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Effects of nutrient addition, mulching and planting-hole size on early performance of *Dryobalanops aromatica* and *Shorea parvifolia* planted in secondary forest in Sarawak, Malaysia

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Abstract

Native species of the Dipterocarpaceae are being planted throughout Southeast Asia as a source of future timber and to restore degraded lands. A detailed understanding of factors controlling seedling performance is required for the successful planting of dipterocarps. Below-ground resource availability is hypothesized to have a significant affect on seedling performance of dipterocarp species when planted in selectively logged forests or in open, degraded areas. This study tested three methods thought to increase below-ground resource availability and thereby improve the performance of two dipterocarp species (*Dryobalanops aromatica* and *Shorea parvifolia*) when grown in degraded secondary forest: nutrient addition, mulching, and increased planting-hole size. Seedlings of the two species were grown in two planting-hole sizes (12 cm × 18 cm and 20 cm × 30 cm), with and without nutrients (NPK), and with and without mulching. The experiment was conducted in two sites (Sampadi and Balai Ringin) in Sarawak, Malaysia, to test for spatial variation in treatment effects. Seedling growth and survival were monitored over 22 months. Seedling survival was >94% for both species and did not differ significantly among any of the treatments. High monthly rainfall throughout the first year of the experiment may have enhanced seedling survival. Nutrient addition had the strongest effect on seedling growth for both species, with nutrient addition increasing growth by >50% at Sampadi and for *D. aromatica* in one block at Balai Ringin. There was significant spatial variation in treatment effects. *S. parvifolia* did not respond to nutrient addition at Balai Ringin, suggesting that the plants may not have received the added nutrients in that site. Mulching had a positive effect on growth at Sampadi, but no effect or a negative effect at Balai Ringin. Further analysis of the specific effects of mulching on resource supply is required. Planting-hole size did not have a consistent significant effect on the growth of either species. This may have been due to the favorable soil water status during the experiment. The results of this experiment emphasize the potential importance of site effects and interactions between site and treatment effects in enrichment planting trials using dipterocarps. Further experimental studies on below-ground resource limitations of dipterocarp growth in a wide range of sites are required. Studies that monitor the availability and fluxes of soil resources will be the most informative.

Keywords: *Dryobalanops*; Enrichment planting; Fertilizer; Mulching; Nutrient addition; *Shorea*

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1. Introduction

Enrichment planting in Malaysia has been motivated by the need to improve regenerating forests for future timber production, and by the desire to restore and thereby protect degraded unproductive areas (Appanah and Weinland, 1993; Kollert et al., 1996). The success of enrichment planting depends on a wide range of factors, including site conditions, species characteristics, the specific planting techniques and treatments applied, as well as social and economic factors (Evans, 1996). While there has been extensive silvicultural research for plantation establishment in the tropics generally (Evans, 1996), the information available for planting indigenous tree species in Malaysia remains limited (Appanah and Weinland, 1993; Raja Barizan and Ibrahim, 1998).

The majority of cases of enrichment planting of native species in Malaysia involve members of the Dipterocarpaceae (Kollert et al., 1996), the dominant tree family of Malaysia's natural lowland forests. A detailed understanding of the factors controlling seedling growth and survival is required for developing areas of enrichment planting. The relationship between dipterocarp seedling performance and light availability has been studied in numerous species and is reasonably well known (e.g., Ismail, 1964; Sasaki and Mori, 1981; Ashton, 1995; Whitmore and Brown, 1996; Ashton et al., 1997; Barker et al., 1997). As saplings, potential plantation dipterocarp species vary from moderately to very shade tolerant. In field trials, rates of dipterocarp growth and survival are consistently better in moderate light levels than in the understorey of either primary or secondary forest (Ang, 1991; Adjers et al., 1995; Raja Barizan, 1996; Raja Barizan and Appanah, 2000).

Despite improved growth rates of dipterocarp saplings when planted in partially open areas or in lines cut through degraded forests, mortality rates remain unacceptably high in planting trials (Adjers et al., 1995; Suhaili et al., 1998). Most trials have been conducted in either selectively logged forests, or in areas that have been logged and then cleared for shifting cultivation. Both logging and shifting cultivation lead to significant changes in below-ground resources that may negatively affect the growth and survival of planted seedlings. In logged forests, substantial areas are cleared of topsoil and compacted leading to nutrient loss, increased soil temperatures, reduced water availability, and changes in the soil microflora (Malmer and Grip, 1990; Nykvist et al., 1994; Nussbaum et al., 1995a).

