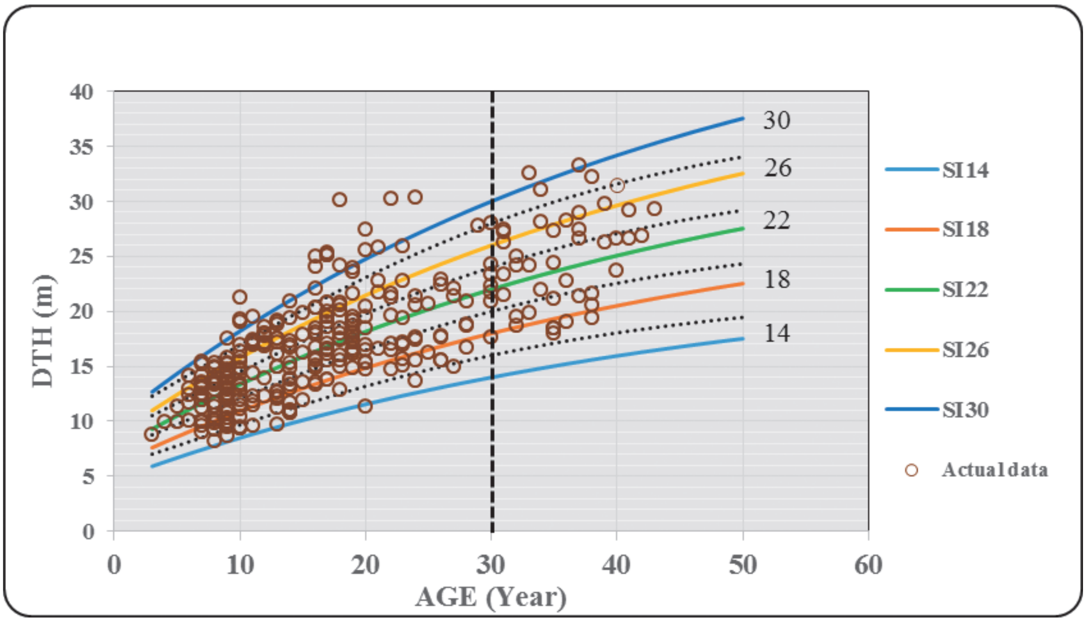

Fig. 5. Site index curve constructed in this study.

Ln *DBH* =

1.7718 – 0.2028 Ln*I* – 0.0753 Ln *1/A* + 0.7879 Ln*Hm* (R^2 = 0.9330) (20)

Where: *I* = initial stand density (trees/ha); *1/A* = inverse age (1/year); *Hm* = average height growth (m); Ln = natural logarithm

Statistical test of yield model

Using model validation data sets, the 35 independent sample units were used for computing stand density, stand basal area, stem volume (volume per tree), and stand volume. The characteristics of the 35 temporary sample plots used in the study are shown in Table 5.

These stand aggregates were computed using a system of multiple linear regression equations presented in Eq. 9–Eq. 12. The average total height and average DBH of the sample plots were independent of the system of equations. They were computed using Eq. 17 and Eq. 18. A statistical comparison of the goodness-of-fit of all sub-models was then performed. The observed values of the 35 sample plots were compared with the corresponding values predicted by the yield prediction equations. The comparisons were made with the help of paired sample t-test. These implied that the observed values of all predictions (stem volume (Vt), stand volume (V), stand basal area (Ba), and stand density (N) were not significantly different from those predicted value at 0.05 level. The results are shown in Table 6. Thus, the system of yield prediction model was judged acceptable.

Using the graphical method, the residuals of the model predictions were evaluated. The distribution of residuals in the stem volume, stand basal area, stand volume, and stand density versus the predicted values are shown in Fig. 6. There were no serious patterns in the distribution of the residuals for all stand aggregates, although some predicted values had rather larger residuals than others.

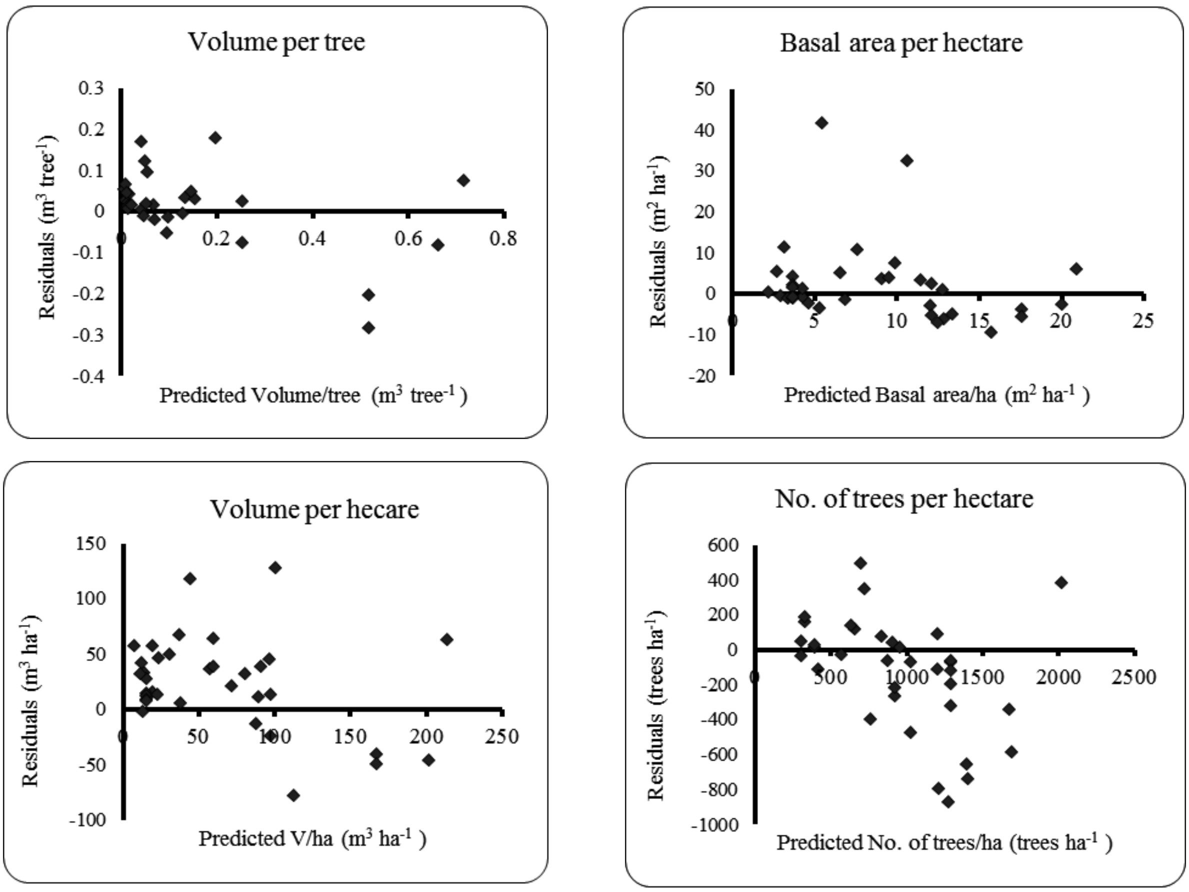

Fig. 6. Residuals versus predicted values for the sub-model of stem volume, stand volume, stand basal area and stand density.

Table 5. Summary of the characteristics of 35 temporary plots used for model validation

Variable	Average	(min, max)	S.D.
Stand age (year)	15.49	(5.00, 34.00)	8.02
Stand basal area (m^2/ha)	10.32	(2.35, 26.82)	5.07
Stand density (tree/ha)	828.77	(268.75, 2404.76)	422.06
Mean diameter (DBH, cm)	13.37	(7.25, 30.39)	5.56
Mean total height (m)	11.91	(6.19, 23.85)	4.22
Dominant tree height (m)	15.01	(8.03, 26.46)	4.52
Stand volume (m^3/ha)	87.83	(10.48, 276.45)	58.10
Stand volume (m^3/tree)	0.14	(0.0202, 0.7898)	0.166

Table 6. The results of paired sample t-test of the yield predictions

	t-value	p-value
V	1.80180	0.0760 ^{ns}
Vt	0.30840	0.7588 ^{ns}
Ba	1.28080	0.2046 ^{ns}
N	-1.20451	0.2326 ^{ns}

Table 7. Summary of the indicator values used to evaluate the performance of the yield prediction models.

