JARQ 45 (3), 317 – 326 (2011) http://www.jircas.affrc.go.jp

Growth Performances of Three Indigenous Tree Species Planted in a Mature *Acacia mangium* Plantation with Different Canopy Openness under a Tropical Monsoon Climate

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Abstract

With the aim of establishing silvicultural techniques for tree species indigenous to monsoon tropical areas, we examined the survivorship and growth performance of three tree species under different light conditions. A 23-year-old *Acacia mangium* plantation was thinned in different ways: group selection thinning (gap creation, 50 m by 60 m in size), 2/3 random selection thinning based on basal area, 1/3 random selection thinning, and no thinning (control). The seedlings of *Hopea odorata*, *H. ferrea*, and *Xylia xylocarpa* var. *kerrii* were planted in each treatment area with three replications. At 30 months after planting, all species achieved a high survival rate (>90%) in all treatments, perhaps owing to intensive tending in the experimental plots. Both stem thickening and height growth were promoted as light conditions improved: most in the gap plot and least in the control plot for all species. *H. ferrea* grew to a large height even in dark conditions, suggesting that this species is considerably shade-tolerant. In contrast, *X. xylocarpa* var. *kerrii* was light-demanding owing to vigorous growth in the gap plot. The growth of the seedlings seemed to be associated with regeneration patterns in their natural habitats. The group selection thinning seemed to be most suitable for the growth of indigenous tree species.

Discipline: Forestry and forest products
Additional key words: group selection thinning, light condition, random selection thinning, survival rate, two-aged system

Introduction

Forest resources have drastically declined in both area and quality over the last several decades across Southeast Asia[7,8]. In Thailand, forest area decreased from 61% of the nation's land area in 1961 to 25% by the end of the 20th century[28]. However, it recovered to approximately 30% in the last decade owing to a government reforestation and protection policy[29]. Thailand now exports wood products (e.g., pulp and particleboard) made of exotic fast-growing trees[28]. In parallel, Thailand imports timbers indigenous to Indochina (e.g., teak, dipterocarp, and pra-du) from neighboring countries (e.g., Malaysia, Laos, and Myanmar) against a background of rapid economic growth and a shortage of domestic forest resourc-

This paper reports the results obtained on "Development of Techniques for Nurturing Beneficial Indigenous Tree Species and Combined Management of Agriculture and Forestry in Northeast Thailand, Tropical Monsoon Regions" sponsored by JIRCAS and Royal Forest Department.
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Received 28 October 2010; accepted 13 January 2011.

es[28]. Indigenous tree species are expected to produce high-value timbers, which are important for commercial products and local consumption. However, silvicultural techniques for indigenous tree species have not improved compared with those of exotic fast-growing trees owing to limited experience and a lack of information about site suitability and growth performance in a given environment[23].

Strong direct sunlight causes high mortality in seedlings, sometimes ending in the failure of forestation in tropical areas[10,25]. In order to deal with this, uneven-aged forest management has been tested in tropical areas[13,25,30]. Advanced studies on uneven-aged forest called "enrichment planting" have been conducted in Malaysia[5]. Most of them follow a "two-aged system" in which advanced stands are thinned in a given pattern (random, stripe, and group selection) for succeeding stands. Residual canopy trees (nurse trees) mitigate the effects of strong sunlight on young seedlings. Many studies found that moderate light conditions promoted the growth of some dipterocarp seedlings in Malaysia[10,14]. Fire in the dry season is one of the main factors that hamper the establishment of forest plantations in the monsoon climate in Thailand[12]. Planting fast-growing trees in large degraded areas of land was significantly effective for containing fires because they covered the ground quickly and suppressed grasses (*Imperata cylindrica* and *Saccharum spontaneum*), which often caused fires in the dry season[30]. Thus, planting indigenous trees after the establishment of fast-growing tree plantations could be a reasonable approach to introducing indigenous trees in large areas of degraded land[30].

The objective of this study is to examine the survival rate and growth performance of three indigenous tree species under different light conditions, which were provided by artificial thinning in a forest plantation, and to gain insight for silvicultural techniques from these results. We applied two methods of thinning to a mature *Acacia mangium* plantation: random selection thinning, and group selection thinning (gap creation). We clarified the responses of each indigenous tree species to light conditions in association with regeneration patterns in the natural habitats of the species. Then, we determined the thinning method that was most suitable for indigenous tree species in the framework of a two-aged system.

Study site and methods

1. Site descriptions

This study was conducted at Sakaerat Silvicultural Research Station, Nakhon Ratchasima Province, in Northeast Thailand. The mean annual air temperature was 25.6 °C and the mean annual rainfall was 1395 mm according to meteorological data collected at the station over the last 10 years (1999 to 2009). This area has a monsoon climate with highly seasonal rainfall and a roughly 4-month dry period from November to February. The soil is deep loamy Acrisol formed on sandstone laid down in the Triassic to Cretaceous periods[24] and generally contains a small amount of organic matter[35]. The vicinity of the study site had been covered with dry evergreen forest until the 1960s. The forest was then encroached on by local people, who converted it into farmland. Although the farmland was cultivated for a couple of decades, most of it was abandoned and covered with tall grasses such as *Imperata cylindrica* and *Saccharum spontaneum*. A reafforestation project by Japan International Cooperation Agency (JICA) and the Royal Forest Department was initiated in 1982 with the planting of exotic fast-growing tree species over 2300 ha by 1994[30]. The area is currently covered with mature fast-growing tree plantations.

