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Growth Performance of Four Dipterocarp Species Planted in a *Leucaena leucocephala* Plantation and in an Open Site on Degraded Land under a Tropical Monsoon Climate

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Abstract

To develop silvicultural methods for dipterocarp species in degraded lands in a tropical monsoon climate, we examined uneven-aged forest management, in which dipterocarp trees were planted under nurse trees, by monitoring their growth for 20 years. In 1989, seedlings of four dipterocarp species (*Dipterocarpus alatus*, *D. turbinatus*, *Hopea odorata* and *Shorea henryana*) were planted beneath a 3-year-old *Leucaena leucocephala* plantation and in an open site in Sakaerat, north-east Thailand. The survival rate and tree size of the dipterocarp seedlings were monitored at both sites until 1995. Surand svival rates of the dipterocarp trees were significantly better under the *Leucaena* plantation. However, no apparent difference was observed in basal area between both sites, since saw vigorous growth of the surviving seedlings compensated for the loss of dead seedlings at the open site. Our results showed that *D. alatus* and *H. odorata* could be planted in an open site due to the vigorous growth of the seedlings, but that it was preferable to plant *D. turbinatus* beneath nurse trees. The *Leucaena* plantation was partially thinned to 50, 75 and 100% (clear-cut) in 1993, and the survival rate and growth of the dipterocarps was monitored until 2009. Thinning had no apparent effect on the survival rates of the dipterocarp seedlings. Although relative growth rates (RGR) of the dipterocarps reduced after thinning, thinning rates did not affect the growth of the dipterocarps. After thinning, dipterocarp trees overtook *Leucaena* in height at all thinning rates, possibly from 1999. An uneven-aged system combining *Leucaena* and dipterocarp trees is likely to be applicable to several dipterocarp species.

Discipline: Forestry and forest products
Additional key words: *Dipterocarpus alatus*, *Dipterocarpus turbinatus*, *Hopea odorata*, *Shorea henryana*, uneven-aged forest management

Introduction

Dipterocarp trees are widely distributed in South-east Asia, and provide a number of ecological services, including conservation of genetic resources and biodiversity, as a carbon sink, and a supply of timber to local and global markets[12]. The growing shortage of forest resourc-

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es in the tropics has underlined the urgency of establishing silvicultural systems using indigenous tree species that are amenable to programmed replanting. Although some dipterocarp species (e.g. *Hopea odorata*) have been widely planted, and empirical knowledge accumulated[2,3], knowledge of dipterocarp species indigenous to local areas remains limited.

Planting dipterocarp trees in an open site sometimes results in failure, owing to strong direct sunlight, competition with weeds[7], and the risk of occasional fire. To prevent failure, trials have been carried out in which dipterocarp trees were planted beneath fast-growing tree plantations in Sri Lanka[4,5], South Kalimantan[20], Peninsular Malaysia[29], Saba, Malaysia[10], and Thailand[19,26,27]. In most cases, fast-growing plantations were logged according to a set pattern (random selection, stripes, gaps); targeting better light conditions for dipterocarp seedlings. Planting dipterocarp trees in secondary or degraded forests, called "enrichment planting," has also been trialed in South-east Asia[7,16,17,29,33]. These strategies appear successful, to the extent that some dipterocarp tree species (e.g. *Dipterocarpus baudii*, *Shorea leprosula*) show optimum photosynthetic or growth performance under moderate light conditions in the initial growth stages[11,29]. While dipterocarp species are mostly light-demanding[3], different species are adapted to a wide range of light conditions and/or soil fertilities[5]. This means an optimal environment specific to each dipterocarp species must be identified.

With the rapid growth of Thailand's monetary and commodity economy, many of its forests have been converted into agricultural land, with a resulting loss of forest coverage from 53.3% in 1961 to 25.3% in 1998, recovering to 30.1% by 2006[25]. Against this trend, and perhaps owing to its flat topography, the forest coverage of north-east Thailand plunged from 42% in 1961 to 15% in 2006[24]. North-east Thailand is an area of low productivity for agricultural and arboreal crops due to its long dry season and poor soils which originate from Mesozoic sandstone. Moreover, fire in the dry season is one of the main factors hampering the establishment of forest plantations in Thailand's monsoon climate[9]. Planting fast-growing trees over large areas of degraded land, however, has proved very effective in containing fires since, once established, trees suppress dominant grasses that are highly susceptible to fire during the dry season [28]. Planting indigenous trees after the establishment of fast-growing tree plantations would therefore appear a good strategy for reintroducing indigenous trees to degraded lands[5].

