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Effects of Two-Stage Thinning of Coppices on Growth and Stem Conditions in a Clear-Cut Teak (*Tectona grandis* L.) Plantation in Thailand

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Abstract

We empirically examined coppice growth characteristics after one- and two-stage thinning in a coppiced teak plantation (2 × 4 m plant spacing) in Nong Bua Lamphu, Thailand, in June 2011. For the one-stage thinning, we thinned all but one sprout per stump (P1), while in the two-stage thinning, we thinned all but two sprouts per stump in the first thinning and a dominant sprout per stump (P2ds) in the second thinning 4 years later. Teak trees were clear-cut at 15 years old in December 2010 at the study site; their growth and stem condition data were available until 8.6 and 4.5 years, respectively. The relative growth rate was estimated by integrating hierarchical Bayesian modeling with a generalized linear mixed model to determine the treatment effects. P2ds caught up with P1 in both diameter at breast height and tree height by year 7 ($P > 0.05$). At year 4.5, P2ds showed 86% healthy coppices, whereas 74% of P1 were healthy due to wind damage within ~2 years of the first thinning. Self-thinning was implied to occur in year 5 for both treatments. In year 4, the growth diameter decelerated, with asymptotically decreasing relative spacing indices of 23 and 20 on the one- and two-sprout plots, respectively. On growth and stem conditions, two-stage thinning showed higher potential than one-stage thinning for teak reforestation under coppice regeneration.

Discipline: Forestry
Additional key words: hierarchical Bayesian modeling, mixed effects model, relative growth rate, relative spacing index, sustainable forestry

Introduction

Teak (*Tectona grandis* L.) is a high-value hardwood in the market; therefore, interest in nature-based and sustainable teak forestry for rural development has increased, along with environmental awareness (Kollert & Cherubini 2012, Kollert & Kleine 2017). In Thailand, teak plantations on private land were initiated following the afforestation support project in 1994, mostly involving small-scale farmers (Mahannop 2004). Niskanen (1998) reported that teak is more profitable than *Eucalyptus camaldulensis* Denhn. in the following three types of Thai forestation: intensive industrial plantations, relatively extensive plantations in communities, and agroforestry or forest farming. However, Noda et al. (2004) highlighted that although teak plantations by small-scale Thai farmers are more profitable than eucalyptus plantations owing to the low input–output ratio based on cash-flow analysis, the initial cost—including planting expenses—is high; no income is obtained until the trees reach a marketable size. Simultaneously, teak plantations are believed to recover by coppicing (Bailey & Harjanto 2005, Kadambi 1972, Tewari 1992), which can reduce the initial cost and have a higher profitability than tree planting (Noda & Himmapan 2017).

Teak has a remarkable ability to regenerate following coppicing (Kadambi 1972), but much of the vigorous

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sprout growth can be lost after several years (Bailey & Harjanto 2005, Minghe & Ritchie 1999). Indeed, Auykim et al. (2017) reported that teak plantations managed by the Thai Forest Industry Organization (FIO) in northern Thailand showed coppices with limited growth in year 9 following a rapid growth stage between years 1-4 of the diameter at breast height (DBH), compared to planted trees. In the FIO teak plantations, the best sprout per stump has been reserved in a thinning treatment since 2003, after a coppice regeneration system following clear-cutting initiated in 2001 (Himmapan & Noda 2012).

Thinning of sprouts on a stump is an important operation in coppice management for pole production (Evans & Turnbull 2004, UK Forestry Commission 2014, Yano et al. 1966) and is usually performed in two stages. For example, in southern Swaziland, *Eucalyptus grandis* coppice is thinned to 3-4 sprouts per stump, followed by a second thinning to retain only one or two sprouts (Evans & Turnbull 2004). An advantage of two-stage thinning over single-stage thinning is that the remaining sprouts offer more opportunities to select and maintain quality stems after the first thinning. However, this thinning type is more time- and cost-consuming (Bailey & Harjanto 2005).

In Indonesia, thinning demonstrated the benefit of managing teak coppices by thinning to the single healthiest stem based on 2-year trials with 4- to 6-year-old coppices (Roshetko et al. 2013). However, the study assessed a short period of the growing phase during years 4-6. Moreover, although the optimal number of sprouts per stump after thinning is dependent on factors such as tree species, stump size, and stand density (Evans & Turnbull 2004, Yanagiya et al. 1966, Yano et al. 1966), there are few studies on teak coppice regeneration focused on not only one but also multiple sprouts per stump.

Therefore, in this study, we pursued the following objectives: 1) Assessing the tree size (measured as DBH and tree height) and stem condition of one and two sprouts per stump achieved by thinning following clear-cutting in a teak plantation; 2) comparing the relative growth rate (RGR) and stem conditions between one sprout per stump (P1) and the dominant of the two sprouts per stump (P2ds); and 3) evaluating the potential of two-stage thinning in coppice management of teak plantations, which reserves two dominant sprouts per stump in a first thinning and removes a suppressed sprout in a second thinning at a suitable time.

Materials and methods

1. Study site

The study was carried out at a private teak plantation (0.32 ha, 17° 24′ N, 102° 14′ E, 251 m a.s.l) in Nong Bua Lamphu Province, northeastern Thailand. The area has a tropical savanna climate (Aw) (Beck et al. 2018), characterized by a wet season beginning in May—with maximum monthly rainfall values in August or September—and a dry season spanning from November to March (Phien et al. 1980). Between 1991-2020, the mean annual rainfall was 1,290 mm, while monthly mean rainfall and temperature values ranged from 7.5 to 229.9 mm and 24.1 to 30.6°C, respectively (Thai Upper Northeastern Meteorological Center 2023). The land is flat, and the site is categorized as a medium grade on a descending soil suitability class (1 to 5) for teak plantation, namely "3g," limited by gravel mix or shallow soil (Noda et al. 2012, Sukchan & Noda 2012). Cassava and other cash crops were cultivated prior to this plantation, with teak trees planted at intervals of 2 × 4 m in 1996. Before December 2010, when all the trees were cut, the forest had not been thinned in 15 years. Although chemical fertilizers were applied to seedling roots when planted, no fertilizers have been used since. The teak coppices were allowed to sprout until January 2011, and the land was weeded once a year before each measurement.

2. Experimental design and field survey

In June 2011, we set up an experimental area covering one- and two-sprout plots with one plot (20 × 40 m) per treatment in the plantation. Thinning of coppices was implemented to thin surplus sprouts to the best or two best sprouts per stump. The sprouts of one-sprout stumps were named P1, while the dominant and secondary sprouts of two-sprout stumps were named P2ds and P2ns, respectively. There were 105 P1 and 95 P2 stumps. The difference in number is attributed to some of the trees having been planted at wider or narrower distances than 2 m intervals; however, most stumps had a regular spacing of 2 × 4 m. Stump diameters did not differ between the P1 plot (13.2 ± 2.9 cm) and the P2 plot (13.8 ± 4.0 cm) by Welch's t-test ($P > 0.05$).

The DBH and tree heights of all sprouts (P1, P2ds, and P2ns) were measured six months after clear-cutting and once a year from June 2011 until July 2019. Additionally, coppice stem conditions were also recorded in June and December 2011, June 2012, and annually until June 2015 to assess wind damage in the early stages. Coppice stem conditions were categorized into five classes in descending order from most severe to least severe in terms of prospects for recovery potential during early sprout growth in this study: dead or no sprouting (Class 5), leaning more than 30º near the point of attachment to the stump (Class 4), forked part being one-third or more of the tree height (Class 3), the upper part of coppice stem bending more than 30º (Class 2), and others, i.e., best conditions (Class 1).