Stand aggregates	Model	MRES	MRES%	RMSE	RMSE%	AMRES	AMRES%	MSE
V (m^3/ha)	Previous	33.919	62.916	52.591	98.767	40.369	74.880	2731.925
	Present	24.631	38.973	48.929	87.989	38.905	61.559	2376.241
Vt (m^2/tree)	Previous	0.037	35.514	0.083	89.714	0.057	55.030	0.007
	Present	0.013	10.296	0.085	81.981	0.055	43.417	0.007
Ba (m^2/ha)	Previous	3.367	42.566	10.389	114.600	5.687	71.896	107.588
	Present	2.511	28.647	10.252	108.143	5.804	66.209	104.914
N (trees/ha)	Previous	-149.629	-15.293	363.945	60.990	257.214	26.289	131797.286
	Present	-123.885	-13.004	349.111	60.536	247.609	25.992	121426.766

Comparison of the yield models

The yield model in this study provided stand-level growth and yield predictions for teak plantations in Northeastern Thailand. The sub-models employed site index values that were computed from the new site index function developed in this study. Therefore, stem volume, stand volume, stand basal area, and stand density were fitted simultaneously using multiple linear regression, whereas the DTH of the stand was predicted independently by the new site index function. It had to be assured that the improve yield model provided more reliable predictions than the model developed in the previous study. Therefore, the bias and the precision of previous and present models were evaluated. MRES, MRES%, RMSE, and RMSE% were applied to assess the accuracy of both models whereas the AMRES, AMRES% and MSE were applied for the evaluation of precision. All indicators were computed and were used to compare the performances of the yield prediction models. The results are presented in Table 7.

Referring to this table, MRES, MRES%, RMSE, and RMSE% were applied to evaluate the accuracy or bias of the yield models. The values of MRES, MRES%, RMSE, and RMSE% of all the stand aggregates produced from the present model were smaller than those of values produced from the previous model. The decreases in MRES% values ranged from approximately 2% to 25%, whereas RMSE% decreased by approximately 0.5% to 11%. The decrease in

MRES% and RMSE% produced stand density predictions that were very small compared with the predictions of others stand aggregates. The apparent effect of these results confirmed that the present yield model clearly provided smaller bias than those of the previous model. This meant that the predictions from the present model had greater accuracy than the previous model.

AMRES, AMRES%, and MSE were indicators applied to evaluate the precision of the yield models. All of yield predictions produced smaller MSE values than the previous model, except for the prediction of stem volume (Vt). The previous model gave smaller MSE values than those of the present model, but the difference was negligible. Therefore, it could be concluded that the present model had greater precision than the previous model; however, the higher precision provided from the present model was not as clear as its accuracy.

Discussion

In this study, the guide curve method was applied to construct a site index curve using 322 observations. This method, when applied directly to all observations, will naturally give low R^2 values and high RMSE values (the mean residuals values for the model used in this study equaled 11.6 m). The reason was due to the effect of the repeat run, *i.e.* different observed values of DTH at the same age. It is impossible to attain a high value for R^2 in such cases, no matter how appropriate the model is, because any model can explain only the variations due to lack of fit and not the pure error variations resulting from repeat runs (Draper and Smith 1981). In a future study, the difference equation method, described by Draper and Smith (1981), should be applied to construct a site index function, and all observations from various sample plots could be checked for the extent of pure error and lack of fit.

The limitation of this study was the small size of the dataset used to evaluate the yield model. We had only 35 observations from 35 sample plots. If unusual evidence occurred in some sample plots the outcome predictions would be less robust. For example, when the stand volume prediction was evaluated it was found that there were two predictions that gave very higher residuals compared with the others (Fig. 6). This evidence could explain that unusual residuals that were caused by the unusually small number of trees in the sample plots at the measurement time. This may be caused by illegal cutting or cutting by the owners of private plantations for utilization or by poor plantation management. If the sample size could be increased, the outcome predictions will show better stability and greater accuracy. In this study, site index values derived from the new site index function had smaller effects on the precision of the yield predictions compared with the effect on accuracy because the system of equations used in the yield model was the same as in the previous study.

Conclusions

In this study, 322 observations collected from various teak stands in Northeastern Thailand were employed to develop a site index function. Four non-linear models, i.e. Gompertz, Hossfeld, Logistic, and Negative exponential, were selected as candidate models for constructing the site index curve. The Gompertz model was the best at predicting the dominant height growth of teak stands because this model provided greater accuracy and precision predicted values than the others. Therefore, the Gompertz model was used as a guide curve to construct the new site index curve for teak stands. The yield prediction model developed in this study applied site index values derived from the new site index function (set of multiple linear regression models) as one of the independent variables in the system of equations to predict stem volume, stand basal area, stand volume, and stand density of teak stands. The site index value, the average DBH and total height of the teak sand were independently estimated from the system of equations. The comparison between the present model and the previous model revealed that the improved yield model provided greater accuracy and precision for yield predictions than the previous model. The results of this study could be applied to generate a yield prediction table for teak plantations in Northeastern Thailand.

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Effects of coppicing and seedling options on financial evaluation of teak (*Tectona grandis* L.) farm plantation management in Thailand

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Abstract

Teak (*Tectona grandis* L.) plantation management has been shown to be a profitable venture in Thailand. However, reduction of the initial investment cost is an important challenge for farmers to be able to conduct sustainable management. In particular, tree planting is the most burdensome part. Teak plantations are considered to be regenerable by coppicing. Therefore, this study established discounted cash flow models for producing teak timber with 15-year or 20-year rotation cycles, and evaluated the profitability of coppicing for reforestation with genetically improved seedlings using incremental net present value (NPV). The results showed that the use of coppicing reduced reforestation costs by nearly 60% compared with seedlings. The incremental NPV was markedly affected by the productivity of coppices and genetic gain in volume production of seedlings.

Keywords: *Tectona grandis*, Coppicing, Genetic improvement, Reforestation, Discounted cash flow

Introduction

Teak (*Tectona grandis* L.) is the premier cultivated high quality cabinet wood of the world and the decline of the natural resources and prudent management objectives (White 1991). Natural teak forests grow in only four countries in the world: India, Lao PDR, Myanmar and Thailand, declined in area by 1.3% between 1992 and 2010, Myanmar is the only country that currently produces quality teak from natural teak forests, and teak planting serves local communities as savings account and the long run helps smallholders improve their livelihoods (Kollert and Cherubini 2010).