Using uneven-aged forest management, we examined the effects of *Leucaena leucocephala* as a nurse tree on dipterocarp seedlings in north-east Thailand, an area with a severe dry season and under a tropical monsoon climate. *Leucaena leucocephala* (Lamk) de Wit is a legume tree originating in South America and widely distributed in tropical areas worldwide, where it is used as firewood, charcoal, fodder, green manure, and for alley cropping[23]. *L. leucocephala* is also used in species-mixed plantations to improve soil moisture and nutrient levels in tropical areas[14,15,21]. We examined the following two questions: (1) whether the presence of nurse trees (*L. leucocephala*) improves the survival rate and growth of dipterocarp seedlings as compared with an open site; and (2) whether the thinning intensity of *L. leucocephala* affects the survival rate and growth of dipterocarp trees. Question (1) was examined by comparing the growth of dipterocarp trees between an *L. leucocephala* plantation and an open site for seven years following planting, while question (2) was examined by long-term monitoring following the thinning of the *L. leucocephala* plantation.

Study site and methods

1. Site description

This study was conducted at the Sakaerat Silvicultural Research Station, under the aegis of the Thai Royal Forest Department, in Nakhon Ratchasima Province, north-east Thailand. The mean annual air temperature was 25.6 ˚C and mean annual rainfall was 1395 mm, according to meteorological data collected at the station over the past decade (1999 to 2009). This area has a monsoon climate with highly seasonal rainfall and a roughly 4-month-long dry period lasting from November to February. The soil is a deep loamy acrisol, formed on sandstone laid down in the Triassic to Cretaceous periods[18] and generally contains only small amounts of organic matter[1]. The area around the study site had been covered with dry evergreen forest until the 1960s. The forest was then encroached by locals, who converted it to farmland. Although the farmland was cultivated for a couple of decades, most was eventually abandoned, after which tall grasses, such as *Imperata cylindrica* and *Saccharum spontaneum*, took over. Grassfires had become common in such grasslands. A reforestation project by the Japan International Cooperation Agency (JICA) and the Royal Forest Department was launched in 1982, and by 1994, over 2300 ha had been planted with exotic fast-growing tree species[26]. The area is currently covered with mature fast-growing tree plantations, mainly comprising *Acacia mangium* and *A. auriculiformis.*

2. Study plot design and dipterocarp species examined

For Question (1), dipterocarp seedlings were planted in two study plots (each measuring 32 x 76 m), one of which was allocated to a *Leucaena leucocephala* plantation (the *Leucaena* plot) and the other to an open site (the control plot). For Question (2), only the *Leucaena* plot was used for the thinning experiment. The *Leucaena* plot was divided into nine small rectangular quadrats which acted as base units for data collection and statistical analysis.

Prior to planting dipterocarps, seedlings of *L. leucocephala*, raised in a nursery for four months, had been planted at 2 x 2 m intervals in a flat study site (14˚30′24″N, 101˚54′13.5″E, 550 m a.s.l.) in the Sakaerat Silvicultural Research Station in April 1986.

Seeds of dipterocarp species (*Dipterocarpus alatus*, *D. turbinatus*, *Hopea odorata* and *Shorea henryana*) were collected in natural forests or from an arboretum near the Sakaerat Station. Each seedling was grown in a plastic bag (6 cm in diameter x 10.5 cm in height) filled with a mixture of soil, ash, sand, and organic compost in proportions of 5 : 3 : 2 : 2, respectively, at the nursery for approximately one year. The seedlings were watered twice daily year-round. Protective plastic mesh sheets at a height of 1.8 m were used to shade the seedlings from direct sunlight. To harden off the seedlings before transplanting, these sheets were removed one month beforehand. In June 1989, the dipterocarp seedlings were transplanted among 3-year-old *L. leucocephala* trees spaced at 2 x 2 m (Fig. 1). The mean height ± standard deviation of the seedlings at the time of transplanting were 35.1 ± 0.5 for *D. alatus*, 30.1 ± 0.6 for *D. turbinatus*, 30.0 ± 0.5 for *H. odorata*, and 31.5 ± 0.6 for *S. henryana* (ANOVA; $F_{3,401}$ = 61.54; p < 0.0001). *D. alatus* was significantly taller than the other dipterocarp species (Tukey's HSD test; p < 0.05). Each dipterocarp species was arranged in a line of 40 seedlings alternating with other species (Fig. 1). As the control plot, dipterocarp seedlings were planted in the same configuration in an open site nearby. For statistical analysis, both the *Leucaena* and control plots were divided into four clusters, each comprising four lines of different dipterocarp species, as