The second thinning of the two-stage treatment in the P2 plot was conducted by removing all P2ns sprouts after a survey in June 2015. The removal timing was determined based on when the diameter growth rate of P2ds equaled that of P1. We investigated how sole P2ds sprouts on a stump responded after P2ns removal.

3. Data analysis

Tree sizes were surveyed throughout the study period to investigate the diameter and height of coppices after thinning, and statistical analysis was conducted. The Games-Howell test was used to identify significant differences between P1, P2ds, and P2ns until the survey in June 2015. After removing all P2ns following the survey in June 2015, the differences between P1 and P2ds were evaluated by Welch's t-test.

To compare the growth of P1 and P2ds sprouts, we calculated the RGR of the DBH and height at each survey interval (Eq. 1). RGR is a standardized measure of growth (Hunt 1989) that allows assessment of the growth performance and efficiency of plants and plant populations (Pommerening & Muszta 2015).

$$\mathrm{RGR} = [\ln{(D_1)} - \ln{(D_0)}]/T, \quad (1)$$

where D_0 and D_1 represent the initial and final plant sizes, respectively, and T is the respective time interval of the period between surveys, annualized by the number of months (Feeley et al. 2007, Kenzo et al. 2011). The periods for calculating RGR were June 2011 to June 2012, June 2012 to June 2013, and June 2018 to July 2019, for a total of eight periods.

For P1 and P2ds, we calculated the plot ($\mathrm{RGR}_{\mathrm{plot}}$) and individual ($\mathrm{RGR}_{\mathrm{sprout}}$) RGRs by combining hierarchical Bayesian modeling (HBM) with a Markov chain Monte Carlo (MCMC) simulation (Clark et al. 2003, Condit et al. 2006, Matsuura 2022). HBM can exploit diverse sources of information to accommodate unknown influences such as individual and group specification; moreover, it enables inference from latent variables and parameters that describe complex relationships (Clark 2005, Matsuura 2022).

To compare RGRs between P1 and P2ds, we applied a generalized linear mixed model with fixed effects of treatment and a random effect of individual differences. We assumed that an expected RGR of the individual sprout i, $\bar{G_i}$ was expressed by a linear predictor $\alpha + \beta F_{j(i)} + r_i$ and a log link function (Bolker et al. 2009, Gelman & Hill 2006, Kubo 2012).

For the individual sprout i at an RGR calculation period, $\bar{G_i}$ is shown as Eq. 2:

$$\bar{G_i} = \exp\left(\alpha + \beta F_{j(i)} + r_i\right) \qquad j(i) \in \{\mathrm{P1}, \mathrm{P2ds}\}, \quad (2)$$

where both α and $\beta F_{j(i)}$ are fixed effects; $F_{j(i)}$ is a dummy variable ($F_{j(i)} = 0$, if $j(i) = \mathrm{P1}$; $F_{j(i)} = 1$, if $j(i) = \mathrm{P2ds}$); and r_i is a random effect of individual difference. When slope β is negative, the $\bar{G_i}$ of P1 is higher than that of P2ds, whereas it is lower when slope β is positive.

We assumed the $\mathrm{RGR}_{\mathrm{sprout}}$ of individual sprout i, G_i had a lognormal distribution (Condit et al. 2006, Feeley et al. 2007), which has two parameters, μ_i and σ_{G}, related to scale and shape, respectively (Forbes et al. 2011) (Eq.4). The lognormal distribution has an expected value defined as $\bar{G_i} = \exp(\mu_i + {\sigma_{\mathrm{G}}}^2/2)$. The parameter μ_i is expressed using the linear predictor $\alpha + \beta F_{j(i)} + r_i$ in Eq. 2 as shown in Eq. 5, derived from Eq. 2 and the expected value equation of lognormal distribution (Gelman & Hill 2006, Kubo 2012). The random effect r_i was assigned a hierarchical prior distribution, with the mean 0 and standard deviation σ_{r} (Eq. 6).

Observations of $\mathrm{RGR}_{\mathrm{sprout}}$ based on measured values (Eq. 1) can include measuring errors and accidental changes in tree top form or bark moisture differences and bark loss between remeasurements (Auykim et al. 2017). Condit et al. (2006) and Feeley et al. (2007) set minimum and maximum values for the diameter growth rate to prevent it from being negative or zero. The likelihood function between observed $\mathrm{RGR}_{\mathrm{sprout}}$ (M_i) and estimated $\mathrm{RGR}_{\mathrm{sprout}}$ (G_i) was assumed based on a normal distribution with a standard deviation σ_{M} (Itoh 2015, Masaki et al. 2013, Masaki et al. 2017) (Eq. 3). For the individual sprout i at an RGR calculation period, our model is as follows:

$$M_i \sim \mathrm{Normal}(G_i, \sigma_{\mathrm{M}}), \quad (3)$$

$$G_i \sim \mathrm{Lognormal}(\mu_i, \sigma_{\mathrm{G}}), \quad (4)$$

$$\mu_i = \alpha + \beta F_{j(i)} + r_i - {\sigma_{\mathrm{G}}}^2/2 \quad j(i) \in \{\mathrm{P1}, \mathrm{P2ds}\}, \quad (5)$$

$$r_i \sim \mathrm{Normal}(0, \sigma_{\mathrm{r}}). \quad (6)$$

In this model, α and β were estimated from noninformative prior distributions (Eqs.7-8); standard deviations σ_{M}, σ_{G}, and σ_{r} were estimated from a weakly informative prior distribution (Eqs. 9-11) where a half-Student's t-distribution (Student_t^{+}($\upsilon = \upsilon_0$, $\mu = 0$, $\sigma = \sigma_0$)) was used to improve the posterior distribution with long tails for noninformative priors (Matsuura 2022). For positive parameters, noninformative priors are the first choice; however, weakly informative priors are often used to stabilize MCMC algorithms and avoid posterior distributions with extremely long tails when there are small amounts of data distribution (Korner-Nievergelt et al. 2015, Matsuura 2022). We used the scale σ (σ_0) of 0.5 in reference to σ_{M}, σ_{G}, and σ_{r} posteriors with a Uniform (0, 100) of noninformative distribution, and used degree of freedom (υ_0) value of 4 (Eqs. 9-11):

$$\alpha \sim \mathrm{Normal}(0{,}100), \tag{7}$$

$$\beta \sim \mathrm{Normal}(0{,}100), \tag{8}$$

$$\sigma_{\mathrm{M}} \sim \mathrm{Student\_t}^{+}(4{,}0{,}0.5), \tag{9}$$

$$\sigma_{\mathrm{G}} \sim \mathrm{Student\_t}^{+}(4{,}0{,}0.5), \tag{10}$$

$$\sigma_{\mathrm{r}} \sim \mathrm{Student\_t}^{+}(4{,}0{,}0.5). \tag{11}$$

For plot j, as shown in Eq.12, $\mathrm{RGR}_{\mathrm{plot}\,j}$ was calculated as an average of the expectation value of $\mathrm{RGR}_{\mathrm{sprout}}$ derived in Eq.2 using posterior estimates of α, β, and r_i, where $F_{j(i)}$ is a dummy variable.

$$RGR_{\mathrm{plot}_j} = \begin{cases} \sum_i \frac{\exp(\alpha + r_i)}{N_j} & i \in \mathrm{P1}, j = \mathrm{P1} \\ \sum_i \frac{\exp(\alpha + \beta + r_i)}{N_j} & i \in \mathrm{P2ds}, j = \mathrm{P2ds} \end{cases}, \tag{12}$$

where N_j is the number of individuals in plot j.

An MCMC sampling for DBH and tree height was conducted for each period from the first to the eighth period, respectively.