In Thailand, the creation of teak plantations on private land was initiated after an afforestation subsidy project in 1994, and most cases involve small-scale farmers (Royal Forest Department 2002; Yokota et al. 2009). The management of teak plantations has been shown to be a profitable activity, an intensive operating model for large-scale business has been proposed (Phothitai 1993). According to a previous study, teak is more profitable than *Eucalyptus camaldulensis* Dehn in all of the following three types of forestation: intensive industrial plantations in Northeast Thailand, relatively extensive plantations in communities, and agroforestry or crop cultivation in forests by farmers (Niskanen 1998). Noda et al.(2004) pointed out for small-scale farmers that: 1) although teak plantation management by farmers in Northeast Thailand was more profitable than that of Eucalyptus plantations due to stably higher log price and higher benefit/cost ratio, the initial investment including expenses for planting is burdensome; 2) no income is obtained for 10 or 20 years before teak trees grow to a marketable size; and 3) it is necessary to discuss methods for the efficient utilization of land by cultivating agricultural crops during this period. A study conducted by Noda et al. (2012b) in Northeast Thailand suggested that combined farm management based on a mixture of agriculture and forestry is expected to reduce initial costs, and that rice production can be the primary element to increase profitability as a land utilization strategy. Teak plantations are believed to be restorable by coppicing (Thaiutsa et al. 2001; Bailey and Harjanto 2005; Himmapan and Noda 2012). Using a discounted cash flow model, a profit analysis of coppicing in *Eucalyptus globulus* plantations in Australia for pulp production was conducted, and the results suggested that coppicing may reduce the initial investment required (Whittock et al. 2004). Himmapan and Noda (2012) showed a preliminary result of monitoring teak plantations up to 22 months old in Kanchanaburi, Thailand, but coppice sprouts from stump of final cutting were better than those from thinning and seedlings, the coppice might be expected as low cost reforestation method and also to reduce the burden of weed control cost. Thus, coppicing in teak timber management has been expected to reduce costs, but no previous studies have included comparative financial evaluations of coppicing for teak timber management for Thai farmers except Noda and Himmapan (2012a). On teak timber production managements for farmers in Thailand, Noda and Himmapan (2012a) made discounted cash flow models and evaluated the profitability of coppicing concerning reforestation with genetically improve seedlings. Noda and Himmapan (2012a), however, studied a limited case of plant spacing 4 m × 4 m in a 15-year rotation cycle. In the present study, a financial evaluation of coppicing in plantations was conducted using the discounted cash flow models in the simulation of teak plantation managements with standard silvicultural alternatives for Thai farmers, thus, plant spacing of 4 m × 4 m and 3 m × 3 m, and short rotation periods of 15 years and 20 years.

Materials and methods

The study area was the northeast region in Thailand, which borders Cambodia and Laos. Two-thirds of the region is covered by the alluvial plateau of the Korat basin with an elevation 100–300 m, and the region is surrounded by mountain ranges to the south, west and northeast (Wongwiwatchai and Paisancharoen 2002). The climate of the region has two major seasons of the southwest monsoon and the northeast monsoon. The southwest monsoon is characterized by the wet season with maximum monthly rainfall of about 300 mm, and the northeast monsoon is mostly dry with very occasional light showers. The annual rainfall and the monthly mean temperature range from 1,100 mm/year and 22°C to 1,800 mm/year and 29°C (Phien et al. 1980). Most of the soils in Northeast Thailand are derived from sandstone, shale, or siltstone (Ragland and Boopuckdee 1988).

In our study, we investigated different silvicultural alternatives, with rotation periods of 15 years and 20 years, and plant spacing of 4 m × 4 m and 3 m × 3 m, as part of the standard management plan for teak plantations (Table 1) developed by the Royal Forest Department for farms in Northeast Thailand.

Cash flow models

Thirty-year cash flow models were created to represent the plantation system (Table 1) developed by the Royal Forest Department for farms in Northeast Thailand, in which trees were planted at intervals of 4 m × 4 m and 3 m × 3 m and logged in 15 years (two rotations in 30 years). In addition, 40-year cash flow models were created to investigate a plantation system in which trees were planted at intervals of 4 m × 4 m and 3 m × 3 m and logged in 20 years (two rotations in 40 years).

As in the previous study (Whittock et al. 2004), two analysis models were created for managing teak plantations from seedlings in the first rotation (1R), and from coppices (coppicing model) or seedlings (seedling model) in the second rotation (2R) (Table 2). The model allows changes in productivity due to coppicing or genetic improvement to be investigated in terms of financial evaluation (Whittock et al. 2004). Because genetic improvement of the seedlings used in the 1R may increase the yield in the 2R, a *VGAIN* (representing the effect of the genetic improvement of seedlings) was adopted as a variable.

The management plan shown in Table 1 was implemented in the 1R, and, in the 2R, modifications were added to the plantation procedures conducted in the first year, depending on the model (Table 3). Although the coppicing model does not involve planting trees, seedlings for supplementary planting were prepared on the assumption of a 10% coppice mortality rate, and the workload required for "alignment and staking" was determined to be 0.5 man-day. Regarding the seedling model, the workload required to perform preparation for re-afforestation, including removal of the roots of logged trees and clearance, was assumed to be heavier. The "percentage cost gain in land preparation" [*r*] was adopted to adjust the workload for "land preparation" and "slash and burn", the base value was determined by reference to *Eucalyptus globulus* plantations in Whittock et al. (2004) (Table 3).

The percentage increase in the volume of trees to the volume of seedlings prior to genetic improvement in the 1R was defined as the coppicing productivity (*CPROD*), and the percentage effect of genetic improvement of seedlings on the increase in the volume production was defined as the *VGAIN*. Variables were the price of logs at the time of logging (*LogPrice*), volumes of logged trees in the coppicing (*Yc*) and seedling (*Ys*) models, and discount rate (*d*) (Table 4):

$$Yc = Yn \times CPROD / 100 \quad \text{......(1)}$$

$$Ys = Yn \times (1 + VGAIN / 100) \quad \text{......(2)}$$

where *Yn* represents the volume of seedlings (not genetically improved) logged in Table 1 (yield log volume).

In the financial evaluation, criteria are calculated using discounted cash flow analysis techniques. The criteria used in the study were the net present value (NPV) (Price 1989; Davis et al. 2005) and incremental NPV (Irvin 1978) as increments in the yield in the coppicing model:

$$NPV = \Sigma (Rt - Ct) / (1 + d/100)^t \quad \text{......(3)}$$

where *Rt*, *Ct* are revenue and cost in year *t*, and *d* is the discount rate in percentage figures. For application of the NPV, we should select the highest NPV from a group of compatible investments (Price 1989). Incremental NPV was used to compare the two mutually exclusive options (Dasgupta and Pearce 1972). A positive incremental NPV indicated that the NPV of coppicing exceeded the NPV of seedlings in the 2R, whilst a negative incremental NPV indicated that the NPV of a seedling crop exceeded the NPV of a coppiced crop in the 2R (Whittock et al. 2004). The incremental NPV was calculated by subtracting the NPV in the seedling model from that in the coppicing model. The models were created using MS-Excel.

Simulation analysis

The responses of outputs to input variables were examined using Oracle Crystal Ball 11 (EPM Information Development Team 2013) to use probability distributions of variables and conduct Monte Carlo simulations with 100,000 iterations for the following steps. First, the effect of coppicing on reducing the initial investment was examined from the viewpoint of cash balance. We, thus, calculated percentage change of economic balances in the first year of the 2R between the coppicing and the seedling models as mean ± standard deviation of percentage changes simulated with the assumptions of variables shown as Tables 4. Second, the effects of the combination of *CPROD* and *VGAIN* on the incremental NPV were analyzed using the decision table tool (EPM Information Development Team 2013). We evaluated responses of incremental NPVs for the combination of *CPROD* and *VGAIN* by discount rate of 10% and 7%, respectively, to additionally compare effects of discount rate. Third, the sensitivity of variables corresponding to incremental NPVs was analyzed under the assumptions (Table 4), using rank correlation coefficients, to identify variables closely related to the effect of coppicing on increasing profits.

The occurrence probabilities of all variables with the exception of the percentage cost gain (*r*) were defined by the triangular distribution, determined by the base, minimum, and maximum values (Table 4). The base, minimum and maximum values of all variables were set with reference to previous studies. The *CPROD* and [*d*] were allowed to vary according to a triangular distribution with maximum and minimum values ±20% of the base value, and the *LogPrice* was ±10% of the base. The *VGAIN* was fitted with a triangular distribution ranging from 0 to 40% with the likeliest value 20%. The [*r*] was allowed to vary from 0% to 100% with a uniform distribution. The costs of labor, seedlings, and fertilizers were 180 baht/man-day, 5 baht/tree, and 10 baht/kg, respectively (Royal Forest Department 2006).

Results and Discussion

Effects of coppicing on reducing the initial investment

The mean percentage changes of economic balances of the coppicing model in the first year of the 2R for the seedling model were calculated as improved by 56.9 ± 3.3% (4 m × 4 m) and 56.8 ± 2.9% (3 m × 3 m). These results were not different between rotations of the 15-year and 20-year, since the cash flow in the first year is not affected by rotation period. The choice of coppicing reduced reforestation costs by nearly 60% compared with the seedling one, where these results were based only on regeneration by coppicing or seedlings in the 2R, not affected by productivity variables.