A study plot was set up in a 23-year-old *Acacia mangium* plantation on a flat terrace in June 2007 (14°30′19″N, 101°53′28″E, 630 m a.s.l.) (Fig. 1). *Acacia mangium* was planted in 1984 with spacing of 2 m by 3 m. After planting *A. mangium*, no artificial thinning was applied in the plantation, but self-thinning reduced tree density from an initial 1650 ha^{-1} to 602 to 926 ha^{-1} (Table 1). At the time of the study, mean DBH and mean tree height were 25.4 to 26.3 cm and 21.5 to 23.9 m respectively (Table 1).

2. Design of the study plot

A canopy gap (50 m by 60 m) was created by group selection thinning in June 2007. Three rectangular quadrates, each measuring 12 m by 36 m, were set up in the

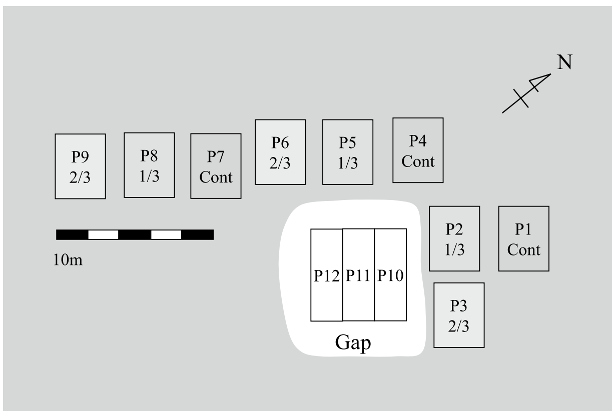

Fig. 1. Location and layout of the study plot
Quadrates indicate the study plots (P1–P12). Meshed area and white blank show *Acacia mangium* plantation and a canopy gap, respectively.

canopy gap, and nine quadrates, each measuring 18 m by 24 m, were set up in the *Acacia mangium* plantation (Figs. 1 and 2). Of these nine, one-third of the live trees (*A. mangium*) were thinned in three quadrates and two-thirds of trees were thinned in another three quadrates on the basis of the basal area of *A. mangium* in June 2007. The remaining three quadrates were left as non-thinning controls. Thus, the study site consisted of 12 quadrates with three replications of four treatments (group selection thinning, two-thirds random selection thinning, one-third random selection thinning and control).

Undergrowth was cleared by cutting shrubs and herbs prior to thinning and planting the seedlings, and litter was removed by scraping the ground surface. Weeds

Table 1. Descriptions of 23-year-old *Acacia mangium* plantation before and after the thinning

Plot	Treatment	Tree density (no. ha^{-1})		Basal area (m^2 ha^{-1})		Thinning rate (%)	DBH (cm)		Height (m)	
		BT	AT	BT	AT		AT	SD	AT	SD
P1	Control	−	741	−	40.44	0	25.4	7.3	21.5	3.3
P4	Control	−	718	−	33.76	0	26.0	6.9	23.9	3.2
P7	Control	−	602	−	35.09	0	26.3	5.9	22.8	2.7
P2	1/3 thinning	787	394	42.54	26.89	36.8	28.7	6.3	25.1	3.3
P5	1/3 thinning	787	394	42.99	25.23	41.3	28.2	4.7	24.5	2.6
P8	1/3 thinning	926	417	41.35	25.61	38.1	27.4	3.7	24.7	2.7
P3	2/3 thinning	671	231	37.40	13.51	63.9	26.7	7.3	25.0	1.6
P6	2/3 thinning	787	255	41.86	13.90	66.8	26.1	5.6	24.9	3.6
P9	2/3 thinning	671	208	33.58	10.81	67.8	25.2	5.6	25.9	4.8

* BT: before the thinning, AT: after the thinning.