An MCMC sampling was run after an initial burn-in period, with three chains and 10,000 iterations per chain. For each run, the burn-in period included enough iterations to not depend heavily on the initial value; after the burn-in period, the draws could be regarded as the MCMC sample from the posterior distribution by drawing a trace plot (Matsuura 2022). The MCMC samplings converged with R-hat < 1.02 for all parameters using the Gelman-Rubin R-hat statistic (Gelman & Rubin 1992, Gelman et al. 2013). The 95% credible intervals (CreIs) of $\mathrm{RGR}_{\mathrm{plot}}$ and $\mathrm{RGR}_{\mathrm{sprout}}$ were set as the 2.5% and 97.5% quantiles of the HBM estimates.

To investigate the adequacy of our RGR estimates, we compared the HBM estimates to the observed values based on non-Bayesian methods that incorporate negative growth measurements in terms of mean and 95% confidence interval (CI) range at each period. For evaluating the differences in overall periods, we calculated the root mean square of the difference (RMSD) between the observed values and HBM estimates (Jamieson et al. 1991) (Eq. 13):

$$\mathrm{RMSD} = \sqrt{\sum_{t=1}^{N} (y_t - \hat{y}_t)^2 / N}, \tag{13}$$

where N is the number of periods (N=8); at period t, y_t is an observed mean, and $\hat{y}_t$ is the corresponding HBM estimated mean.

We used R v4.2 (R Core Team 2022) for all analyses and Stan v2.26 (Stan Development Team 2021) for the HBM estimations. In a Stan program, following Eqs. 3-11 coded in the parameters block and model block, Eq. 12 was performed in the generated quantities block to apply posterior inference.

Results

1. Changes in the size of teak coppices

During the period in which P2ns was retained, the DBH and height of P1 sprouts exceeded those of P2ds after years 2.5 and 3.5, respectively (Fig. 1). From year 1.5 onward, P2ns had the smallest DBH and height, while the differences among the groups increased by small degrees until the end of year 4.5. The DBH and height values in year 4.5 were 9.0 ± 2.0 cm and 10.0 ± 1.7 m for P1, 8.0 ± 2.1 cm and 8.8 ± 2.0 m for P2ds, and 6.5 ± 1.8 cm and 7.5 ± 2.2 m for P2ns.

At year 4.5, the DBH and height mean values of teak coppices differed significantly between P1, P2ds, and P2ns (P1 > P2ds > P2ns) (Fig. 1). Two years after removing P2ns in year 4.5, there became no difference in DBH (10.4 ± 2.1 cm vs. 10.2 ± 1.9 cm) and tree height (11.7 ± 1.8 m vs. 11.3 ± 1.4 m) between P1 and P2ds.

After the removal of P2ns in year 4.5, P1 still showed greater DBH and height values than those of P2ds in year 5.5 (Fig. 1). However, there were no subsequent significant differences observed in their DBH and height values, with the gap between those of P1 and P2ds narrowed. In year 8.6, P2ds reached a DBH of 11.3 ± 2.2 cm and a height of 12.9 ± 1.7 m, while P1 showed a DBH of 11.2 ± 2.3 cm and height of 13.0 ± 2.0 m.

On tree crown development in plant spacing of 2 × 4 m, in the 2 m spacing, crowns of individual trees in both plots contacted those of neighboring trees in June 2014 and became sufficiently in crown closure in June 2015. However, in the 4 m spacing, the tree crowns came in contact with neighboring trees in July 2017 in both plots.

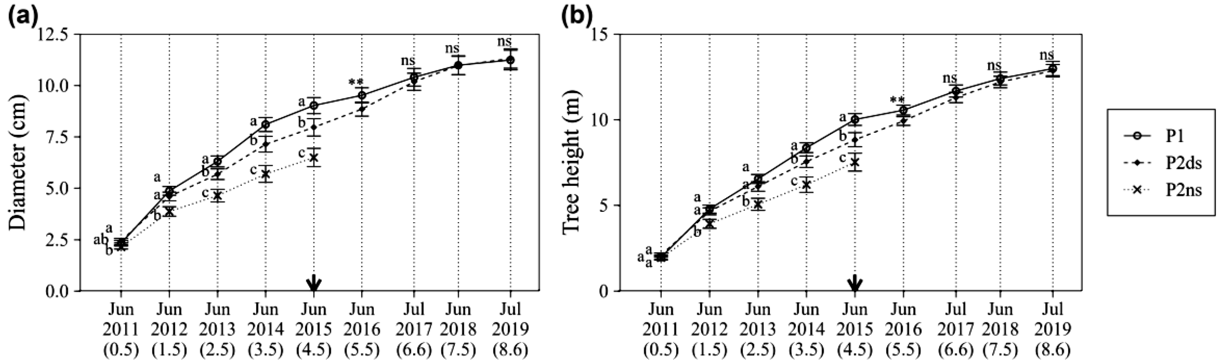

Fig. 1. Changes in diameter at breast height (a) and height (b) for coppices in the one-sprout plot and two-sprout plot managed by thinning of coppice teak

P1 represents a sprout reserved per stump in the one-sprout plot, while P2ds and P2ns show the primary and secondary of two sprouts reserved per stump in the two-sprout plot, respectively. Numbers in parentheses indicate the age in years after clear-cutting. In each survey timing, different letters indicate significant differences by the Games-Howell test at the 5% level; and the difference in P-value is shown by Welch's t-test (**: $P < 0.01$; *: $P < 0.05$; ns: no significance). Symbols and error bars indicate the means and 95% confidence intervals, respectively. Vertical lines and a downward arrow indicate the timing of each survey and when the second thinning was conducted by removing all P2ns sprouts after a survey in June 2015, respectively.

2. Comparison of relative growth rates on teak coppices

Based on the HBM estimates, we compared the RGRs of P1 and P2ds for DBH and height. The RGRs of both P1 and P2ds generally decreased with age, greatly dropping by third from years 1 to 2 (Fig. 2). Until year 4.5, the RGRs of P1 exceeded those of P2ds for both DBH and height on the whole (Fig. 2); however, the gap narrowed with increasing age because the coefficient β (Eq. 5) got closer the null expectation (β = 0), with an increase of 95% CreI (Table 1). The RGR of P2ds for DBH equaled that of P1 in the fourth period (years 3.5 to 4.5, namely, year 4), with the RGRs of P1 decreasing in year 5 and recovering the following year (Fig. 2).

After the removal of P2ns, the RGRs of P2ds typically exceeded those of P1, although the height RGR values were comparable from year 7 onward (Fig. 2).

There were few differences between the RGR means estimated with HBM and the observed values for both P1 and P2ds across all intervals. The differences and RMSD were within ±0.01 cm cm^{-1} y^{-1} and < 0.00 cm cm^{-1} y^{-1} for DBH and within ±0.01 m m^{-1} y^{-1} and < 0.00 m m^{-1} y^{-1} for height, respectively (Appendix Table). However, the 95% CreI or CI of plot RGR determined using HBM estimates were narrower than those using observed values for both P1 and P2ds at all intervals (Appendix Table).

3. Differences in coppice stem conditions

The proportion of Class 1 sprouts was 91% for both P1 and P2ds in year 0.5; this proportion decreased to 73% in P1 and 89% in P2ds by year 1.5 (Fig. 3). The number of Class 4 sprouts increased in P1 compared with those in P2ds between years 1 and 1.5: 11% vs. 1% and 18% vs. 1% of sprouts, respectively. In year 2.5 and onward, the Class 1 proportions in P1 and P2ds were ~74% and 86%, respectively, with no evident changes during the study period. Class 4 sprouts in P1 decreased to ~1% after recovering with aging, which resulted in P1 having higher proportions of Class 3 (~9% vs. ~2%) and Class 2 (~12% vs. ~8%) sprouts than P2ds. No differences were observed in Class 5 proportions between P1 (~4%) and P2ds (~4%) during the study period.