Effects of the combination of *CPROD* and *VGAIN*

The relationship between the incremental NPV and the combination of the *CPROD* and *VGAIN* is shown on Fig. 1 by rotation and spacing. The results from different discount rates are overlaid together.

1) Discount rate 10%

When the discount rate was 10%, the *CPROD* was 70% to 130% and the *VGAIN* was -10% to 40%, and the change in the incremental NPV was 5,096 (-2,557 to 2,539) baht/rai (4 m × 4 m) and 5,026 (-2,434 to 2,592) baht/rai (3 m × 3 m) in the 15-year rotation, and 4,521 (-2,451 to 2,070) baht/rai (4 m × 4 m) and 4,167 (-2,177 to 1,990) baht/rai (3 m × 3 m) in the 20-year rotation.

If the productivity of the coppiced crop was equivalent to the 1R seedling crop (*CPROD* was 100%), then genetic gain (*VGAIN*) would be required at a minimum of ~15% (4 m × 4 m) and ~16% (3 m × 3 m) in the 15-year rotation, and ~10% (4 m × 4 m) and ~13% (3 m × 3 m) in the 20-year rotation for a seedling crop to have an NPV higher than the coppiced crop (incremental NPV < 0) (Fig. 1). If *CPROD* was 110%, then the thresholds of VGAIN would be increased to ~25% (4 m × 4 m) and ~26% (3 m × 3 m) in the 15-year rotation, and ~21% (4 m × 4 m) and ~23% (3 m × 3 m) in the 20-year rotation for a seedling crop to have a negative incremental NPV.

With no genetic improvement effect on seedlings (*VGAIN* was 0%), the change in productivity of the coppiced crop to the seedling crop (*CPROD*) would need to be at least ~85% (4 m × 4 m) and ~84% (3 m × 3 m) in the 15-year rotation, and ~90% (4 m × 4 m) and ~88% (3 m × 3 m) in the 20-year rotation for the coppice crop to have a higher NPV than the seedling crop (incremental NPV > 0).

If the productivity of the coppiced crop was equivalent to the seedling crop (*CPROD* was 100%) with no genetic improvement in the seedlings (*VGAIN* was 0%), then the NPV of the coppicing model was higher compared with the seedling model by 12.9 ± 2.5% (4 m × 4 m) and 21.1 ± 4.7% (3 m × 3 m) in the 15-year rotation, and 3.3 ± 0.5% (4 m × 4 m) and 5.1 ± 0.7% (3 m × 3 m) in the 20-year rotation.

2) Discount rate 7%

When the discount rate was 7%, the *CPROD* was 70 to 130% and the *VGAIN* was -10 to 40%, and the change in the incremental NPV was 10,823 (-5,820 to 5,003) baht/rai (4 m × 4 m) and 10,527 (-5,509 to 5,018) baht/rai (3 m × 3 m) in the 15-year rotation, and 12,084 (-6,929 to 5,155) baht/rai (4 m × 4 m) and 11,200 (-6,279 to 4,921) baht/rai (3 m × 3 m) in the 20-year rotation. The lower the discount rate became, the more the change in volume production by the *CPROD* or *VGAIN* had elastic effects on the profits.

If the productivity of the coppiced crop was equivalent to the 1R seedling crop (*CPROD* was 100%), then genetic gain (*VGAIN*) would need to be at least ~11% (4 m × 4 m) and ~13% (3 m × 3 m) in the 15-year rotation, and ~7% (4 m × 4 m) and ~8% (3 m × 3 m) in the 20-year rotation for a seedling crop to have an NPV higher than the coppiced crop (incremental NPV < 0) (Fig. 1). If *CPROD* was 110%, then the thresholds of *VGAIN* would be required to be up to ~21% (4 m × 4 m) and ~23% (3 m × 3 m) in the 15-year rotation, and ~17% (4 m × 4 m) and ~18% (3 m × 3 m) in the 20-year rotation for a seedling crop to have a negative incremental NPV.

With no genetic improvement effect on seedlings (*VGAIN* was 0%), the change in productivity of the coppice crop to the seedling crop (*CPROD*) would need to be at least ~90% (4 m × 4 m) and ~87% (3 m × 3 m) in the 15-year rotation, and ~94% (4 m × 4 m) and ~92% (3 m × 3 m) in the 20-year rotation for the coppiced crop to have a higher NPV than the seedling crop (incremental NPV > 0).

If the productivity of the coppiced crop was the same as the seedling crop (*CPROD* was 100%) with no genetic improvement in the seedlings (*VGAIN* was 0%), then the NPV of the coppicing model was higher compared with the seedling model by 8.1 ± 1.3% (4 m × 4 m) and 11.1 ± 1.8% (3 m × 3 m) in the 15-year rotation, and 2.6 ± 0.4% (4 m × 4 m) and 3.5 ± 0.5% (3 m × 3 m) in the 20-year rotation. The lower the discount rate became 7% from 10%, the less the coppicing model had gain in the NPV on the seedling model.

Sensitivity of variables corresponding to incremental NPVs

CPROD and *VGAIN* correlated with the incremental NPV (Table 5). For the NPV, the discount rate (*d*) was strongly and negatively correlated, and log price at final logging (*LogPrice15* in the 15-year rotation; *LogPrice20* in the 20-year rotation) was moderately correlated. The "percentage cost gain in land preparation" [*r*] was not correlated with either. These results suggested that *CPROD* and *VGAIN* are important in the selection of methods for coppicing or planting in the 2R, and that it is necessary to increase the unit log price by improving the log quality at the final time of logging to effectively increase profits.

It is believed that in areas where coppices can grow into mature trees, coppicing is a more effective reforestation method compared with planting seedlings, which grow relatively slowly (Harcombe and Marks 1983; Ohkubo 1992). Himmapan and Noda (2012) and Kwame et al. (2014) studied growth performances of coppiced trees, but only until 1 or 2 years after coppicing. In 3-, 8-, and 13-year-old teak plantations in Java, the mean height and diameter at breast-height of coppiced trees were larger than those of planted trees (Bailey and Harjanto 2005). This means that the *CPROD* is almost always 100% or higher. According to a study on teak breeding in Thailand, the volume of seedlings cultivated in a seed orchard tended to be 5–12% larger (Wellendorf and Kaosa-ard 1988). Kjaer and Suangtho (1997) estimated that seedlings from classified seed stands are expected to have at least 8% higher production value than seedlings from unclassified seeds (this increased production value originated from both improved production volume and better stem form) (Kaosa-ard et al. 1998). Therefore, *VGAIN* is estimated to be approximately 10% if genetically selected seedlings are not used in the 1R and adopted in the 2R, and 0% otherwise. In this case, if the *CPROD* is 100 or 110%, which is lower than the threshold of the *VGAIN* (about 15 or 25%) calculated based on the results of the present study, the effect of coppicing on increasing profitability is supported. However, as the results of previous study show (Whittock et al. 2004), when the actual *VGAIN* is close to the above-mentioned threshold, or the NPV of the coppicing model is similar to that of the seedling model, it is necessary to select a method with a lower risk that helps promote the growth of trees more effectively.

Conclusion

The present study examined the effects of changes in productivity of a coppiced crop and the genetic gain in volume production of seedlings on a financial evaluation to compare coppiced and seedling options for teak plantations with 15- and 20-year rotations, including the efficacy of coppicing with a focus on differences in the regeneration method in the 2R. The results suggested that coppicing reduces the initial investment, and its profitability may be greater than that of planting seedlings. As future challenges, it will be necessary to examine the ranges of variables used for the analyses and the validity of the models.