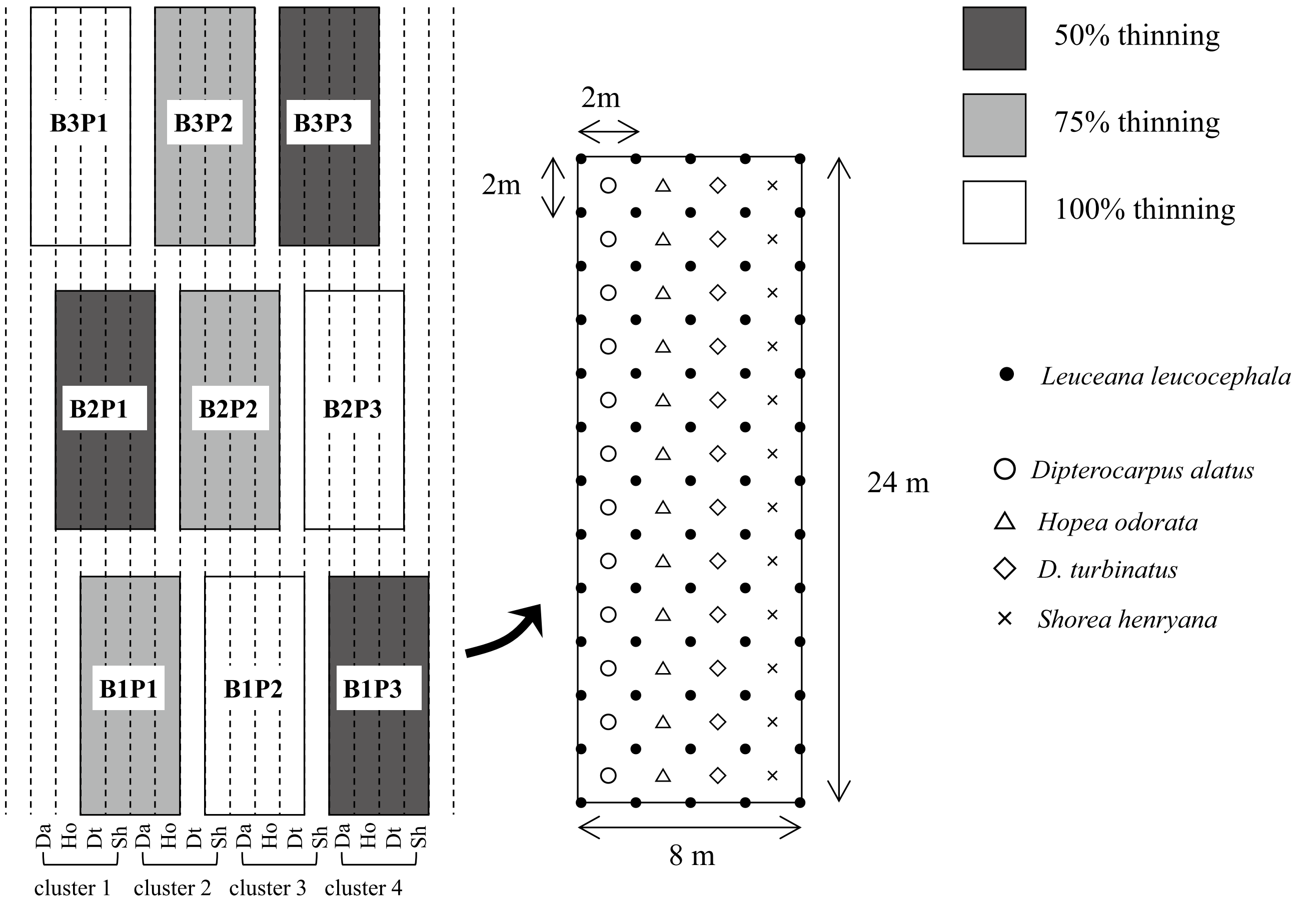

Fig. 1. Layout of the study plot in a *Leucaena leucocephala* plantation

The vertical broken lines show the planting lines of *L. leucocephala*. The dipterocarp species were planted alternately between the *L. leucocephala* lines, as shown at the bottom of the layout. Da: *Dipterocarpus alatus*, Ho: *Hopea odorata*, Dt: *D. turbinatus*, Sh: *Shorea henryana*. The stand of dipterocarps was divided into 4 clusters for statistical analysis with the control plot and rectangular quadrats were used to monitor the effects of thinning of *L. leucocephala*.

shown in Fig. 1.

Nine rectangular quadrats, each measuring 8 by 24 m, were set up in the *Leucaena*. plot (Fig. 1); three of which were randomly selected for three treatments: 50 and 75% thinning based on tree number, and clear-cutting (100% thinning) (Fig. 1). The thinned trees were selected mechanically in a checkered pattern in the 50%-thinned plot. Three of five lines were cut alternatively and additional trees were thinned in the remaining two lines in the 75%-thinned plot. Thinning was done in December 1993.

Dipterocarpus alatus occurs gregariously along rivers of up to 500 m in altitude in Indochina and Thailand. This tree grows to a very large size, and is a crucial source of construction timber[22]. *Dipterocarpus turbinatus* is indigenous to Indochina, distributed along riparian fringes at altitudes up to 350 m[31]. The silvicultural traits of this species are less well known. *Hopea odorata* is an evergreen tree indigenous to Indochina[22], where it grows in riparian or flat landscapes. Its timber is known as *merawan* and is employed for numerous uses, including construction and floorboards[22]. This species has been widely introduced in South-east Asia owing to its excellent growth performance[27]. *Shorea henryana* is a large tree found in dry evergreen forests up to an altitude of 900 m in Indochina and Peninsular Malaysia[22] and dominating the dry evergreen forest in Sakaerat[6]. The timber is a hard and heavy type, called *white meranti*, and used for special purposes such as shipbuilding[22].