In P2ns, Class 1 only accounted for 59% of the stumps in year 0.5, sharply decreasing to 43% in year 1, which was followed by a slight decrease to 24% in year 4.5. In contrast, Class 2 sprouts increased in similar proportions to those in which Class 1 decreased. In P2ns, Class 4 accounted for 32% of the sprouts in year 0.5, after which their proportion slowly decreased to 15% in year 4.5. Conversely, the proportion of Class 5 sprouts increased from 10% to 31% between years 0.5 and 4.5. The Class 3 (forked stem) proportion showed similar values for P2ds and P2ns during the observation period. A lack of Class 2 and Class 3 sprouts in year 0.5 was observed across P1, P2ds, and P2ns.

Between years 4.5 and 5.5, nine and ten coppice trees of P1 and P2ds, respectively, ~10% each in number had died. These dead trees were significantly smaller in

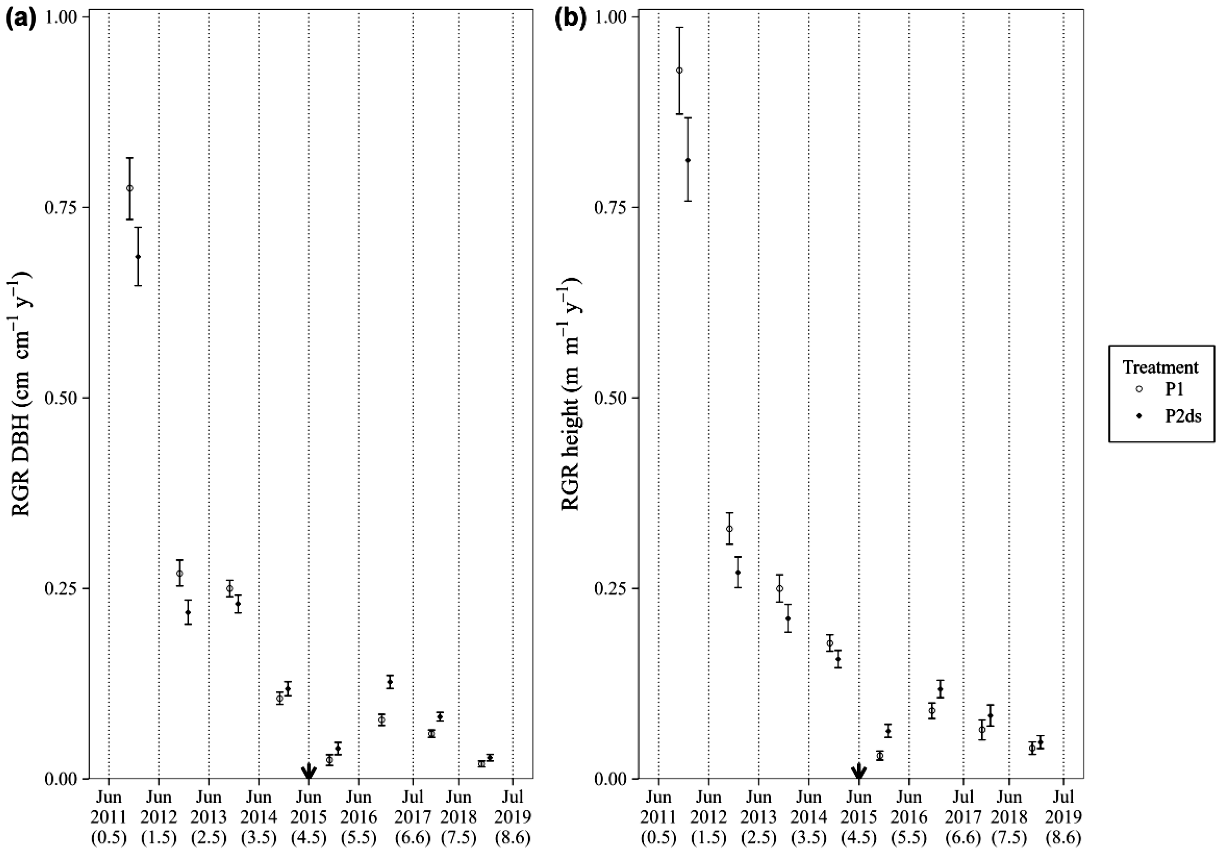

Fig. 2. Hierarchical Bayesian modeling estimates for relative growth rates in diameter at breast height (a) and tree height (b) for sprouts in the one-sprout plot and dominant sprouts in the two-sprout plot

Numbers in parentheses indicate the age in years after clear-cutting. Symbols and error bars indicate the means and 95% credible intervals, respectively. Vertical lines and the downward arrow indicate the timing of each survey and when the second thinning was conducted by removing all P2ns sprouts after a survey in June 2015, respectively. Symbols are offset horizontally to improve clarity. HBM: hierarchical Bayesian modeling; P1: a sprout reserved on a stump in the one-sprout plot; P2ds: the dominant of two sprouts reserved per stump in the two-sprout plot.

Table 1. Coefficient β (mean and 95% credible interval) of the fixed effect variable F, based on hierarchical Bayesian modeling

No.	Period	Age (y)	Coefficient β	
			DBH	Height
1	Jun.2011-Jun.2012	0.5 to 1.5	–0.12 (–0.21 to –0.03)	–0.13 (–0.24 to –0.03)
2	Jun.2012-Jun.2013	1.5 to 2.5	–0.21 (–0.32 to –0.10)	–0.19 (–0.29 to –0.08)
3	Jun.2013-Jun.2014	2.5 to 3.5	–0.08 (–0.15 to –0.02)	–0.17 (–0.29 to –0.05)
4	Jun.2014-Jun.2015	3.5 to 4.5	0.11 (–0.01 to 0.23)	–0.13 (–0.23 to –0.03)
5	Jun.2015-Jun.2016	4.5 to 5.5	0.48 (0.11 to 0.86)	0.72 (0.47 to 0.99)
6	Jun.2016-Jul.2017	5.5 to 6.6	0.50 (0.38 to 0.62)	0.27 (0.12 to 0.43)
7	Jul.2017-Jun.2018	6.6 to 7.5	0.32 (0.21 to 0.44)	0.26 (0.01 to 0.52)
8	Jun.2018-Jul.2019	7.5 to 8.6	0.35 (0.11 to 0.62)	0.18 (–0.10 to 0.46)

The variable F is discrete and denotes 0 (P1) and 1 (P2ds), as described in Eq. 2 and Eq. 5. The 95% credible interval (CreI) of β is used to assess the effect of the variable F on growth rate by comparing it with the null expectation (i.e., $\beta = 0$). For RGR, P1 > P2ds when 95% CreI < 0, P1 < P2ds when 95% CreI > 0, and no consistent changes were observed when 95% CreI has $\beta = 0$.