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Table 1. Management plans for planted teak forest plantations

Rotation period 15 years; plant spacing 4 m × 4 m																
Activity	Unit	Year														
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Survey	man-day	0.5														
Land preparation	man-day	4														
Slash and burn	man-day	4														
Survey road	man-day	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Fire line	man-day	1														
Alignment and Staking	man-day	2														
Planting and seedling transportation	man-day	3														
Weeding	man-day	4	6	6	6	6	6	2	2	2	2	6	2	2	2	2
Fertilizing	man-day	0.5	0.5	0.5				0.5	0.5				0.5	0.5		
Replanting and survival rate checking	man-day	1	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Pruning	man-day							1	1	1	1		1	1	1	1
Tending cutting 50%	man-day					5										
Logging	man-day										7					7
Number of seedlings	tree	120														
Amount of fertilizer	kg	50	50	50			50	50				100	100			
Yield log volume	m^3	0	0	0	0	3	0	0	0	0	5	0	0	0	0	9
Log price	baht/m^3	0	0	0	0	1,500	0	0	0	0	3,000	0	0	0	0	5,000
Rotation period 15 years; plant spacing 3 m × 3 m																
Activity	Unit	Year														
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Survey	man-day	0.5														
Land preparation	man-day	4														
Slash and burn	man-day	4														
Survey road	man-day	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Fire line	man-day	1														
Alignment and Staking	man-day	2														
Planting and seedling transportation	man-day	3														
Weeding	man-day	4	6	6	6	6	6	2	2	2	2	6	2	2	2	2
Fertilizing	man-day	0.5	0.5	0.5				0.5	0.5				0.5	0.5		
Replanting and survival rate checking	man-day	1	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Pruning	man-day							1	1	1	1		1	1	1	1
Tending cutting 50%	man-day					5										
Logging	man-day										7					7
Number of seedlings	tree	200														
Amount of fertilizer	kg	75	75	75			75	75				75	75			
Yield log volume	m^3	0	0	0	0	4	0	0	0	0	5	0	0	0	0	8
Log price	baht/m^3	0	0	0	0	1,500	0	0	0	0	3,000	0	0	0	0	5,000

The above are shown as value per rai. 1 rai = 0.16 ha. Source: Royal Forest Department (2006).

Table 1. Management plans for planted teak forest plantations (cont'd)

Rotation period 20 years; plant spacing 4 m × 4 m

Activity	Unit	Year 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Survey	man-day	0.5																			
Land preparation	man-day	4																			
Slash and burn	man-day	4																			
Survey road	man-day	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Fire line	man-day	1																			
Alignment and staking	man-day	2																			
Planting and seedling transportation	man-day	3																			
Weeding	man-day	4	6	6	6	6	6	2	2	2	2	6	2	2	2	2	6	2	2	2	2
Fertilizing	man-day	0.5	0.5	0.5				0.5	0.5				0.5	0.5				0.5	0.5		
Replanting and survival rate checking	man-day	1	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Pruning	man-day							1	1	1	1		1	1	1	1		1	1	1	1
Tending cutting 50%	man-day					5															
Logging	man-day										7					7					7
Number of seedlings	tree	120																			
Amount of fertilizer	kg	50	50	50			50	50				100	100				100	100			
Yield log volume	m^3	0	0	0	0	3	0	0	0	0	5	0	0	0	0	5.5	0	0	0	0	12
Log price	baht/m^3	0	0	0	0	1,500	0	0	0	0	3,000	0	0	0	0	5,000	0	0	0	0	7,000

Rotation period 20 years; plant spacing 3 m × 3 m

Activity	Unit	Year 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
Survey	man-day	0.5																			
Land preparation	man-day	4																			
Slash and burn	man-day	4																			
Survey road	man-day	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Fire line	man-day	1																			
Alignment and staking	man-day	2																			
Planting and seedling transportation	man-day	3																			
Weeding	man-day	4	6	6	6	6	6	2	2	2	2	6	2	2	2	2	6	2	2	2	2
Fertilizing	man-day	0.5	0.5	0.5				0.5	0.5				0.5	0.5				0.5	0.5		
Replanting and survival rate checking	man-day	1	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Pruning	man-day							1	1	1	1		1	1	1	1		1	1	1	1
Tending cutting 50%	man-day					5															
Logging	man-day										7					7					7
Number of seedlings	tree	200																			
Amount of fertilizer	kg	75	75	75			75	75				75	75				75	75			
Yield log volume	m^3	0	0	0	0	2.5	0	0	0	0	4.5	0	0	0	0	5	0	0	0	0	11.5
Log price	baht/m^3	0	0	0	0	1,500	0	0	0	0	3,000	0	0	0	0	5,000	0	0	0	0	7,000

Table 2. The formation used to evaluate the incremental NPV of seedlings and coppice crops

Case	The first rotation (1R)	The second rotation (2R)
Case 1: Seedling Model	Plantation from seedlings	Plantation from genetically improved seedlings
Case 2: Coppicing Model	Plantation from seedlings	Plantation from coppices

NPV: net present value.

Table 3. Assumed changes for activities of the 1st year in first rotation (1R), second rotation seedling (2R seedling) and second rotation coppice (2R coppice)

Activity		1R	2R seedling	2R coppice
Land preparation	man-day	4	4 ・ (1 + *r* /100)	1
Slash and burn	man-day	4	4 ・ (1 + *r* /100)	1
Alignment and Staking	man-day	2	2	0.5
Planting and seedling transportation	man-day	3	3	0
Number of seedlings	tree	*n* *1	*n*	*n* × 10/100

*1: The *n* is number of seedlings on Table 1.

Table 4. Variables used in the models and their assumptions

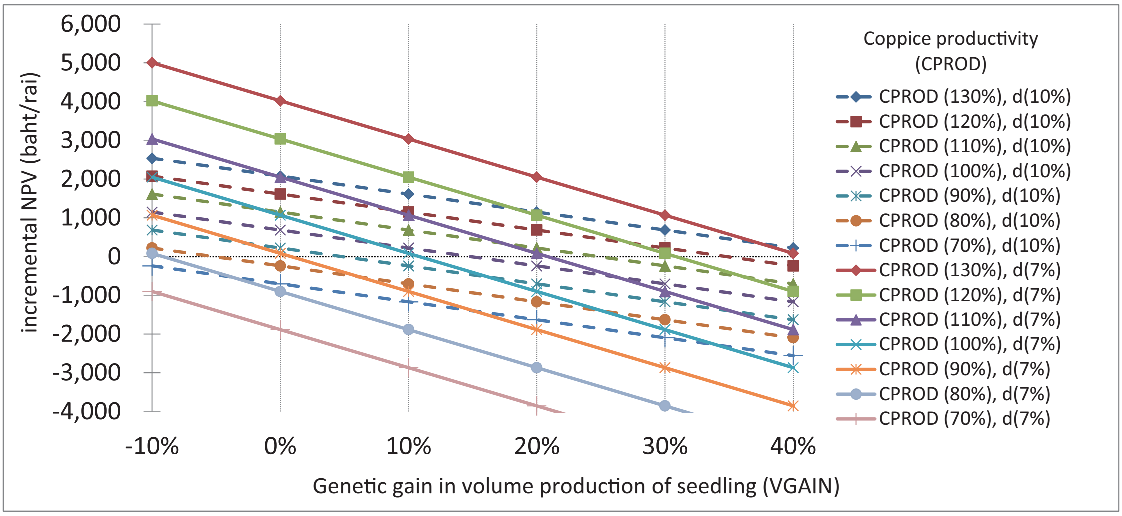
Variable	Unit	Description	Assumptions for variables		
			Base value	Range	Reference
CPROD	%	The percentage change in productivity of coppices in relation to the first rotation yield	100	80-120	Whittock et al.(2004)
VGAIN	%	The percentage genetic gain in volume production of seedlings over the first rotation	20	0-40	Whittock et al.(2004)
r	%	The percentage cost gain in land preparation, slash and burn to plant seedlings over the first rotation	50	0-100	Whittock et al.(2004)
LogPrice5	baht/m^3	The teak log price yielded at the 5 years old	1,500	1,350-1,650	RFD(2006)
LogPrice10	baht/m^3	The teak log price yielded at the 10 years old	3,000	2,700-3,300	RFD(2006)
LogPrice15	baht/m^3	The teak log price yielded at the 15 years old	5,000	4,500-5,500	RFD(2006)
LogPrice20	baht/m^3	The teak log price yielded at the 20 years old	7,000	6300-7700	RFD(2006)
d	%	Discount rate	10	8-12	Niskanen (1998)
Y	m^3/rai	Yield volume	-	-	-