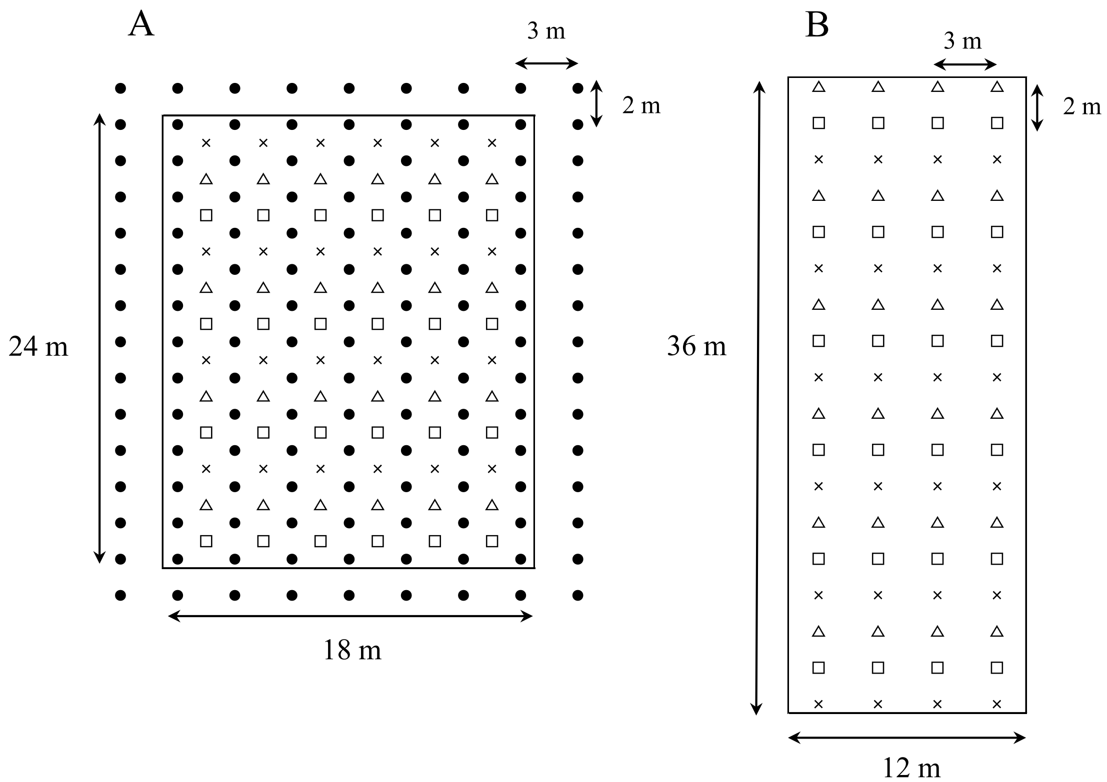

Fig. 2. Layout of planted seedlings in the random selection thinning plots (A) and in the gap (the group selection thinning plots) (B)
● : *Acacia mangium*, □ : *Hopea odorata*, △ : *H. ferrea*, × : *Xylia xylocarpa* var. *kerrii*.

were removed every two months in the rainy season during the study.

3. Indigenous tree species examined

Three indigenous tree species were selected. *Hopea odorata* Roxb. is an evergreen dipterocarp tree that often dominates in dry evergreen forest[3,32], although its distribution is limited around the Sakaerat Station. This species has been widely introduced in Southeast Asia owing to its excellent growth performance. The timber known as "merawan" is utilized for construction, floorboards, and furniture[26]. It is known that seedlings show considerable shade tolerance, yet they also grow well in open spaces[1,16,32].

Hopea ferrea Lanessan is an evergreen dipterocarp tree that is locally abundant in evergreen forest on rocky ridges and slopes[26]. This species is found to be dominant in dry evergreen forest around the Sakaerat Station, accounting for 60 percent of total basal area[2]. The timber commercially known as "giam" is quite heavy and used for posts, as well as boat and bridge construction[26]. The physiology and growth performance of seedlings are less well known because of little silvicultural experience.

Xylia xylocarpa (Roxb.) Taubert var. *kerrii* (Craib & Hutch.) I.C. Nielsen is a deciduous leguminous tree indigenous to India and Indochina. This tree occurs in dry dipterocarp forest or mixed deciduous forest at low density[19,27]. This species is common in the dry dipterocarp forest around the Sakaerat Station[17]. The hard and durable wood is used for posts, flooring, bridges, and furniture[27].

All seedlings originated from seeds collected in natural forest around the Sakaerat Station. The seedlings were germinated in plastic bags under the shade of a mesh screen in a nursery of the Sakaerat Station. The screen was removed for hardening two months in advance of transplanting. At the time of transplanting, the seedlings of *Hopea odorata* and *H. ferrea* were two years old and those of *Xylia xylocarpa* var. *kerrii* were six months old. All the seedlings were transplanted in the study plots with spacing of 2 m by 3 m (Fig. 2) in late June 2007. Each species was planted in a line, which was formed in different arrangements as shown in Fig. 2.

4. Data collection and analysis

Stem diameter at 30 cm above the ground (D_{30}) was measured using a digital caliper (Mistutoyo, SC-15S). The vertical height of the highest bud of the seedlings was measured using a measuring rod (Taketani, ST-66). Measurement was carried out bimonthly from July 2007 to January 2010.