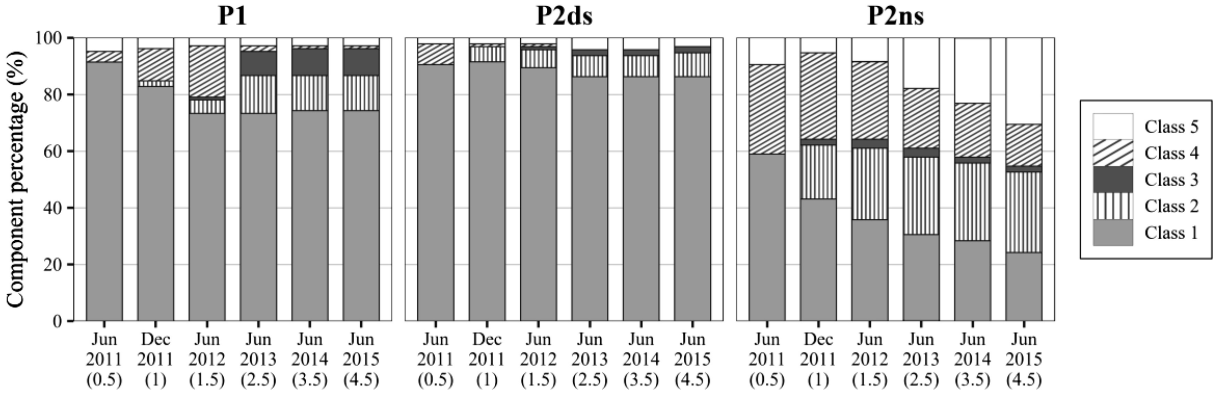

Fig. 3. Changes in stem condition classes for coppices in the one-sprout plot and two-sprout plot managed by thinning of coppice teak

n = 105 (P1), 95 (P2ds), and 95 (P2ns). Numbers in parentheses indicate the age in years after clear-cutting. P1: a sprout reserved per stump in the one-sprout plot; P2ds: the dominant of two sprouts reserved per stump in the two-sprout plot; P2ns: the secondary of two sprouts reserved per stump in the two-sprout plot.

diameter and height than the remaining living trees by the Wilcoxon rank sum test ($P < 0.05$ and $P < 0.001$ in P1 and P2ds, respectively) and did not appear in any other observation periods.

Discussion

1. Size dependency of relative growth rate

The RGR typically declines with increasing tree size and/or age (Mencuccini et al. 2005, Rose et al. 2009). Iida et al. (2014) and Prado-Júnior et al. (2017) estimated the RGR of stem diameter as a function of stem diameter using HBM to evaluate size-dependent changes in RGR and account for variable uncertainty. These studies confirmed that the RGR was correlated with functional traits such as tree height and crown width within a limited range of small stem diameters; thus, the decline in the RGR of the stem diameter is sharper in small stem diameters and becomes gentler with larger stem sizes. In this study, similar to the studies by Iida et al. (2014) and Prado-Júnior et al. (2017), the observed RGRs of individual coppices were strongly associated with initial tree size within a range of small trees in the first period (year 1), and this association weakened in year 2 and was only marginal from year 3 onward (Fig. 4). Additionally, we focused on evaluating the effects of different thinning coppice treatments with a simplified model. Thus, our HBM did not use tree size variables to estimate RGRs. As our mean HBM estimates were very similar to the observed plot RGRs, while displaying little variation, applying our HBM may have removed measuring errors such as accidental changes.

2. Growth performance of different thinning treatments

P1 sprouts had a greater DBH and height than P2ds sprouts in year 4.5, owing to P1 having a greater growth rate than P2ds until year 3 ($P < 0.05$) (Figs. 1, 2). However, in terms of stem conditions, P1 had a lower number of no defect (Class 1) coppices than P2ds (74% vs. 86%) in year 4.5. Compared with P2ds, P1 had both more leaning trees at years 1 and 1.5 and a higher incidence of forked tops from year 2.5 onward (Fig. 3). The poorer stem conditions of P1 were probably due to its greater height RGR and the fact that a single sprout was standing on each stump; rapid height growth would have produced stem tops that are fragile against winds.

The drop in RGRs of both P1 and P2ds in years 4 and 5 (Fig. 2) was likely due to crown closure of individual trees in the 2 m interval of plant spacing 2 × 4 m, and ~10% dead trees each in number of P1 and P2ds were caused by self-thinning of Yoda et al. (1963) until June 2016 between year 4.5 to 5.5; in the next period of year 6 the RGRs showed increase by self-thinning, especially RGR of P2ds reacted in more increase to second-stage thinning of P2ns removal. For the next periods following year 6, the decrease in the RGRs was likely due to the start of contact between tree crowns in the 4 m spacing from July 2017. We supposed this indicates that there was strong competition with neighbors in regenerating stands in the 2 m and 4 m spacing, and a measure to reduce stand density was required to improve the light environment, including pruning. To investigate the emergence of dead trees, changes in the relative spacing index (RSI) (Wilson 1946) over time were assessed. The RSI is defined as the ratio of the average distance between trees to the average

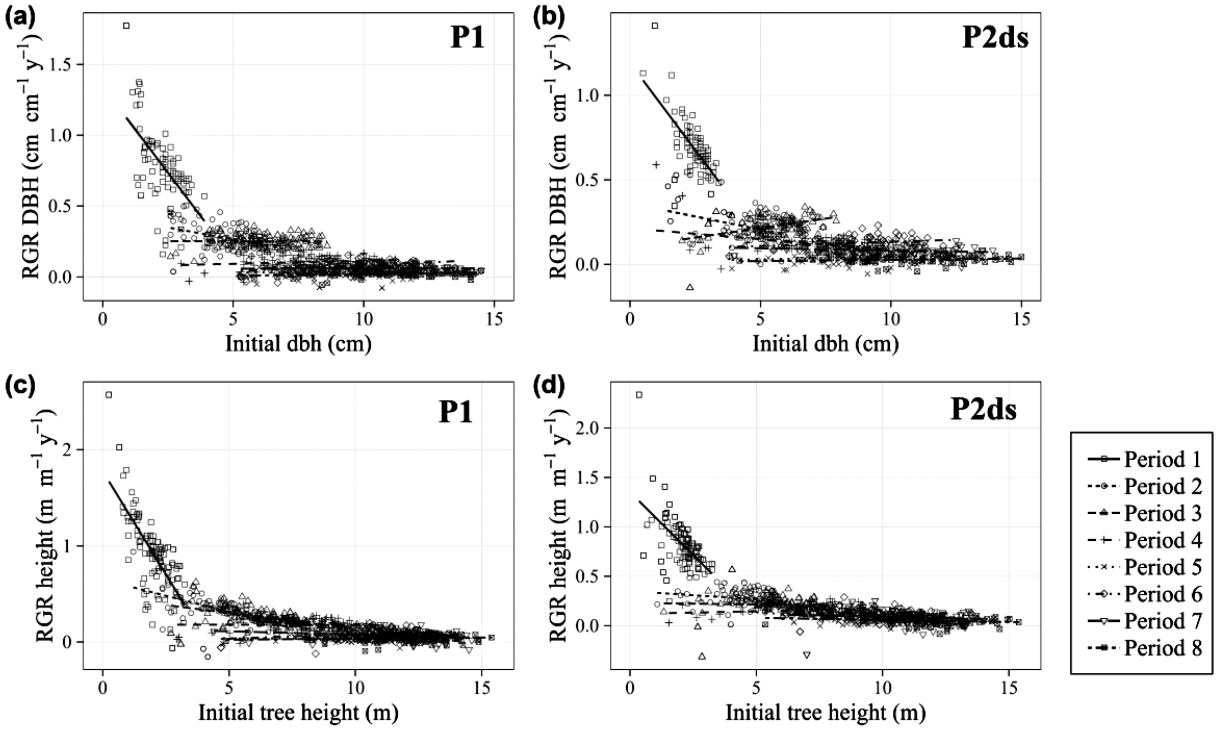

Fig. 4. Changes in the relationship between the observed relative growth rates (RGRs) and initial tree size for each period

P1: a sprout reserved per stump in the one-sprout plot; P2ds: the dominant of two sprouts reserved per stump in the two-sprout plot.

dominant height of the stand (Zhao et al. 2010). The RSI is a useful stand density measure to determine thinning regimes in managed plantations (Nishizawa 1972, Nishizono et al. 2013, Tewari & Alvarez-Gonz 2014, Wilson 1946, Wilson 1979, Zhao et al. 2010). RSI values decreased to 23 and 20 on the P1 and P2 plots, respectively, in the year the standing dead trees occurred, after which they plateaued or gradually decreased (Fig. 5). The proper RSI values (upper and lower bounds) for thinning have been reported for several species, such as spruce (16, 14), Jack pine (25, 20), loblolly pine (30, 20) (Wilson 1946, Wilson 1979, Zhao et al. 2010), and *Cryptomeria japonica* (21, 13) (Nishizawa 1972). However, upon searching literature, we found no previous studies reporting the thinning criteria RSI values for teak; thus, further data are necessary regarding teak stand density and growth with different ages and site qualities.