3. Data collection and analysis

(1) *Leucaena leucocephala*

Stem diameter at breast height (DBH) and height of *L. leucocephala* were measured in December 1993 (seven years after planting and before thinning), December 1994 (after thinning) and September 2009. The survival rate, mean DBH, mean tree height and total basal area were calculated for each rectangular quadrat. Hypothesizing that the mean value (N = 3) followed a normal distribution, ANOVA was applied to each parameter in each year.

(2) Effects of nurse trees on dipterocarp seedlings

The stem diameter at ground level (D_0) and height of the dipterocarp seedlings were measured annually from 1989 to 1996 in both the *Leucaena* and control plots. The survival rates, mean D_0, mean height and basal area of the dipterocarp seedlings were calculated for each species in each cluster. To detect the statistical differences among the species, Tukey's HSD test was applied to the data in 1994 for both plots. Hypothesizing that the mean value (N = 4) follows a normal distribution, the Student's *t*-test was applied to the data to identify any statistical differences between the *Leucaena* and control plots, while a statistical analysis was applied to the survival rate after arcsine transformation. The measurements were halted in the control plot in 1995 for budgetary reasons.

(3) Effects of thinning

The stem diameter at ground level (D_0) or DBH, and the height of the dipterocarp seedlings were measured intermittently from 1989 to 2009 in the *Leucaena* plot, while the survival rates, mean D_0 or DBH, and mean height of seedlings were calculated for each rectangular quadrat. To identify any statistical differences among species or thinning rates, Tukey's HSD test was applied to the data. The survival rate was also arcsine-transformed for the statistical analysis and two-way ANOVA was applied to the data (D_0 or DBH, tree height) to detect the effects of thinning on the dipterocarp species, and any interactions. Relative growth rates (RGR) were calculated for the D_0 and height of the dipterocarp seedlings before and after thinning. Two-way ANOVA was applied to the data set of RGR as in tree-size data, while a *t*-test was applied to the RGR data to detect the effects of thinning. JMP[30] was used for all statistical analyses.

Results

1. Growth of *Leucaena leucocephala*

Ninety-seven to 100 percent of the *L. leucocephala* trees remained seven years after planting, and showed a mean DBH of 4.8 - 6.1 cm, tree height of 6.1 - 7.0 m, and basal area of 5.43 - 8.24 m^2 ha^{-1} at rectangular plot level. ANOVA revealed no significant difference in parameters (i.e. DBH, height and basal area) among the three treatments assigned for different thinning rates (50, 75 and 100%) (data not shown). In December 1994 (approximately one year after thinning), the number of trees and basal area decreased in proportion with the thinning rate, although the basal area varied significantly in the 50%-thinned plots (3.26 - 5.07 m^2 ha^{-1}). Significant differences were also observed in the number of trees (ANOVA: $F_{2,6}$ = 930.25; p < 0.0001%) and mean basal area ($F_{2,6}$ = 21.35; p < 0.001%), clearly owing to thinning, while none was observed in mean DBH or tree height. Fifteen years after thinning, the growth of *L. leucocephala* was poor, showing a mean DBH of 8.0 - 9.5 cm, 6.9 - 8.5 cm in the 50- and 75%-thinned plots, respectively, and tree heights of 7.5 - 9.1 m and 6.2 - 9.0 m, respectively. ANOVA for the last data set (in 2009) showed no significant difference in any parameter, probably due to the wide variations in their values (data not shown).

2. Effects of nurse trees on survival and growth of the dipterocarp species

In both the *Leucaena* and open plots, the survival rates of the dipterocarp seedlings stabilized after a rapid decrease in the first two years after planting (Fig. 2). *Dipterocarpus alatus* seedlings tended to show a high survival rate in both plots, while those of *D. turbinatus* were significantly lower than the other species (Fig. 2, Table 1). The survival rates of dipterocarps in the *Leucaena* plot significantly exceeded those in the open plot, except for *D. alatus* (Table 1).

The growth of the dipterocarp seedlings was slow during the first four years in both plots, and then accelerated in 1993 (Fig. 2). In both plots, *D. alatus* and *H. odorata* tended to outgrow the other two species (Table 1). The stem diameter at ground level (D_0) and height of the *D. alatus* seedlings were significantly greater in the open plot than the *Leucaena* plot at the individual tree level, although this trend was not observed in the other three species (Table 1). The basal area of *D. alatus* significantly exceeded that of the other species, while that of *D. turbinatus* was relatively small (Table 1). Although individual *D. alatus* seedlings were larger in the open plot, no statistical differences were observed in total basal area between the seedlings in the open and *Leucaena* plots (Table 1), perhaps due to the significant variation in data among the plots. The basal area of *D. turbinatus* was significantly greater in the *Leucaena* plot than in the open plot (Table 1).