There have been relatively few experimental tests of nutrient limitation of dipterocarp seedling growth in the field (Raja Barizan and Ibrahim, 1998). Nursery studies using potted seedlings have shown that the addition of both nitrogen (Yap and Moura-Costa, 1996; Bungard et al., 2000) and phosphorus (Sundralingam et al., 1985; Gunatilleke et al., 1997) may enhance the growth of dipterocarp seedlings (but see Turner et al., 1993; Burslem et al., 1995). Whether these results reflect nutrient limitations in the field is unknown (Burslem et al., 1995). Forest departments in Malaysia routinely apply nutrients to dipterocarps when planted in secondary, degraded forests (Appanah and Weinland, 1993; Krishnapillay, 2002), but whether the nutrient effects are species- or site-specific remains largely untested. The few field experimental studies that have been conducted suggest that nutrient limitation may be common in enrichment planting conditions. Phosphorus applied to potted seedlings had a significant positive effect on seedling performance following out-planting in two dipterocarp species in Peninsular Malaysia (Raja Barizan and Appanah, 2000). Nussbaum et al. (1995b) found strong growth responses to nutrient addition on very low fertility, heavily compacted, log-landing sites with no topsoil. Seedlings grown in the same sites with topsoil replaced had growth rates similar to nutrient addition plots suggesting that in logged areas outside of compacted areas, seedling growth may not be as severely nutrient limited. Further work is needed to assess whether nutrient limitation is widespread in enrichment planting conditions, and more generally which components of below-ground resources are most limiting to seedling growth during tree establishment. This will facilitate the development of techniques for ameliorating these effects and enhancing dipterocarp enrichment planting success.

In this study, we conducted a field experiment to test three methods thought to enhance below-ground resource availability, and thereby improve the performance of dipterocarp seedlings when planted to enrich degraded secondary forest. The three methods were: nutrient addition, mulching, and increased planting-hole size. Nutrient availability may strongly limit sapling performance as discussed above. Mulching is thought to help in soil moisture retention, by excluding weeds from early colonization, and by subsequently becoming a source of nutrients through decomposition (Evans, 1996; Suhaili et al., 1998). The size of the hole into which seedlings are planted may also significantly affect seedling survival and growth through changes in soil aeration, rooting density, or rates of infiltration. The survival and growth of seedlings of two native dipterocarp species under these three different planting methods were monitored in a field experiment in Sarawak. The experiment was conducted in two sites in order to assess the degree to which responses vary spatially.

2. Study species

Two dipterocarp species, *Dryobalanops aromatica* Gaertn. f. and *Shorea parvifolia* Dyer, were selected for this experiment. These species were chosen due to their importance for Malaysia's timber industry and their purported suitability for large scale planting (Ismail, 1964; Abdul Rahman et al., 1996). They have been widely used in enrichment planting and are thought to be among the more promising dipterocarp plantation species due to their relatively fast growth (Wyatt-Smith, 1963; Kollert et al., 1996). Under natural conditions, *D. aromatica* grows in patches on well-drained, leached, sandy to sandy-clay soils. It is particularly common on sandstone-derived ridges and hilltops in exposed sites that are prone to water stress (Ashton, 1964; Itoh et al., 1997). *S. parvifolia* normally occurs on clay soils, or sandy soils with a high clay fraction (Ashton, 1964). It is often found in low-lying areas on moderately fertile soils with abundant soil water. Both species are moderately to very shade tolerant as seedlings (Barker et al., 1997; Itoh et al., 1999), and as saplings and poles they perform best in moderate to high light levels (Wyatt-Smith, 1958; Adjers et al., 1995; Schwarzwaller et al., 1999).

3. Materials and methods

3.1. Study sites

The experiment was conducted in two sites in west Sarawak, Malaysia: Sampadi Forest Reserve (1°32′N, 110°05′E; hereafter Sampadi) which is 72 km southwest of Kuching, and Balai Ringin Protected Forest (1°02′N, 110°48′E; Balai Ringin) which is 120 km southeast of Kuching. Both sites have an aseasonal climate with all months receiving on average >100 mm of rain. Average annual rainfall for Sampadi is 4100 mm, and for Balai Ringin is 3500 mm. Both sites are in the lowlands (<300 m) with a similar topography of low undulating hills. The sites are also similar in vegetation cover and history of land-use change. Both sites were originally covered in primary, lowland, mixed dipterocarp rain forest. The forests were first logged in the 1970s. Logging roads provided easy access for shifting cultivators who cleared the land and planted hill rice. Following the abandonment of shifting cultivation in the mid- to late-1990s, forest has regenerated and now consists of young secondary successional forest dominated by species of *Macaranga*, *Ficus* and *Mallotus*, as well as *Endospermum malaccense* and *Alstonia angustiloba*. The canopy of the secondary vegetation was very open and ca. 5–10 m tall.

3.2. Soil sampling and analysis

The soils of Sampadi are a combination of sandstone-derived, coarse-grained, humult ultisols, and finely clayey alluvial soils of the Merit Series. The geology of Balai Ringin is heterogeneous consisting of a mixture of shale with fine-grained sandstones, and large areas of medium- and coarse-grained sandstone. The soils of the Balai Ringin study area belong to the Bandang and Saratok families and are mainly greyish colored with a coarse to finely loamy texture (Melling and Siong, 1995).