After the self-thinning, P2ds had higher growth rates than P1, owing to the second thinning treatment to remove P2ns (Fig. 2 and Table 1). The removal of P2ns helped P2ds achieve equal DBH and height values to those of P1 from year 6.6 onward until the end of the observation period (Fig. 1). In addition, P2ds comprised a higher proportion of undamaged trees than P1, with no

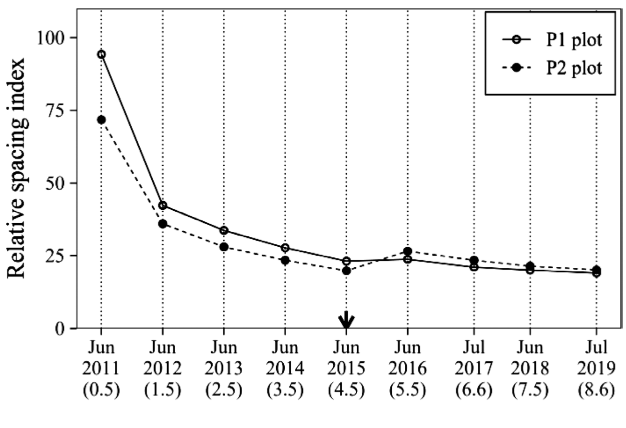

Fig. 5. Changes in relative spacing indices over time

Numbers in parentheses indicate the age in years after clear-cutting. Vertical lines and the downward arrow indicate the timing of each survey and when the second thinning was conducted by removing all P2ns sprouts after a survey in June 2015, respectively. For the P2 plot, the relative spacing index was calculated using both P2ds and P2ns until June 2015, and using P2ds from June 2016. P2ds: the dominant of two sprouts reserved per stump in the two-sprout plot; P2ns: the secondary of two sprouts reserved per stump in the two-sprout plot.

evident damaged stems in either P1 or P2ds.

To interpret the growth level measured in this study site, we compared our data to that of coppiced teak trees from previous studies. Available data on teak coppice growth are limited; however, Himmapan et al. (2017) reported RGRs for DBH and height based on a five-year monitoring of five-year-old coppice teak trees in Uttaradit, Thailand. The conditions were similar to those of P1 coppices in our study, with the same planting distance (2 × 4 m) and one-stage thinning coppice treatment after clear-cutting a 10-year-old teak plantation. Compared with the findings of RGRs (0.12 ± 0.02 cm, 0.08 ± 0.01 cm, and 0.07 ± 0.00 cm for DBH, and 0.09 ± 0.02 m, 0.06 ± 0.02 m, and 0.05 ± 0.01 m for height) of Himmapan et al. (2017), at ages 6, 7, and 8, respectively our P1 coppices had a slightly smaller RGR for DBH but an almost equal RGR for height.

3. Potential and timing of two-stage thinning

Our nine-year observation after clear-cutting showed that a dominant sprout per stump (P2ds) under two-stage thinning achieved equal DBH and height values to those of a single sprout per stump (P1) under one-stage thinning by year 6.6 (Fig. 1). Moreover, within around two years after the first thinning event, P2ds maintained a high proportion of healthy coppices, whereas P1 showed more damaged stems, with leaning trees (Fig. 3). This suggests that reserving two sprouts per stump in a first thinning event can improve the tolerance of sprouts to windy conditions compared to that by reserving a single sprout. Therefore, we conclude that two-stage thinning treatments of coppice teak may be more effective than one-stage thinning in teak reforestation on growth and stem conditions, supporting recommendations made by Evans & Turnbull (2004), Yanagiya et al. (1966), and Yano et al. (1966) on *E. grandis*, *Quercus acutissima*, and *Quercus crispula*, respectively.

Regarding the timing of second thinning, Yanagiya et al. (1966) denoted that it is generally suitable when a dominant-subordinate relationship is observed, according to previous studies on broad-leaved trees. Auykim et al. (2017) suggested that year 5 requires the silvicultural intervention of teak coppice trees to increase their yield, as coppice DBH growth decelerated in year 5 in a clear-cut FIO teak plantation (4 × 4 m planting distance) in Lampang, Thailand. But in the present study, year 2.5 would be the suggested timing of second thinning, when dead trees increase in P2ns (Fig. 3) and just before the DBH growth of P2ds decelerating (Fig. 2). Additionally, the 20 to 23 RSI identified in this study could be used as an indicator of self-thinning emergence in coppiced teak plantations (Fig. 5).

One and two sprouts were reserved per stump after the first thinning event in this study. The number of reserving sprouts depends on the species, stand density, and site quality of the broad-leaved trees (Yanagiya et al. 1966, Yano et al. 1966). In *Q. crispula* of bigger coppices (~1 m height), 1-2 sprouts have been reserved (Yano et al. 1966), 2-3 in *E. saligna* by Howland (as cited in Evans & Turnbull 2004) and *Q. acutissima* (Yanagiya et al. 1966), and 3-4 sprouts in *E. grandis* (Evans & Turnbull 2004) and *Q. crispula* of smaller coppice (~0.5 m height) (Yano et al. 1966). Thus, in practice, reserving around three sprouts per stump in a first thinning event may be preferable in teak plantations for timber production, owing to its above-average sprout mortality.

This study has some limitations. Only one teak plantation was used for the first thinning at the beginning of the teak first growing season. The best season for thinning coppice is typically just before the beginning of the vegetative activity when the sap starts to rise (Kadambi 1972). Otherwise, thinning stimulates the development of additional unwanted shoots from epicormic buds in teak (Kadambi 1972) and *Quercus serrata* (Katakura & Okumura 1989). Time must also be allowed for calluses to develop around the stump and provide a sufficiently secure base for a fast-growing coppice (Evans & Turnbull 2004). Liu et al. (2011) have indicated that the most effective coppice thinning seasons for biomass production are the end > beginning > middle of the first growing seasons of *Q. acutissima*. Therefore, further data collection on teak coppice growth performance is encouraged to clarify the factors that regulate teak coppice responses for achieving different timing and seasons in thinning treatment with different stump ages and site qualities.

Conclusions

Two years after a second thinning on teak coppice trees, the dominant sprouts of two-sprout stumps (P2ds) achieved the same DBH and height as the sprouts of one-sprout stumps (P1) before seven years old. While until the second thinning after the first thinning, the P1 were greater than the P2ds in DBH and height. This suggests that the second thinning enhances the growth of P2ds due to the removal of the secondary sprouts of the two-sprout stumps. P2ds also showed less damage, maintaining a high proportion of healthy coppice trees during the fragile period after the first thinning treatment because they grew alongside another coppice. We suggest that for teak reforestation using coppice regeneration, two-stage thinning on coppice teak has more potential than one-stage thinning. Further, our results showed that, before the second thinning, self-thinning occurred in year 5 for all treatment types. This accompanied a noticeable deceleration in DBH growth, indicating that sprouts may be highly competitive with regenerating neighbors. This also suggests that a second thinning with pruning is beneficial when diameter growth begins to decelerate. The timing for this may correspond with the decreasing RSI observed in this study. However, to determine the timing of a second thinning of coppice teak, site quality and tree conditions must be considered. These results contribute to advancing teak coppice management for sustainable plantation forestry.