3. Effects of thinning on the survival and growth of dipterocarp species

The survival rates of all the dipterocarp species decreased rapidly within the first two years after planting, by the time of thinning (Fig. 3). According to two-way ANOVA, the survival rates differed significantly among the dipterocarp species throughout the course of the study ($p < 0.05$ for 1989; $p < 0.001$ for the rest), while no significant differences emerged among the treatments with different thinning rate. *Dipterocarpus alatus* and *H. odorata* tended to exceed the other two species in individual tree size, irrespective of treatment (Tables 2 and 3). No significant differences were observed among the thinning rate in each species during the course of the study, except for *H. odorata* in 1991 (Fig. 3, ANOVA: $F_{2,6} = 15.17$; $p < 0.01$)

Two-way ANOVA revealed significant pre-thinning differences in the size of dipterocarp seedlings before the different thinning rates were applied (Tables 2 and 3). No

Table 1. Survival rate, size and basal area of four dipterocarp species (N = 4) in the open site (OP) and in the *Leucaena* plantation (LP) in 1994. Standard deviation is shown in parentheses

	Species	Open site		Leucaena plantation		
Survival rate (%)	*D. alatus*	78.0	a	83.7	a	ns
	D. turbinatus	6.1	c	44.3	b	OP<LP**
	H. odorata	60.7	b	75.4	a	OP<LP*
	S. henryana	53.8	b	79.7	a	OP<LP**
Stem diameter at the ground (cm)	*D. alatus*	7.2 (1.1)	a	5.1 (1.0)	a	OP>LP*
	D. turbinatus	2.5 (0.6)	c	2.6 (0.3)	b	ns
	H. odorata	4.6 (0.9)	b	3.6 (0.3)	b	ns
	S. henryana	3.1 (0.1)	bc	2.9 (0.2)	b	ns
Height (cm)	*D. alatus*	287 (39)	a	215 (39)	ab	OP>LP*
	D. turbinatus	158 (29)	b	159 (13)	c	ns
	H. odorata	304 (41)	a	263 (19)	a	ns
	S. henryana	163 (11)	b	179 (16)	bc	ns
Basal area ($m^2 \cdot ha^{-1}$)	*D. alatus*	8.88 (4.08)	a	5.07 (2.14)	a	ns
	D. turbinatus	0.09 (0.06)	b	0.79 (0.42)	b	OP<LP*
	H. odorata	2.98 (1.33)	b	2.28 (0.38)	b	ns
	S. henryana	1.12 (0.15)	b	1.43 (0.31)	b	ns

Different letters to the right of the figure indicate a significant difference among dipterocarp species at the 5% level. Significant differences between the open site (OP) and *L. leucocephala* (LP) are shown in the rightmost column: **: at the 1% level,*: 5% level, and ns: not significant.

interaction was observed at any time between dipterocarp species and the effect of thinning rate on DBH or seedling height. The relative growth rate (RGR) plunged after thinning except for the 50%-thinned plots in *D. turbinatus* and *S. henryana* (*t*-test in Table 4), while significance levels tended to be higher in *D. alatus* and *H. odorata* than in the remaining two species. Moreover, the significance levels tended to be higher in D_0 than tree height (Table 4). Two-way ANOVA showed that the RGR of D_0 differed among dipterocarp species before thinning, although this did not apply after thinning (Table 4). Unlike tree size (Tables 2 and 3), thinning rate (*or* local site difference among blocks in which different thinning rates were allocated) did not affect RGR (Table 4). No interaction was observed in RGR (Table 4). At the time of thinning, *L. leucocephala* (H = 6.1 - 7.0 m in 1993) was clearly taller than the dipterocarp seedlings (cf. Table 3). Heightwise, the dipterocarp trees caught up with and overtook *L. leucocephala* for every treatment until 2009, and possibly since 1999.