The survival rate of the seedlings at 30 months after planting was calculated in each plot for each species. In order to test the effect of the thinning methods and planted species on the survival rate of the seedlings, the Kruskal-Wallis test was applied to the survival rates of the species in each treatment and among the treatments in each species. Means of D_{30} and height were calculated for each plot for each species. ANOVA was applied to each data set in a given time in order to detect the effect of thinning. The Tukey's HSD test was applied to the data set of January 2010 (30 months after planting) to detect the effect of thinning on the study plots, or to detect a significant difference among the species. We used JMP[31] for all statistical analyses. "Height/diameter ratio (H/D ratio)" is a commonly used indicator of relative windfirmness[22]. H/D ratio was calculated from mean D_{30} and height of the seedlings at 30 months after planting in each species in each plot.

The light environment on the forest floor was estimated by hemispherical photography. Hemispherical photographs were taken at 24 points per plot on overcast days in November 2007 and June 2009. A digital camera (Nikon, Coolpix 4500) with a fisheye lens (Nikon, Fisheye converter FC-E8) was set on a tripod at a height of 1.2 m above the ground. Exposure of the camera was set to one stop below that determined automatically. "Sky factor" was calculated for each image using the software LIA32[33]. Sky factor indicates the relative light illuminance in a given place in a forest or plant community with high accuracy[11], where "0" indicates no opening in the sky and "100" indicates perfectly open sky.

Results

1. Light environment on the seedlings

Sky factor was highest in the gap plots (60.6 to 65.2 in average) and lowest in the control plots (23.0 to 24.7) in November 2007 (Table 2). Sky factor at the thinning plots varied depending on their position against the canopy gap. Sky factor of P3 of the 2/3 thinning plots was significantly higher than those of the other 2/3 thinning plots. Sky factor of P2 (1/3 thinning plot) was significantly higher than that of P6 and P9 (2/3 thinning plots), while sky factor of P8 (1/3 thinning plot) was not significantly different from that of P1 and P7 (control plots). It is clear that light conditions around the gap (P2, P3, and P5) were improved because of the proximity to the gap (cf. Fig. 1). At 19 months after first measurement, sky factor in the random selection thinning plots was significantly reduced by 1.7 to 6.2 points (Table 2). There was no specific trend in the control plots. Sky factor did not change in the gap plots except for in Plot 10, where natural trees left in the gap partially shaded the seedlings.

2. Survival and growth patterns of the seedlings

During the 30 months, *H. odorata* and *H. ferrea* maintained quite high survival rates (> 95%) in every treatment (Fig. 3). *X. xylocarpa* var. *kerrii* also achieved high survival rates (> 90%) in every treatment. There was no significant difference in survival rate among the planted species or among the treatments according to the Kruskal-Wallis test.

There was no significant difference in stem diameter (D_{30}) or height of the seedlings, with the exception of D_{30} of *H. ferrea*, until the end of the first dry season (Fig. 4). As the rainy season started, differences in the size of seedlings started to appear. The difference in height growth of *X. xylocarpa* var. *kerrii* was more prominent and it developed earlier than *H. odorata* and *H. ferrea*. From the second rainy season, the growth patterns showed logistic-like curves for each year starting with the rainy season and ceasing in the dry season, which produced step-like curves (Fig. 4). The difference in size among the treatments was clearer in *X. xylocarpa* var. *kerrii* while it was small in *H. ferrea*. At the end of the observation (30 months after planting), the seedlings were clearly largest in the gap plots (Tables 3 and 4). Differences in size between the random selection thinning plots or between the random selection thinning plots and the control plots were not clear (Tables 3 and 4).

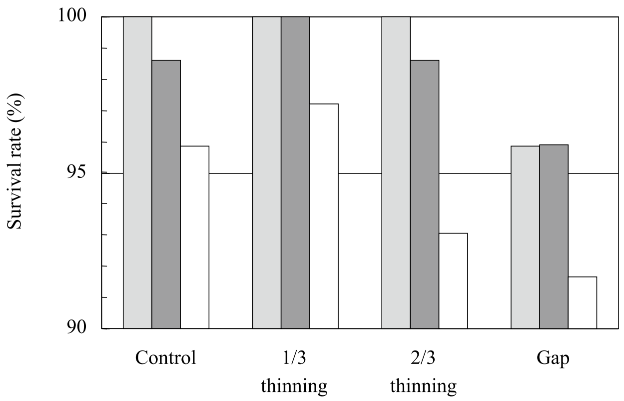

Fig. 3. Survival rate of the seedlings at 30 months after planting in each treatment
□ : *Hopea odorata*, ■ : *Hopea ferrea*, □ : *Xylia xylocarpa* var. *kerrii*.

3. Growth reaction to light environment

The increment of stem diameter during the 30 months was not different among species in dark conditions, as in the control plots (A, Fig. 5). As light conditions improved, however, differences in the increment started to appear. In the brightest conditions in the gap plots, the difference was very clear, showing the largest increment in *X. xylocarpa* var. *kerrii* and the smallest in *H. ferrea*. Thus, the regression line of *X. xylocarpa* var. *kerrii* was steepest, showing a light-demanding feature. A similar trend was observed in height increment, with the exception of a large increment of *H. ferrea* in dark conditions (B, Fig. 5). H/D ratio was clearly different among the species. It was highest in *H. ferrea*, ranging from 120 to 157, which represents a slender stem (Fig. 6). In contrast, H/D ratio of *X. xylocarpa* var. *kerrii* ranged from 58 to 78, representing a stocky stem. H/D ration of *H. odorata*, which exhibits an intermediate shape, ranged from 76 to 103. There was a decreasing trend in H/D ratio (i.e., the stem became more slender) in reduced light conditions in *H. odorata* and *H. ferrea*, while it remained constant in *X. xylocarpa* var. *kerrii* (Fig. 6).