Table 5. Rank correlations for NPVs including incremental NPV

Rotation period 15 years; plant spacing 4 m × 4 m				
Variable	1R	2R seedling	2R coppice	incremental NPV
CPROD	-	-	0.21	0.67
VGAIN	-	0.19	-	-0.66
r	-	-0.06	-	0.16
d	-0.92	-0.92	-0.91	0.17
LogPrice5	0.08	0.07	0.07	-0.02
LogPrice10	0.19	0.16	0.17	-0.01
LogPrice15	0.33	0.29	0.30	-0.03
Rotation period 15 years; plant spacing 3 m × 3 m				
Variable	1R	2R seedling	2R coppice	incremental NPV
CPROD	-	-	0.22	0.67
VGAIN	-	0.20	-	-0.67
r	-	-0.06	-	0.15
d	-0.91	-0.91	-0.90	0.15
LogPrice5	0.12	0.11	0.11	-0.02
LogPrice10	0.19	0.17	0.17	-0.02
LogPrice15	0.32	0.27	0.28	-0.03

Rotation period 20 years; plant spacing 4 m × 4 m				
Variable	1R	2R seedling	2R coppice	incremental NPV
CPROD	-	-	0.10	0.66
VGAIN	-	0.09	-	-0.65
r	-	-0.02	-	0.10
d	-0.97	-0.97	-0.97	0.27
LogPrice5	0.04	0.04	0.04	0.00
LogPrice10	0.09	0.08	0.08	-0.01
LogPrice15	0.10	0.09	0.09	-0.01
LogPrice20	0.19	0.17	0.17	-0.03
Rotation period 20 years; plant spacing 3 m × 3 m				
Variable	1R	2R seedling	2R coppice	incremental NPV
CPROD	-	-	0.10	0.66
VGAIN	-	0.10	-	-0.65
r	-	-0.02	-	0.11
d	-0.96	-0.97	-0.96	0.24
LogPrice5	0.04	0.04	0.04	0.00
LogPrice10	0.09	0.08	0.08	-0.01
LogPrice15	0.10	0.09	0.09	-0.01
LogPrice20	0.20	0.18	0.18	-0.03

(a) Rotation period 15 years; plant spacing 4 m × 4 m



(b) Rotation period 15 years; plant spacing 3 m × 3 m

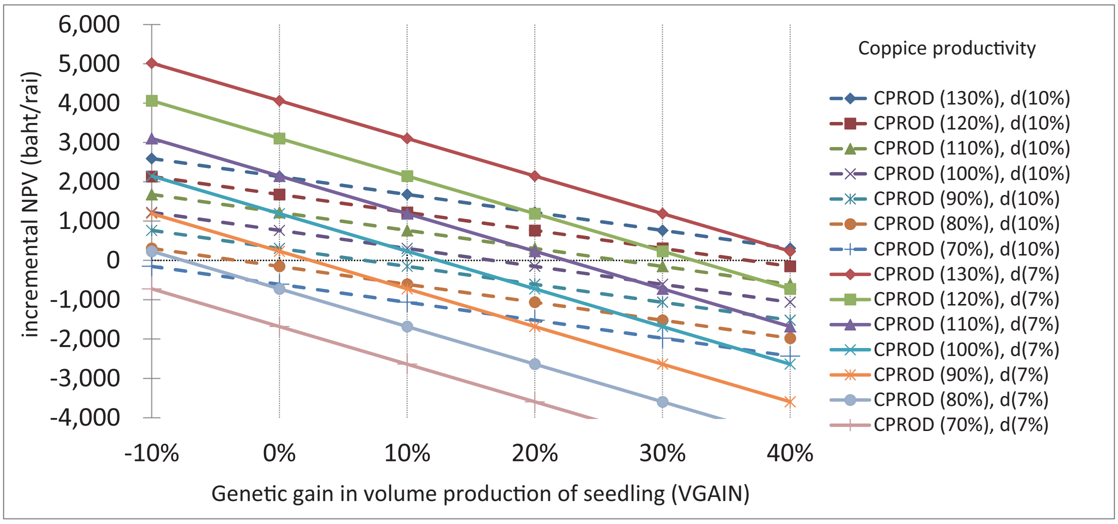
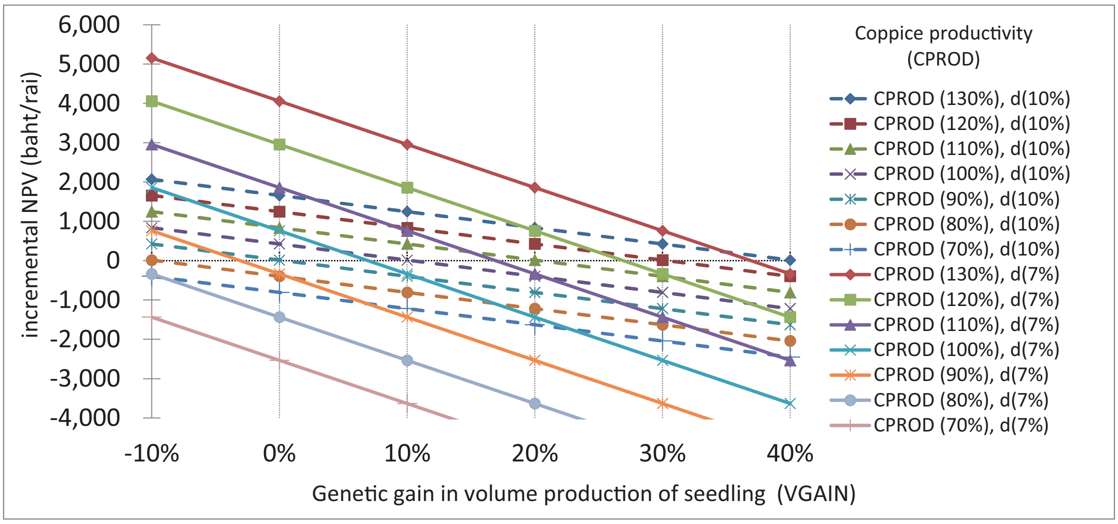


Fig. 1. Relationship between the combination of coppice productivity, seedling genetic gain and incremental NPV

(c) Rotation period 20 years; plant spacing 4 m × 4 m



(d) Rotation period 20 years; plant spacing 3 m × 3 m

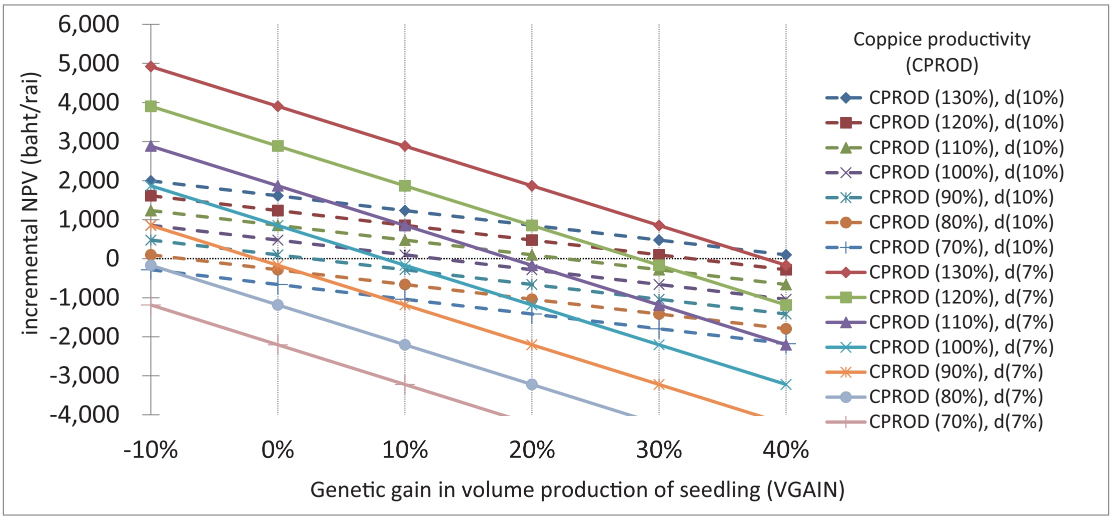


Fig. 2. Relationship between the combination of coppice productivity, seedling genetic gain and incremental NPV (cont'd)