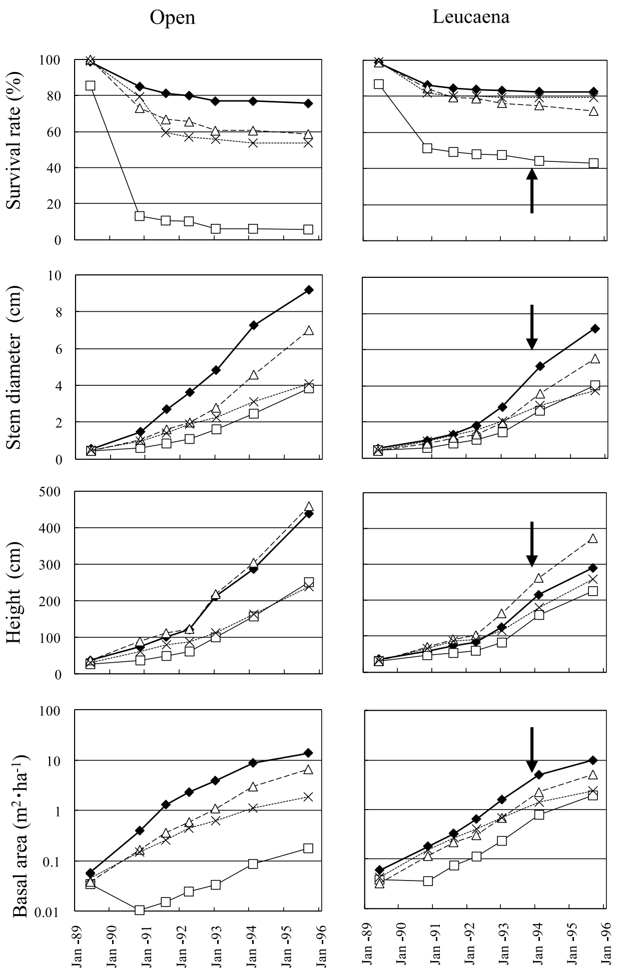

Fig. 2. Survival rates and growth of four dipterocarp species in an open site (left) and in an *L. leucocephala* plantation (right) from 1989 to 1996

The symbols show the mean values (N = 4) in each cluster (cf. Fig. 1). Filled diamond (◆): *Dipterocarpus alatus*, open triangle (△): *Hopea odorata*, open square (□): *D. turbinatus*, criss-cross (×): *Shorea henryana*. The solid arrows show the time of thinning of *L. leucocephala*.

Discussion

1. The effect of *L. leucocephala* on dipterocarp trees

The growth of *L. leucocephala* is highly dependent on soil properties, light, and temperature[23]. Compared with the growth data reported worldwide[8,15], however, the productivity of *L. leucocephala* was relatively low in Sakaerat, indicating the unsuitability of the soil. The acidity of the soil (pH 4.8 - 5.9) around the Sakaerat Station[1] may have been responsible, since *L. leucocephala* is not suited to acid soils[23].

In the current study, the presence of *L. leucocephala* clearly improved the survival rate of the *D. turbinatus*, *H. odorata*, and *S. henryana* seedlings. Among these species, however, the effect on stand growth (i.e. stand basal area) was observed only in *D. turbinatus*. Despite a proportion of *H. odorata* and *S. henryana* dying in the open site, the vigorous growth of the surviving seedlings compensated for the loss. Similar observations have been reported in previous studies in the Sakaerat Station[26], and other tropical areas, such as Saba, Malaysia[13] and Vietnam[17]. Although *D. alatus* can be planted in an open site, it could also survive and grow in *L. leucocephala* plantations, eventually overwhelming the other species in the basal area (cf. Fig. 2). A number of studies have reported constrained dipterocarp tree growth and/or survival rate under a closed canopy of fast-growing trees (e.g. Caribbean pine[4,5], *Acacia mangium*[20,27]).

The effect of thinning is also unclear from the tree size data alone (Tables 2 and 3). However, RGR showed a drastic reduction in growth after thinning in most species and thinning rates (Table 4). RGR generally decrease as plants grow larger. Considering the fact that the reduction in growth occurred in the short term, it might be attributable to some sort of negative effects of thinning, such as drastic changes in light conditions (Table 4). Although a significant difference was observed among plots thinned at different rates in 1995 (Tables 2 and 3), it must have been partly due to the heterogeneous productivity of the site, not solely the thinning rate, because significant differences had been observed before thinning. However, RGR was not impacted by thinning rate or local site productivity (Table 4). Previous studies have demonstrated that moderate-sized gaps (openings) or stripe cutting in fast-growing plantations boosts the performance of dip-