Discussion

1. Growth performance of the seedlings and their habitats

It was remarkable that all the species exhibited such high survival rates under all light conditions. The survival rate of *H. odorata* was rather high compared with survival rates in previous studies[5,16,30]. According to an observation in a mixed deciduous forest in Western Thailand, the survival rate of *Xylia xylocarpa* var. *kerrii* seedlings, which were transplanted into a natural forest after growing in a nursery for one month, was 87% in a

Table 2. Sky factor for each treatment and year

Treatment	Control			1/3 thinning			2/3 thinning			Gap		
Plot	P1	P4	P7	P2	P5	P8	P3	P6	P9	P10	P11	P12
2007 Nov	24.7 fg	23.0 g	24.6 fg	32.8 d	31.2 de	25.5 f	38.3 c	30.4 e	29.8 e	60.6 b	65.2 a	64.2 a
2009 Jun	22.1 f	23.9 f	24 ef	27.2 d	26.5 d	23.9 f	32.2 c	26.1 de	26.4 d	55.5 b	66.1 a	63.9 a
	↓***	↑*	ns	↓***	↓***	↓***	↓***	↓***	↓***	↓**	ns	ns

Different letters beside the number indicate significant difference among the plots at 5% level.
Arrows and asterisks show the trend of increase/decrease of sky factor during 19 months and level of significance (***, <0.001; **, <0.01; *, <0.05), respectively.

gap while it was 16% under a forest canopy at one year after planting[21]. This survival rate was low and variable depending on the light conditions compared with our results because they had planted very young seedlings that could not survive transplanting. Intensive tending, such as clearing undergrowth, scraping, and frequent weeding (cf. design of the study plot in this paper), may have allowed high survival rates of the seedlings in this study.

H. odorata naturally distributes in flat landscapes near streams in dry evergreen forest[4,26]. Bunyavejchewin et al.[4] found that the frequency distribution of DBH of *H. odorata* follows a normal distribution with a mode at 80–100 cm DBH class in seasonal dry evergreen forest in Western Thailand. Regeneration of *H. odorata* is not continuous but needs a large disturbance, such as the falling of large trees[4].

In contrast, *H. ferrea* shows a reverse-J distribution with a peak at the smallest DBH class in dry evergreen forest near Sakaerat Silvicultural Research Station, suggesting that *H. ferrea* regenerates continuously[2]. In fact, a number of *H. ferrea* saplings survived in the dry evergreen forest despite there being few gaps in the forests[2]. It seems that the growth performances of the indigenous tree species observed in the current study reflect regeneration patterns in the natural habitat of each species. *H. ferrea* can grow under a canopy of fast-growing trees, such as under the gapless canopy of their original forest. Meanwhile, they cannot grow very well in gap sites, re-