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Case studies on enterprise types of processing and sales of planted teak timbers

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Abstract

To examine the processing and sales of planted teak timber in Thailand, we analyzed the behavior of the Lop Buri Private Forest Plantation Cooperative Limited (PFPC) and Tha Sao Sawmill LTD., Partnership (Tha Sao Sawmill) as excellent examples, and the Nong Bua Lam Phu PFPC as an example targeting efforts to strengthen and stabilize future management. It was clear that the Lop Buri PFPC had received economic support, largely from an influential member of the cooperative and had many customers to match the supplies around Lop Buri city, hence its management was stable. It was also clear that most of the teak furniture materials consumed in Tha Sao Sawmill's factory were delivered from the companies' own planted forests and used specific techniques for the coating process, which gave it a sales advantage over other companies. Conversely, the Nong Bua Lam Phu PFPC, located in northeastern Thailand, lacked such advantages. Accordingly, recapitalization of the latter cooperative was considered inevitable to strengthen and stabilize its management.

Keywords: teak plantation, forest plantation, Cooperative Limited, teak furniture

Introduction

The Royal Forest Department (RFD) has widely developed teak plantations in Thailand from 1994 to 2001 because of the severity of the loss of natural teak forests (Yokota et al. 2009). The teak forests which were planted during this period have matured and some have already been harvested and utilized. In the meantime, several Private Forest Plantation Cooperatives Limited (PFPCs) were founded under the guidance of RFD for the development of forest management by private forest owners (Himmapan et al. 2010). A large part of their main businesses involved the harvesting and processing of teak trees (Furuya et al. 2012)

As previously stated, the majority of sales of wood products derived from natural teak forests occurred before the 1990's in Thailand. The management of teak plantations and the utilization of teak wood derived from plantations is major concern because of the decline in natural teak resources in the last 16 years. Therefore, objective of this study is to grasp the actual situation of 3 cases which product and sale teak wood products. We analyzed the behavior of the Tha Sao Sawmill LTD., Partnership and Lop Buri PFPC as excellent examples. Tha Sao Sawmill has developed teak plantation in private comparatively since 1980's. Lop Buri PFPC has managed own teak wood saw mill. We analyzed the Nong Bua Lam Phu PFPC as an example targeting efforts to strengthen and stabilize future management (Fig.1).

A report by Furuya et al. (2012) described the current functions and expected roles of some PFPCs, including Lop Buri PFPC and Nong Bua Lam Phu PFPC. In another study, Himmapan et al. (2010) described the current situation and management solutions implemented at Nong Bua Lam Phu PFPC. The present study aims to clarify the point of improvement on Nong Bua Lam Phu PFPC more sharply, comparing with advantage of Tha Sao Sawmill and Lop Buri PFPC.

Method and materials

In July 2012, the President of Tha Sao Sawmill in Uttaradit Province, the President of Lop Buri PFPC in Lop Buri Province, and the leading committee member of Nong Bua Lam Phu PFPC in Nong Bua Lam Phu Province were interviewed. The excellent function and successful practices of the Lop Buri PFPC and Tha Sao Sawmill were analyzed, and the function and practices of Nong Bua Lam Phu PFPC were analyzed as an example in targeting efforts to strengthen and stabilize future management.

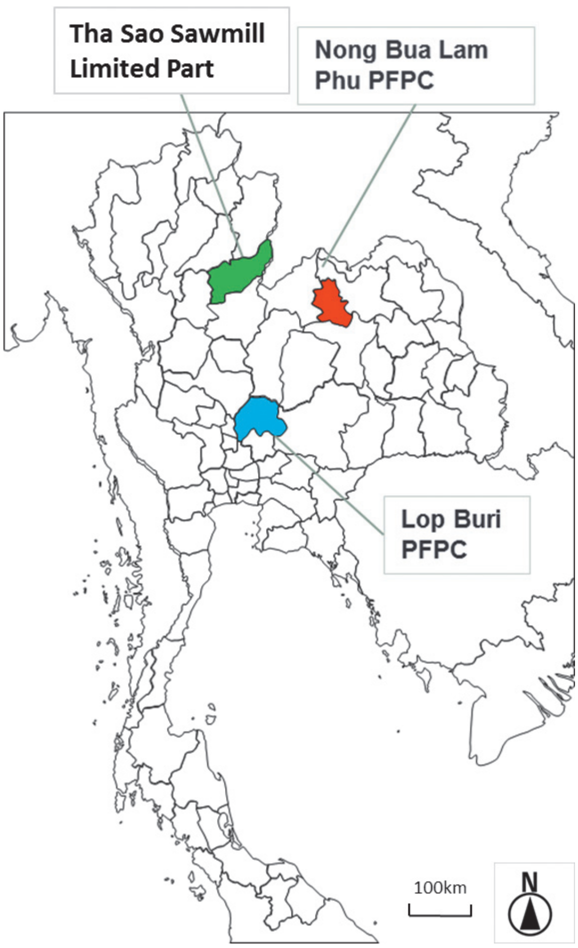

Fig. 1. Location of investigation examples

Results

Tha Sao Sawmill

In 1979, the father of the current President established the Tha Sao Sawmill Limited Partnership, and in 1984, he began to plant teak creating a small-sized plantation. A large-scale plantation was developed in 2002, and the size of the plantation was approximately 600 ha (3,500 rai) in 2012.

The planted teak trees have just matured in recent years, and material supplied from its own teak plantation is handled. The whole of the teak plantation area is located in Uttaradit Province; therefore, the cost of unprocessed teak transportation to the saw mill was relatively low.

One successful characteristic of the company was that they had set up integrated production systems through felling, sawing, and furniture making. They regularly used approximately 4,000 m3 of logs/month, and most of the products were made to suit the Western culture. Consequently, their products created a different demand from that of traditional Thai.

One of their unique technical characteristics was the use of an anti-UV treatment coating on their wood products. The technique produced a luster on the wood products and improved durability. Tha Sao Sawmill was the only company to use this technique in Thailand at the time of research in 2012, and therefore produced superior wood products when compared with other teak manufacturers. Furthermore, the company used an important sales strategy whereby they only sell their products to their directly managed shops. The company had a nationwide sales network in Thailand; shops are located in Bangkok (Fig.2), Chiang Mai, Phuket, Chon Buri, and Surat Thani.

Fig. 2. Tha Sao Sawmill’s shop in Bangkok.

Tha Sao Sawmill is located in Uttaradit Province in the Northern part of Thailand where teak trees grow naturally. This brings an important advantage on Tha Sao Sawmill's products because teak wood products made in this area are considered to be of excellent quality. Therefore, this background research confirmed that the products had a reputation as an excellent local brand, namely "TS-teak", and the company sold their products nationwide.

Lop Buri PFPC

Lop Buri PFPC was established in 2000 with 110 members, but the number of members has gradually increased through invitation by existing members. Consequently, there were 193 members in PFPC, with an average age of over 60 years in 2012.

Almost half of the members lived in Bangkok or around Bangkok. The main business of most of the members was not forestry, and although their main business interests varied, most of the members chose teak plantation as a secondary business, which was less labor-intensive, and converted their land use from cash crops to teak plantation. The members owned 30–1,000 rai of land, including individual farms, and manage 20–400 rai of teak plantation. Over time, the members whose main business was farming have decreased. Although some members live in Lop Buri Province and their main business was farming, they only managed a relatively small area of plantation, which was approximately 50 rai.

Important services offered by Lop Buri PFPC were the management of a teak wood saw mill, the provision of information to members concerning business and technical advice, and conducting a study tour. The committee, which consisted of 7 members, met every 3 months and made important decisions about Lop Buri PFPC's activities.