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References

Auykim, A. et al. (2017) Growth of teak regenerated by coppice and stump planting in Mae Moh Plantation, Lampang province, Thailand. *Agric. Nat. Resour.*, **51**, 273-277.

Bailey, J. D. & Harjanto, N. A. (2005) Teak (*Tectona grandis* L.) tree growth, stem quality and health in coppiced plantations in Java, Indonesia. *New Forests*, **30**, 55-65.

Beck, H. E. et al. (2018) Present and future Köppen-Geiger climate classification maps at 1-km resolution. *Sci. Data*, **5**, 180214.

Bolker, B. M. et al. (2009) Generalized linear mixed models: a practical guide for ecology and evolution. *Trends Ecol. Evol.*, **24**, 127-135.

Clark, J. S. (2005) Why environmental scientists are becoming Bayesians. *Ecol. Lett.*, **8**, 2-14.

Clark, J. S. et al. (2003) Coexistence: how to identify trophic trade-offs. *Ecology*, **84**, 17-31.

Condit, R. et al. (2006) The importance of demographic niches to tree diversity. *Science*, **313**, 98-101.

Evans, J. & Turnbull, J. W. (2004) *Plantation forestry in the tropics, 3rd edition: The role, silviculture and use of planted forests for industrial, social, environmental and agroforestry purposes.* Oxford University Press, Oxford, UK.

Feeley, K. J. et al. (2007) Decelerating growth in tropical forest trees. *Ecol. Lett.*, **10**, 461-469.

Forbes, C. et al. (2011) *Statistical distributions (4th edition).* John Wiley & Sons, NJ, USA.

Gelman, A. & Hill, J. (2006) *Data analysis using regression and multilevel/hierarchical models.* Cambridge University Press, Cambridge, UK.

Gelman, A. & Rubin, D. B. (1992) Inference from iterative simulation using multiple sequences. *Stat. Sci.*, **7**, 457-472.

Gelman, A. et al. (2013) *Bayesian data analysis, 3rd edition.* CRC Press, FL, USA.

Himmapan, W. & Noda, I. (2012) A preliminary result of coppicing trials in teak plantations in Kanchanaburi, Thailand. *JIRCAS Working Report*, **74**, 13-18.

Himmapan, W. et al. (2017) The growth of coppiced teak in northern Thailand. *JIRCAS Working Report*, **85**, 31-37.

Hunt, R. (1989) *Basic growth analysis: Plant growth analysis for beginners.* Springer Netherlands, Dordrecht, Netherlands.

Iida, Y. et al. (2014) Linking size-dependent growth and mortality with architectural traits across 145 co-occurring tropical tree species. *Ecology*, **95**, 353-363.

Itoh, H. (2015) Bayesian estimation of tree diameter-height relationships involving species differences and measurement errors. *Bull. For. & For. Prod. Res. Inst.*, **14**, 73-74 [In Japanese].

Jamieson, P. D. et al. (1991) A test of the computer simulation model ARCWHEAT1 on wheat crops grown in New Zealand. *Field Crops Res.*, **27**, 337-350.

Kadambi, K. (1972) Silviculture and management of teak. *Forestry Bulletin*, **24**, Stephen F. Austin State University, TX, USA.

Katakura, M. & Okumura, S. (1989) Coppicing and fertilization on matured stands of konara (*Quercus serrata*) secondary forest (Konara niji-rin no bōgakōshin to seibokurin-hibai). *Bull. Nagano Prefecture Forestry Research Center*, 1-13 [In Japanese].

Kenzo, T. et al. (2011) Growth and photosynthetic response of four Malaysian indigenous tree species under different light conditions. *J. Trop. For. Sci.*, **23**, 271-281.

Kollert, W. & Cherubini, L. (2012) *Teak resources and market assessment 2010* (*Tectona grandis* Linn. f.). Planted Forests and Trees Working Paper FP/47/E, FAO, Rome, Italy.

Kollert, W. & Kleine, M. (2017) *The global teak study: Analysis, evaluation and future potential of teak resources.* IUFRO World Series Vol. 36, IUFRO, Vienna, Austria.

Korner-Nievergelt, F. et al. (2015) *Bayesian data analysis in ecology using linear models with R, BUGS, and Stan.* Academic Press, London, UK.

Kubo, T. (2012) *Introduction to statistical modeling for data analysis: Generalized linear models, hierarchical Bayesian models, and MCMC* (*Dēta kaiseki no tame no tōkei moderingu nyūmon: Ippannka senkei moderu・kaisō Bayes moderu・MCMC*). Iwanami Shoten [In Japanese].

Liu, Z. et al. (2011) Influence of thinning time and density on sprout development, biomass production and energy stocks of sawtooth oak stumps. *For. Ecol. Manag.*, **262**, 299-306.

Mahannop, N. (2004) The development of forest plantations in Thailand. *In* Enters, T. & Durst, P. B. (eds), What does it take?: the role of incentives in forest plantation development in Asia and the Pacific, RAP PUBLICATION 2004/27, FAO RAP, Bangkok, Thailand, pp. 211-236.

Masaki, T. et al. (2013) How do thinning intensities affect long-term growth of tree height in a Japanese cedar plantation? *J. Jpn. For. Soc.*, **95**, 227-233 [In Japanese with English abstract].

Masaki, T. et al. (2017) Height-diameter relationships of 29 tree species in the Ogawa Forest Reserve. *Bull. For. & For. Prod. Res. Inst.*, **16**, 121-142 [In Japanese with English abstract].

Matsuura, K. (2022) *Bayesian statistical modeling with Stan, R, and Python*. Springer Nature, Singapore.

Mencuccini, M. et al. (2005) Size-mediated ageing reduces vigour in trees. *Ecol. Lett.*, **8**, 1183-1190.

Minghe, L. & Ritchie, G. A. (1999) Eight hundred years of clonal forestry in China: I. traditional afforestation with Chinese fir (*Cunninghamia lanceolata* (Lamb.) Hook.). *New Forests*, **18**, 131-142.

Nishizawa, M. (1972) *Forest mensuration* (*Shinrin sokutei*). Norin-shuppan, Tokyo, Japan [In Japanese].

Nishizono, T. et al. (2013) Relationship between relative yield index and relative spacing index: theoretical derivation of the relationship and its characteristics. *Jpn. J. For. Plann.*, **47**, 16-28 [In Japanese with English abstract].

Niskanen, A. (1998) Financial and economic profitability of reforestation in Thailand. *For. Ecol. Manag.*, **104**, 57-68.

Noda, I. & Himmapan, W. (2017) Effects of coppicing and seedling options on financial evaluation of teak (*Tectona grandis* L.) farm plantation management in Thailand. *JIRCAS Working Report*, **85**, 87-98.

Noda, I. et al. (2004) *Profitability analysis of teak plantation management for small scale farmers in the northeast Thailand*. JICA Study Report, Royal Forest Department & JICA, Bangkok, Thailand.

Noda, I. et al. (2012) *Soil suitability map for teak plantation in Udon Thani and Nong Bua Lam Phu Provinces*. RFD-JIRCAS Joint Research Project, Bangkok, Thailand. https://doi.org/10.34556/0002000158 [In Thai with English description].