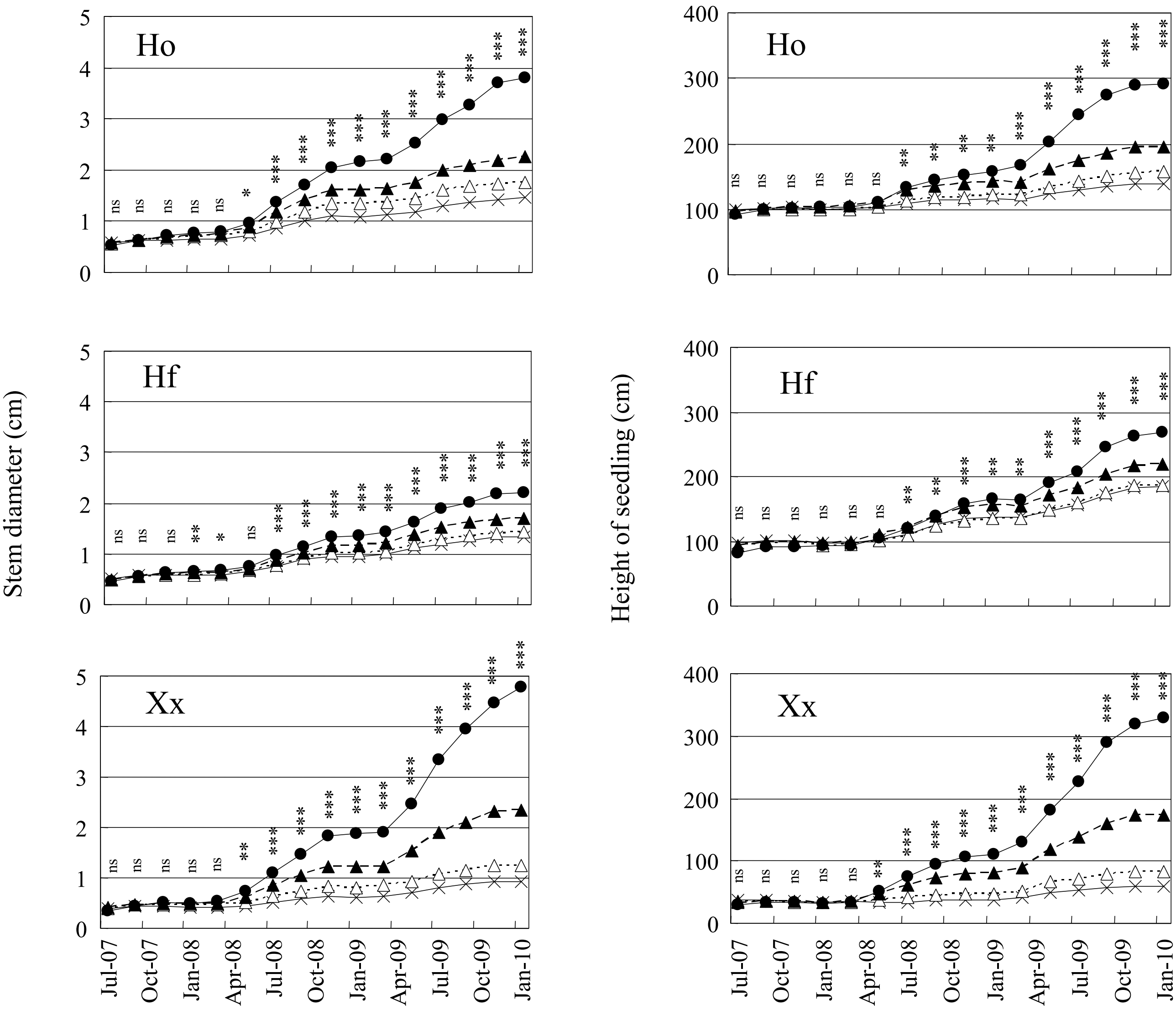

Fig. 4. Growth profile of the indigenous tree seedlings

Asterisks show significant difference among the treatments by ANOVA (***, significant at 0.1% level; **, 1% level; *, 5% level; ns, not significant).

●: Gap, ▲: 2/3 thinning, △: 1/3 thinning, ×: Control.

flecting the fact that they do not adapt to strong light conditions at an early stage of their life history. In contrast, *H. odorata* grows quickly in bright conditions, while its growth is limited in dark conditions. This may be due to its regeneration strategy, by which saplings wait for gap formation.

According to the growth pattern for different light conditions (Fig. 5), *X. xylocarpa* var. *kerrii* showed the most marked light-demanding feature among the species. Although the DBH distribution pattern of *X. xylocarpa* var. *kerrii* was not clear, the survival rate and height growth of seedlings were higher in gap sites than under the canopy of a mixed deciduous forest[21]. Seedlings of *X. xylocarpa* var. *kerrii* were found to be rather tolerant of drought and fire[21], although seed production and seedling recruitment were rare in the forest[20]. Rapid growth in a

Table 3. Stem diameter (at 30 cm above the ground) of the seedlings at two and a half years after planting

Treatment	Plot	*Hopea odorata*				*Hopea ferrea*				*Xylia xylocarpa* var. *kerrii*			
		Mean (cm)	SD			Mean (cm)	SD			Mean (cm)	SD		
Control	1	1.53	0.41	cd	x	1.30	0.23	cd	y	0.76	0.19	d	z
	4	1.73	0.40	cd	x	1.55	0.21	bc	xy	1.35	0.55	cd	y
	7	1.10	0.29	d	x	1.16	0.16	d	xy	0.70	0.40	d	y
1/3 thinning	2	1.99	0.49	bc	x	1.54	0.29	bc	y	1.52	0.65	bcd	y
	5	1.93	0.44	bc	x	1.38	0.35	cd	y	1.45	0.72	bcd	y
	8	1.36	0.36	cd	x	1.35	0.19	cd	x	0.76	0.23	d	y
2/3 thinning	3	2.62	0.72	b	x	1.82	0.38	b	y	2.38	0.95	bc	x
	6	2.13	0.68	bc	xy	1.71	0.30	b	y	2.46	0.85	b	x
	9	2.00	0.60	bc	xy	1.63	0.49	bc	y	2.15	0.72	bc	x
Gap	10	3.46	1.57	a	x	2.22	0.38	a	y	4.27	1.72	a	x
	11	4.27	1.52	a	x	2.32	0.44	a	y	4.86	1.84	a	x
	12	3.67	1.11	a	y	2.16	0.47	a	z	5.19	1.66	a	x

Different letters to the right of the numerical value indicate significant difference at 5% level: a, b, c, d and e among plots in each species, and x, y, and z among species in each plot.