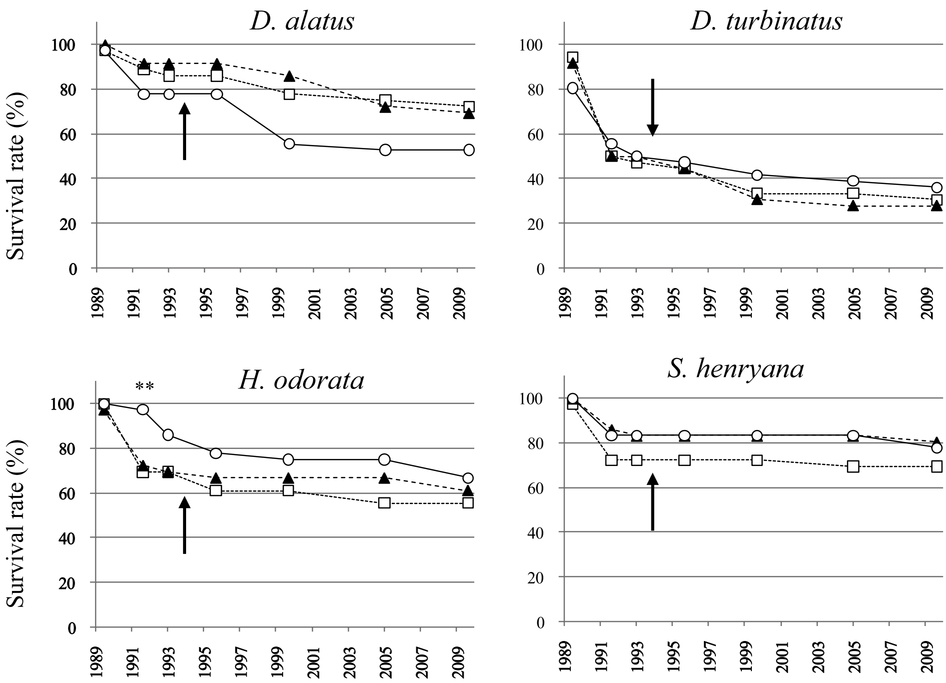

Fig. 3. Time course of survival rate of the four dipterocarp species with different thinning rates

The symbols show the mean survival rate (N = 3) in each rectangle quadrate (cf. Fig. 1). The solid arrows show the time of thinning of *L. leucocephala*. Open circle (○): 100% thinning (clear-cut), filled triangle (▲): 75% thinning, open square (□): 50% thinning. **: significant at 1% level by ANOVA (see the text).

Table 2. Stem diameter of four dipterocarp species over 20 years. Means (standard deviation) are shown (N = 3)

Species	Thinning rate	D_0 (cm)						DBH (cm)					
	(%)	1993			1995			1999			2009		
D. alatus	50	2.8 (0.3)	a	xy	7.2 (0.7)	a	-	7.3 (1.2)	a	-	11.8 (1.8)	a	-
	75	3.5 (0.4)	a	x	8.5 (0.2)	a	-	8.9 (1.2)	a	-	13.9 (2.0)	ab	-
	100	2.7 (0.3)	a	y	7.2 (1.1)	a	-	8.4 (2.1)	a	-	10.3 (3.4)	ab	-
D. turbinatus	50	1.2 (0.2)	b	-	3.2 (1.1)	c	-	3.9 (0.9)	b	-	6.2 (0.6)	b	-
	75	1.4 (0.3)	c	-	4.9 (1.4)	c	-	6.0 (1.8)	b	-	9.5 (2.4)	bc	-
	100	1.4 (0.3)	c	-	3.8 (1.1)	b	-	4.6 (2.2)	b	-	8.4 (2.9)	bc	-
H. odorata	50	1.8 (0.1)	b	-	4.9 (0.5)	b	-	6.8 (0.9)	a	y	12.7 (2.5)	a	-
	75	2.3 (0.4)	b	-	6.7 (0.7)	b	-	9.1 (1.0)	a	x	15.9 (1.0)	a	-
	100	1.9 (0.2)	bc	-	5.2 (0.6)	b	-	8.2 (0.6)	a	xy	14.1 (3.8)	a	-
S. henryana	50	1.9 (0.2)	b	-	3.5 (0.0)	bc	y	3.7 (0.8)	b	-	7.8 (1.1)	b	-
	75	2.2 (0.2)	b	-	4.2 (0.6)	bc	x	4.4 (1.0)	b	-	7.9 (0.9)	c	-
	100	2.2 (0.3)	b	-	4.2 (0.5)	b	x	5.2 (0.3)	b	-	8.4 (1.6)	c	-
Two-way ANOVA	Species	***			***			***			***		
	Thinning rate	***			***			**			*		
	Interaction	ns			ns			ns			ns		

Different letters to the right of the figure indicate significant difference at the 5% level: a, b, and c among dipterocarp species for each thinning rate, and x, y, and z among thinning rates in each species. Significant differences in two-way ANOVA are shown at the bottom as ***: Significant at the 0.1% level, **: 1% level, *; 5% level, ns: not significant.

Table 3. Tree height (m) of four dipterocarp species over 20 years. Means (standard deviation) are shown (*N* = 3)