Phien, H. N. et al. (1980) Rainfall distribution in northeastern Thailand. *Hydrol. Sci.*, **25**, 167-182.

Pommerening, A. & Muszta, A. (2015) Methods of modelling relative growth rate. *For. Ecosyst.*, **2**, 10.1186/s40663-015-0029-4.

Prado-Júnior, J. A. et al. (2017) Functional traits shape size-dependent growth and mortality rates of dry forest tree species. *Plant Ecol.*, **10**, 895-906.

R Core Team (2022) *R: A language and environment for statistical computing*. R foundation for statistical computing, Vienna, Austria.

Rose, K. E. et al. (2009) The costs and benefits of fast living. *Ecol. Lett.*, **12**, 1379-1384.

Roshetko, J. M. et al. (2013) Teak systems' contribution to rural development in Indonesia. *In* Proceedings of the World Teak Conference 2013, 24-27 Mar. 2013, Bangkok, Thailand, pp.1-18. http://www.worldagroforestry.org/sea/Publications/files/paper/PP0327-13.PDF. Accessed on 2 November 2014.

Stan Development Team (2021) *Stan reference manual*.

Sukchan, S. & Noda, I. (2012) Improvement of soil suitability mapping for teak plantations in Northeast Thailand. *JIRCAS Working Report*, **74**, 27-32.

Tewari, D. N. (1992) *A monograph on teak* (*Tectona grandis* Linn. f.). International book distributors, Dehra Dun, India.

Tewari, V. P. & Alvarez-Gonz, J. G. (2014) Development of a stand density management diagram for teak forests in southern India. *JFES*, **30**, 259-266.

Thai Upper Northeastern Meteorological Center (2023) Upper northeastern. Thai Meteorological Department. http://www.khonkaen.tmd.go.th/. Accessed on Nov. 22, 2023.

UK Forestry Commission (2014) Chapter 19: Coppice. *In* NFI Survey Manual – 1st cycle field data collection, London, UK. https://cdn.forestresearch.gov.uk/2022/02/19_coppice_june_2014.pdf. Accessed on Feb. 15, 2024.

Wilson, F. G. (1946) Numerical expression of stocking in terms of height. *J. For.*, **44**, 758-761.

Wilson, F. G. (1979) Thinning as an orderly discipline: A graphic spacing schedule for red pine. *J. For.*, **77**, 483-486.

Yanagiya, S. et al. (1966) Some studies on the kunugi (*Quercus acutissima* Carr.) forest in the Tohoku district. *Bull. For. & For. Prod. Res. Inst.*, **188**, 1-62 [In Japanese with English resume].

Yano, T. et al. (1966) Study in the selective cutting of Japanese oaks (1) On the establishment of the test forest. *Reports of the Kyushu University Forests*, **21**, 1-23 [In Japanese with English resume].

Yoda, K. et al. (1963) Self-thinning in overcrowded pure stands under cultivated and natural conditions (Intraspecific competition among higher plants. XI). *J. Inst. Polytech. Osaka City Univ. Ser. D.*, **14**, 107-129.

Zhao, D. et al. (2010) Development and applications of the relative spacing model for loblolly pine plantations. *For. Ecol. Manag.*, **259**, 1922-1929.

Appendix Table. Differences in relative growth rates (RGRs) between the observed values and hierarchical Bayesian modeling (HBM) estimates

(a) RGR DBH (cm cm^{-1} y^{-1})

Period	Age (y)	Treatment	Observed values	Δm [a]	Range of interval [b]	
			Mean and 95% CI		Observed	HBM
Jun.2011-Jun.2012	0.5 to 1.5	P1	0.78 (0.72 to 0.83)	0.00	0.11	0.08
		P2ds	0.69 (0.65 to 0.72)	0.00	0.07	0.08
Jun.2012-Jun.2013	1.5 to 2.5	P1	0.27 (0.25 to 0.29)	0.00	0.03	0.03
		P2ds	0.22 (0.20 to 0.24)	0.00	0.04	0.03
Jun.2013-Jun.2014	2.5 to 3.5	P1	0.25 (0.24 to 0.26)	0.00	0.02	0.02
		P2ds	0.23 (0.22 to 0.24)	0.00	0.03	0.02
Jun.2014-Jun.2015	3.5 to 4.5	P1	0.11 (0.10 to 0.11)	0.00	0.02	0.02
		P2ds	0.12 (0.11 to 0.13)	0.00	0.03	0.02
Jun.2015-Jun.2016	4.5 to 5.5	P1	0.03 (0.02 to 0.03)	0.00	0.01	0.01
		P2ds	0.04 (0.03 to 0.05)	0.00	0.02	0.02
Jun.2016-Jul.2017	5.5 to 6.6	P1	0.08 (0.07 to 0.09)	0.00	0.01	0.01
		P2ds	0.13 (0.12 to 0.14)	0.00	0.02	0.02
Jul.2017-Jun.2018	6.6 to 7.5	P1	0.06 (0.06 to 0.06)	0.00	0.01	0.01
		P2ds	0.08 (0.07 to 0.09)	0.00	0.01	0.01
Jun.2018-Jul.2019	7.5 to 8.6	P1	0.02 (0.02 to 0.02)	0.00	0.01	0.01
		P2ds	0.03 (0.02 to 0.03)	0.00	0.01	0.01
RMSD [c]		P1		0.00		
		P2ds		0.00		

(b) RGR height (m m^{-1} y^{-1})

Period	Age (y)	Treatment	Observed values	Δm [a]	Range of interval [b]	
			Mean and 95% CI		Observed	HBM
Jun.2011-Jun.2012	0.5 to 1.5	P1	0.93 (0.85 to 1.01)	0.00	0.15	0.11
		P2ds	0.82 (0.76 to 0.87)	0.00	0.11	0.11
Jun.2012-Jun.2013	1.5 to 2.5	P1	0.33 (0.30 to 0.35)	0.00	0.05	0.04
		P2ds	0.27 (0.26 to 0.29)	0.00	0.03	0.04
Jun.2013-Jun.2014	2.5 to 3.5	P1	0.25 (0.23 to 0.27)	0.00	0.04	0.04
		P2ds	0.21 (0.19 to 0.23)	0.00	0.04	0.04
Jun.2014-Jun.2015	3.5 to 4.5	P1	0.18 (0.17 to 0.19)	0.00	0.02	0.02
		P2ds	0.16 (0.15 to 0.17)	0.00	0.02	0.02
Jun.2015-Jun.2016	4.5 to 5.5	P1	0.03 (0.03 to 0.04)	0.00	0.01	0.01
		P2ds	0.06 (0.05 to 0.07)	0.00	0.02	0.02
Jun.2016-Jul.2017	5.5 to 6.6	P1	0.09 (0.08 to 0.10)	0.00	0.02	0.02
		P2ds	0.12 (0.11 to 0.13)	0.00	0.02	0.02
Jul.2017-Jun.2018	6.6 to 7.5	P1	0.07 (0.05 to 0.08)	0.00	0.02	0.03
		P2ds	0.08 (0.07 to 0.10)	0.00	0.03	0.03
Jun.2018-Jul.2019	7.5 to 8.6	P1	0.04 (0.03 to 0.05)	0.00	0.02	0.02
		P2ds	0.05 (0.04 to 0.06)	0.00	0.02	0.02
RMSD [c]		P1		0.00		
		P2ds		0.00		

[a] Δm = (Observed mean) – (HBM estimated mean).
[b] Range of interval indicates the range of 95% CI for observed values and the range of 95% CreI for HBM values.
[c] RMSD: root mean square of the difference between observed mean and HBM estimated mean, shown as Eq.13.
CI: confidence interval; CreI: credible interval.