Lop Buri PFPC was well managed and made a profit from a teak wood saw mill (Fig.3). The provision of good management allowed the members to receive dividends amounting to 10% of their annual contribution.

The cooperative's teak wood saw mill is located in the suburbs of Lop Buri City. One of the influential members owned the saw mill site and machines, and it was rented to the cooperative at a relatively low amount, thus saving the cooperative's money. Although the management of the cooperative's teak wood saw mill depended on an influential member, the merit of management based on a cooperative system was the steady capability to procure teak wood from a plantation belonging to many members.

In total, 21 people living in the neighboring area were employed at the teak wood saw mill. Of these employees, 4 work in the saw mill section, 7 work in the transportation section, and 10 work in the furniture making section, in which 3 of these employees were veterans and skilled engineers. The remaining 7 employees were apprentices in the furniture making section and had only been employed for a short time. It was anticipated that these 7 apprentices would be skilled furniture makers in the future, but this might not be the case and was dependent on their disposition. The apprentices were paid a daily wage, which encouraged them to come to work every day. By motivating employees in this way reduced the issue of managing difficulties at the saw mill.

Fig. 3. Furniture factory managed by Lop Buri PFPC

A variety of different types of teak timber were used at the saw mill. Long and straight teak woods were used for flooring, walls, or ornaments, whereas short and uneven teak wood was used for furniture, such as chairs.

The majority of purchasers of the custom-made teak furniture were ≥40 years old and were residents of the neighboring areas who had obtained retail information by mouth to mouth communication. Although 90% of purchasers bought teak furniture from Lop Buri PFPC for themselves, 10% of purchasers own furniture shops and bought teak furniture to sell at their shops. Teak timber was also sold to local carpenters; 80% of carpenters lived in Lop Buri city and 20% resided in suburbs of Lop Buri city. Customers from Bangkok seldom came to buy their products.

Lop Buri PFPC was selling 60% of their total products as timber and 40% was sold as furniture. Total profits from timber sales were approximately 80% and from furniture sales were approximately 20% in 2011. Thus, more profit was gained from timber production than from furniture making.

The unprocessed teak wood used at the PFPC's saw mill was transported from the cooperative member's teak forest to the saw mill's wood yard after the members had cut the teak timber. The timber prices paid to members were based on the prices which the Forestry Industry Organization (FIO) has regulated at that time. In some cases, the PFPC's saw mill bought unprocessed teak wood from members at a higher price than the current price in the neighborhood. The saw mill manager considered that such cases could motivate the member's own teak forest management.

The manager of the saw mill believed that improvement of product quality and furniture design, adding a higher value on the products, and diversification of products were required for the future.

Nong Bua Lam Phu PFPC

Nong Bua Lam Phu PFPC was established in 2000 with 70 members and has expanded to 303 members in 2012, as a result of active invitation by PFPC's leading members.

In 2002, a saw mill and factory were set up adjacent to the PFPC office. But the land of saw mill and factory were not belong to PFPC. The function of the PFPC was limited to business consultations and guidance for members in 2012.

The committee consists of 13 members who met twice a month and made important decisions about Nong Bua Lam Phu PFPC's activities. The PFPC provided information through regional representative members to the local members. As mentioned above, the current service of the PFPC was limited to business consultations and guidance for members; therefore, the committee considered that it was very important to build a good relationship of trust between the PFPC and each member.

Nong Bua Lam Phu PFPC was established at the time when teak plantation had been highly promoted by the government, resulting in many farmers being interested in planting teak trees on their farm land. The government promotion has now ceased; therefore, farmers rarely planted new teak plantations. Most of the teak trees planted were not yet mature and were at the stage for thinning, and it was rare for any farmer to conduct clear-cutting at this point. However, once a farmer had conducted clear-cutting of the teak forest, the farmer tended to change to pant other species.

On an average, teak forest plantation of 30 rai (approximately 5 ha) was managed by each member, and in most cases only teak trees were planted on their forestry land. They also owned an average of 30 rai of farm land, and in many cases they rotated cash crops.

Farmer members planted teak trees intending to use the wood to build their houses in the near future or to supply a source of revenue for the next generation. Hence, they did not expect a yearly income from their forestry and looked forward to mature teak trees for clear-cutting with proper thinning.

Members obtained technical information about teak plantation from RFD through the PFPC, and most of them decided the timing for thinning individually. The majority of thinned teak wood was transported to the saw mill adjacent to the PFPC office.

There were two ways in which some members cut and sold teak trees. One was by cutting the trees themselves and the other was the sale of standing trees. When members cut trees and transported them to the PFPC factory by themselves, they got paid for the timber at the time of their arrival. Conversely, when members chose to sell standing trees, they were paid cash after subtracting the felling cost from the total teak wood price at the time of felling. It was estimated that the ratio of felling of trees by members was approximately 60%, and the sale of standing trees was approximately 40%.

Usually, when some members conducted clear-cutting of 15 years old trees on their teak plantation, they obtained approximately 30 tons (approximately 60 m^3) of teak wood/ rai. In this case, it was proposed that the total teak wood price would be 300,000 Baht and the felling cost would be 100,000 Baht. The actual teak wood price was revised every 2 years and was determined by referring to the price stated by FIO or from information from RFD. The PFPC mediated between its members and the felling company, and the intermediary fee was an important source of income for the PFPC.

There was no rule that members had to sell their teak wood to the PFPC factory, but in fact most of the members did sell their teak wood to the factory. There were some members who conducted clear-cutting and sold their teak woods intending to convert the plantation species.

The business of the PFPC was not only limited to the presentation of information to the members and mediation between its members and the felling company but also the source of income was limited. Therefore, the PFPC was planning to set up its own saw mill and factory in 2012 so that the profit could be returned to its members. To execute this plan, the PFPC needed to receive additional capital because of insufficient original funds.

Discussion

Table 1 shows the features of the 3 cases which were interviewed and mentioned above. It can be seen that most of the material used to manufacture teak furniture in Tha Sao Sawmill's factory was produced by the companies' own teak forests and that used specific techniques for the furniture coating process, which gave it a sales advantage over other companies. It has also been shown, that Lop Buri PFPC had received economic support, largely from an influential member of the cooperative, and supplied to many customers around Lop Buri City; therefore, it can be concluded that its management is stable.

Conversely, Nong Bua Lam Phu PFPC, which was located in the North-Eastern region of Thailand, lacks such advantages. The fact that Nong Bua Lam Phu PFPC did not manage not only its own saw mill and factory but also its own land meant that the recapitalization of Nong Bua Lam Phu PFPC was considered inevitable to strengthen and stabilize its management and capital.

The management of Lop Buri PFPC paid an annual dividend to the members, supposedly to ensured that the members were motivated by that profit to keep their teak forest plantations. Conversely, it was not so easy for Nong Bua Lam Phu PFPC's members to keep up their motivation to manage their teak plantations for the future. Therefore, it may be expected that some members are inclined to change the plantation tree species to another more profitable one. Although the acquisition of new capital and the setting up of a new factory are difficult tasks for Nong Bua Lam Phu PFPC, these operations were expected to be promptly conducted considering these situations.

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Table 1. Comparison of investigation example

	Tha Sao Sawmill	Lop Buri PFPC	Nong Bua Lam Phu PFPC
Year of the establishment	1979	2000	2000
Business content	Management of teak plantation	Processing of teak wood products	Advising for teak plantation
	Processing of teak wood products	Advising for teak plantation	Arrangement for the buying and selling teak woods
	House building		
Product	Teak furniture, Flooring material, House	Teak wood products, Teak furniture	
Sales contact and marketing area	5 directly managed shop in Thailand	Lop Buri city and neighborhood area	
Characteristic of the products, sales and organization	Integrated production systems through felling, sawing, and furniture making	High demand in Lop Buri city and neighborhood area	
	Products are made to suit the Western culture	Strong support from one of the influential members	
	Specific techniques for the furniture coating process	Dividends to the members	

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