Species	Thinning rate (%)	1993			1995			1999			2009		
D. alatus	50	1.22 (0.18)	ab	y	2.89 (0.53)	b	-	5.68 (0.85)	ab	-	10.42 (1.60)	a	-
	75	1.53 (0.14)	ab	x	3.47 (0.08)	ab	-	6.81 (0.79)	b	-	11.56 (1.19)	ab	-
	100	1.20 (0.06)	ab	y	2.84 (0.18)	ab	-	6.37 (1.20)	ab	-	10.86 (2.99)	ab	-
D. turbinatus	50	0.63 (0.11)	c	-	1.98 (0.67)	bc	-	4.27 (0.65)	bc	y	6.90 (0.50)	b	-
	75	0.89 (0.22)	c	-	2.48 (0.57)	c	-	6.02 (1.32)	bc	x	10.02 (0.64)	bc	-
	100	0.79 (0.03)	b	-	2.19 (0.48)	b	-	4.90 (1.08)	b	xy	8.92 (1.70)	b	-
H. odorata	50	1.51 (0.21)	a	-	3.66 (0.11)	a	-	6.73 (0.45)	a	y	10.49 (2.91)	a	y
	75	1.96(0.46)	a	-	4.15 (0.47)	a	-	8.24 (0.74)	a	x	13.78 (0.31)	a	x
	100	1.46 (0.29)	a	-	3.43 (0.20)	a	-	7.25 (0.53)	a	xy	12.36 (3.45)	a	xy
S. henryana	50	0.93 (0.31)	bc	y	2.48 (0.41)	c	-	3.65 (0.44)	c	y	8.37 (1.52)	ab	-
	75	1.28 (0.27)	bc	x	2.89 (0.52)	bc	-	4.82 (0.90)	c	xy	8.65 (0.81)	c	-
	100	1.19 (0.26)	ab	xy	2.96 (0.35)	ab	-	5.30 (0.21)	b	x	8.62 (1.15)	b	-
Two-way ANOVA	Species	***			***			***			***		
	Thinning rate	***			**			***			**		
	Interaction	ns			ns			ns			ns		

Explanations as in Table 2

Table 4. Relatrive growth rate (cm·cm^{-1}·yr^{-1}) of dipterocarp trees (*N* = 3) before and after the thinning of *L. leucocephala*

Species	Thinning rate (%)	Before thinning (Jan. 1993 – Feb. 1994)		After thinning (Feb. 1994 – Sept. 1995)		*t*-test for pre- vs. post-thinning	
		D_0	Height	D_0	Height	D_0	Height
D. alatus	50	0.389	0.368	0.189	0.169	***	**
	75	0.388	0.362	0.179	0.161	***	**
	100	0.39	0.356	0.207	0.186	***	**
D. turbinatus	50	0.329	0.368	0.171	0.228	ns	ns
	75	0.418	0.42	0.243	0.203	ns	**
	100	0.407	0.47	0.212	0.15	*	**
H. odorata	50	0.421	0.382	0.188	0.178	***	**
	75	0.389	0.274	0.262	0.201	**	ns
	100	0.373	0.318	0.245	0.22	***	*
S. henryana	50	0.263	0.396	0.148	0.209	ns	ns
	75	0.271	0.321	0.158	0.198	**	**
	100	0.27	0.32	0.169	0.24	**	ns
Two-way ANOVA	Species	***	ns	ns	ns		
	Thinning rate	ns	ns	ns	ns		
	Interaction	ns	ns	ns	ns		

*: Significant at the 5% level, **: significant at the 1% level, ***: significant at the 0.1% level, ns: not significant.

terocarp seedlings[5,20,27]. Although our results seem to contrast with these previous studies, the dipterocarps grew steadily after thinning, retaining their long-term survival rates (Tables 2 and 3, Fig. 3). In summary, thinning rates had no apparent effects on the survival rates and growth of dipterocarp trees, while thinning inhibited the growth of dipterocarps in the short term.

It is remarkable that the dipterocarp trees could overtake *L. leucocephala* in height, despite the fact 50% of the *L. leucocephala* stems were left. This is quite different from the case of *Acacia auriculiformis* and *Eucalyptus camaldulensis*, which were used as nurse trees for *Hopea odorata* at the Sakaerat Station[26]. Because *A. auriculiformis* and *E. camaldulensis* had grown tall (>11 and >15 m in height, respectively) at the time of thinning, dipterocarp trees (*Hopea odorata*; mean height 1.15 to 1.59 m) were ultimately unable to catch up with them. Meanwhile, *Hopea odorata* overtook *Senna siamea*, a moderately-growing tree at Sakaerat Station, achieving excellent growth of *H. odorata*[26]. Thus, growing dipterocarp trees in a *L. leucocephala* plantation could be feasible in terms of improvement of the survival rate, provided thinning is applied at the proper time.

2. Species selection and suitable forest management

Our results suggest that *D. alatus* and *H. odorata* can be planted in both open sites and forests where seedlings should retain a certain survival rate and growth. Conversely, *D. turbinatus* should be planted under shade rather than in open sites. *Shorea henryana* exhibited equivalent growth in the *Leucaena* and open plots. It could thus be profitable to grow dipterocarp trees together with *L. leucocephala*, as we demonstrated in the current study, to maintain the survival rate of dipterocarp seedlings and obtain intermediate crops produced by the thinning of *L. leucocephala*. Because *L. leucocephala* is used for firewood or charcoal, thinning at a stem size (DBH) of 5 - 7 cm would be of practical use.

In summary, uneven-aged forest management combining *L. leucocephala* and dipterocarp species facilitated the survival rate of the dipterocarps and could provide planters with intermediary crops. This method is potentially useful; not only for timber production but also to rehabilitate degraded land, as McNamara et al.[16] and Sovu et al.[32] have demonstrated in Indochina.

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