Table 4. Height of the seedlings at two-and-a-half years after planting

Treatment	Plot	*Hopea odorata*				*Hopea ferrea*				*Xylia xylocarpa* var. *kerrii*			
		Mean (cm)	SD			Mean (cm)	SD			Mean (cm)	SD		
Control	1	141	36	cde	y	170	33	e	x	48	21	e	z
	4	162	36	bcde	y	205	45	cde	x	92	53	de	z
	7	114	34	e	y	179	43	de	x	40	23	e	z
1/3 thinning	2	173	39	bcd	x	200	40	cde	x	103	57	cde	y
	5	168	42	bcde	x	168	53	e	x	98	66	cde	y
	8	127	48	de	y	193	34	cde	x	47	21	e	z
2/3 thinning	3	208	57	b	x	220	59	bcd	x	158	68	bcd	y
	6	196	52	bc	x	225	61	abc	x	193	85	b	x
	9	183	42	bcd	xy	212	69	cde	x	167	56	bc	y
Gap	10	271	104	a	x	275	46	a	x	295	108	a	x
	11	312	102	a	x	267	60	ab	x	332	118	a	x
	12	289	75	a	y	264	61	ab	y	360	88	a	x

Explanations as in Table 3.

gap plot may support the assumption that regeneration of *X. xylocarpa* var. *kerrii* adapts to large disturbances including fires, which frequently occur in mixed deciduous forest in monsoon Asia.

In summary, *H. odorata* is tolerant to shading but its growth performance is maximized under bright conditions. *H. ferrea* is considerably shade-tolerant, which may make it more suitable for the rehabilitation of degraded forests. *X. xylocarpa* var. *kerrii* is a rather light-demanding species, which is not suitable for growing under the canopy of plantations.

2. Suitable thinning method for indigenous tree species

Previous studies have shown that the survival rate of some indigenous tree seedlings decrease in open sites, although the growth rate of the survived seedlings was increased[10,18]. Kamo et al.[13] reported that the survival rates of indigenous trees (e.g., *Eusideroxylon zwageri*, *Dryobalanops lanceolata*, *Shorea mecistopteryx*) drastically decrease under open site conditions. These observations show that the growth performances of some indigenous tree species are not high in open sites in tropical areas. In the current study, we did not set up an open site owing to limitations of space and budget. It is assumed that survival rates of seedlings are reduced in open sites given the trends in seedling survival rates: lower survival in the gap plot (cf. Fig. 3). However, a moderately low survival rate may be acceptable if final crop density is

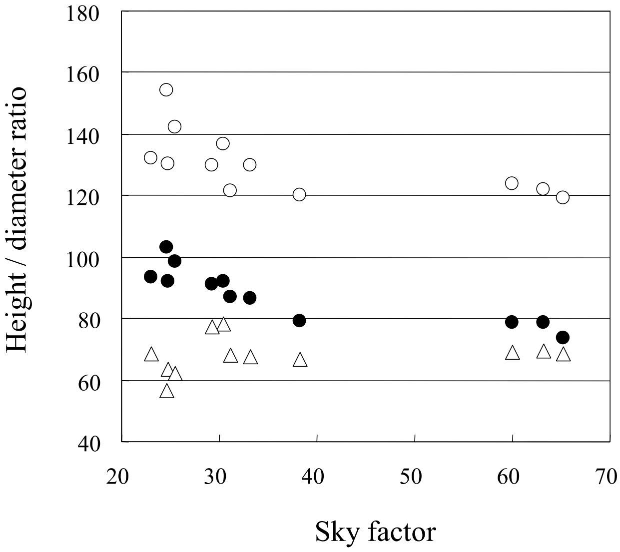

Fig. 6. Relationship between sky factor and height/diameter ratio
Symbols as in Fig. 5.

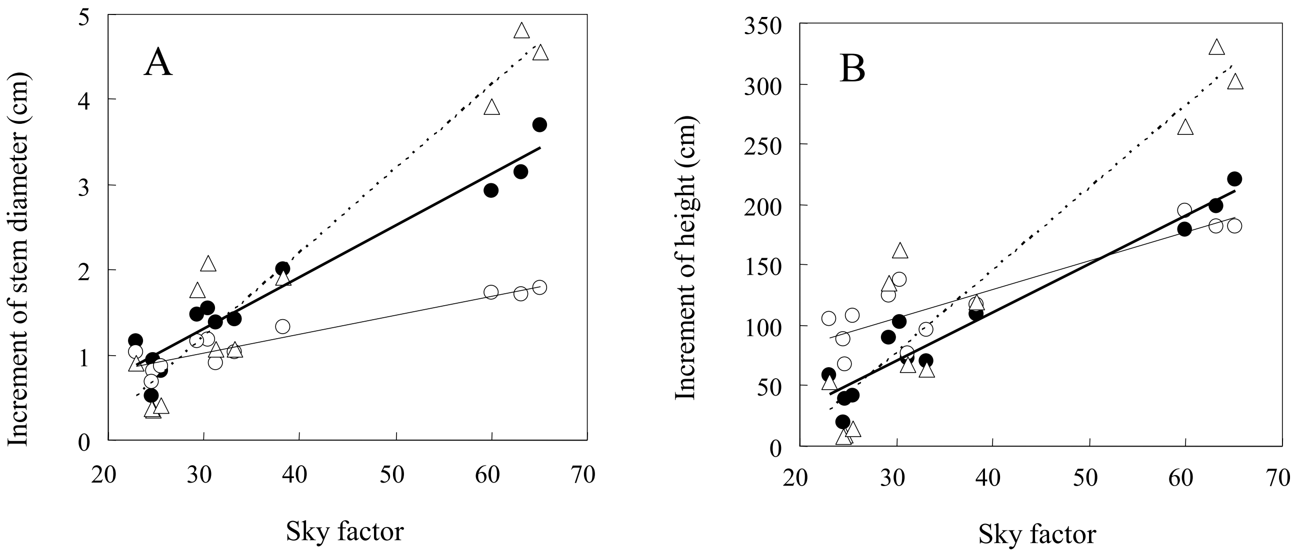

Fig. 5. Relationship between sky factor and increment of stem diameter (A) and height (B) of the indigenous tree seedlings during 30 months

Bold line, thin line and broken line show linear regression lines of *Hopea odorata*, *H. ferrea* and *Xylia xylocarpa* var. *kerrii*, respectively.
Stem diameter, Ho; y = 0.0609 x – 0.5246 (R^2 = 0.9448, $P < 0.0001$),
Stem diameter, Hf; y = 0.0225 x – 0.3407 (R^2 = 0.8864, $P < 0.0001$),
Stem diameter, Xx; y = 0.0985 x – 1.7480 (R^2 = 0.9285, $P < 0.0001$),
Height, Ho; y = 3.9903 x – 49.3204 (R^2 = 0.9337, $P < 0.0001$),
Height, Hf; y = 2.3707 x + 34.3302 (R^2 = 0.7878, $P < 0.0001$),
Height, Xx; y = 6.7997 x – 126.6723 (R^2 = 0.8810, $P < 0.0001$).
● : *Hopea odorata*, ○ : *H. ferrea*, △ : *Xylia xylocarpa* var. *kerrii*.

kept at 150 to 250 trees ha^{-1}, as described by Lapongan & Kelvin[18]. *H. odorata* can grow well in open sites, despite survival rates being reduced by 50.9 to 69.4% at 17 years after planting, which corresponds to 290 to 400 trees ha^{-1} [30].

Coniferous trees grown under a canopy tend to have a large H/D ratio (slender stem) and they were found to be vulnerable to windthrow damage after thinning[22]. In that context, *H. odorata* and *H. ferrea* seedlings established in the gap plot may be tolerant to strong winds. It is interesting that *X. xylocarpa* var. *kerrii* did not change in terms of stem slenderness in any light condition.

In the framework of a two-aged (two-layer) system, planting seedlings after creating a gap (group selection thinning) in a fast-growing tree plantation yielded high growth performance in the seedlings. The canopy of *A. mangium* started to recover in the thinning plots for which the light intensity on the seedlings declined, while it maintained the same level in the gap (Table 2). Despite the slight improvement of light conditions in the random selection thinning plots, growth of the seedlings was promoted along the gradient of light conditions (Figs. 4 and 5). However, it is assumed that their growth will be suppressed in random selection thinning plots in the near future. The random selection thinning method seems to have another disadvantage from the aspect of logging efficiency. Kondo & Imai[15] found that nearly 40% of lower trees were destroyed or injured in random selection thinning while around 10% were destroyed or injured in stripe selection thinning in two-storied forest (*Larix kaempferi* in upper layer and *Chamaecyparis obtusa* in lower layer). This shows that the vertical overlap of canopy tree and lower tree is harmful for lower trees at harvest time.

The size and shape of a gap are critical for the growth of seedlings because they determine light conditions. Height growth was found to be facilitated by increasing gap size in cool-temperate areas[34]. However, Coates[6] demonstrated that gaps do not need to be very large (0.1–0.2 ha or larger) for most tree species to achieve growth rates similar to those in open sites. In the current study, approximately double the height of the upper story was set for the gap size (50 m x 60 m; 0.3 ha). Fujimori[9] described that double the height of the upper story could be a threshold of logging size for dividing group selection thinning from clearcutting. Logging at double the surrounding tree height may achieve both high growth performance in the seedlings and lower impact on the environment. In order to introduce group selection thinning under a two-aged system, it will be necessary to establish a predictive model in which the light conditions and growth of planted seedlings can be simulated in a given gap size.

Acknowledgments

We are grateful to Dr. Tadao Gotoh of Forestry and Forest Products Research Institute (FFPRI) for his advice on statistical analysis and kind assistance in implementing this study. We thank Dr. Ryuichi Tabuchi of JIRCAS for valuable comments on the draft. We also thank the staff of Sakaerat Silvicultural Research Station for their assistance in data collection.

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