Soil sampling was conducted during site preparation for planting. Nine soil cores were taken at Sampadi and 12 were taken at Balai Ringin. Sampling was evenly distributed across each site. Samples were collected from 0 to 20 and 20 to 30 cm depth with a 2.5 cm diameter soil auger. Soil samples were air-dried, ground and sieved with a 2 mm mesh sieve for chemical analysis. Total N, total P, available P (Bray) and exchangeable cations were determined following standard methods outlined in Chin (1993).

3.3. Experimental design and implementation

The experiment involved two species, two sites, four soil treatments, and two planting-hole sizes. For each species in each site, the eight treatment combinations (four soil treatments by two planting-hole sizes) occurred once in each of two blocks. In each treatment combination, 25 seedlings were line-planted in five rows of five trees with a spacing of 5 m between adjacent trees. In total, 1600 seedlings were included in the experiment.

Seeds of both species were germinated in 12 cm × 18 cm polythene bags filled with a mixture of one part sand and three parts topsoil. The seedlings were planted in the nursery in March 1999, and kept under two layers of neutral-density shade netting (ca. 20% full sun) before being transported to the field for planting in October 1999.

Seedlings were planted in the field in the middle of 2 m wide cleared lines aligned east-west, following the normal reforestation practice of the Sarawak Forest Department (SFD). Prior to planting, all vegetation in each line was slashed with a parang or cut with a chainsaw close to ground level. Cut wood was stacked in between the planting lines. Leaf litter was either stacked in between planting lines or used in the mulch treatment (see below). No burning was carried out. Following planting, climbers and weeds directly interfering with the planted seedlings were removed every 6 months.

3.4. Experimental treatments

The four soil treatments were an untreated control, mulch addition, nutrient addition, and a combination of mulch and nutrient addition. For mulch addition, slashed grass and woody debris resulting from line clearing were accumulated to 4 cm thick on the soil surface for 50 cm surrounding the seedlings. For nutrient addition, 100 g of NPK fertilizer (12:12:12; Sebatian Biru, Pertubuhan Peladang, Malaysia) was buried in ca. 5 cm deep holes around the seedlings. Fertilizer was applied 1 week after planting prior to the addition of mulch, and then at 6-month intervals after planting, as is the typical SFD practice. The mulch plus nutrient addition treatment involved the same quantities as in separate treatments.

Seedlings were planted into either 12 cm × 18 cm (diameter × depth) or 20 cm × 30 cm holes. The smaller planting-hole was dug with a hand-held augur as is currently the practice of the SFD in reforestation projects. The larger planting-hole was dug with a motorized auger (Model: BT360, STIHL, Germany). Removed soil was repacked around the roots of all seedlings after planting.

3.5. Data collection and analysis

Seedling stem height and diameter, and survival were assessed immediately after planting, and after 22 months. Plant height to the tip of the apical shoot was measured to the nearest 1 cm. Stem diameter was measured at 10 cm above ground level with electronic calipers.

A nested-factorial analysis of variance (ANOVA) was used to analyze treatment effects on relative growth rates. The model included the terms: S, T, P, B(S), S × T, S × P, T × P, S × T × P and an error term, where S is sites, T is soil treatments, P is planting-hole size, and B(S) is blocks nested within sites. Interactions with the block term could not be estimated because there was no replication of treatments within blocks (Underwood, 1997). The analysis found significant block-within-site effects for *D. aromatica* growth, so treatment effects were analyzed separately for each species. Post-hoc comparisons following significant ANOVAs were tested with Tukey HSD tests. Analyses were performed using JMP version 4.0.4 (SAS Institute, Cary, NC). Tests for differences in mortality rates used logistic regression analysis using the same model terms as for the growth analyses.

4. Results

4.1. Soil properties

The two sites used for this experiment, Sampadi and Balai Ringin, had similarly low levels of soil nutrients (Table 1). Balai Ringin soils had slightly higher concentrations of available and total phosphorus than Sampadi soils, however the differences were only significant for available phosphorus at 20–30 cm. Soil carbon from 0 to 20 cm was significantly greater in Sampadi soils.

4.2. Seedling survival

Seedling survival was high among all treatments for both species in this experiment. Mortality over 22

Table 1
Soil chemical properties at the two experimental sites: Sampadi (SA; $n = 9$ per depth) and Balai Ringin (BR; $n = 12$)

Site	Depth (cm)	N (%)	C (%)	Available P (ppm)	Total P (ppm)	Ca (cmol/kg)	Mg (cmol/kg)	K (cmol/kg)	Na (cmol/kg)	CEC (cmol/kg)
SA	0–20	0.119 (0.01)	1.63 (0.09)[*]	5.44 (0.56)	76.4 (11.7)	1.47 (0.31)	0.24 (0.05)	0.225 (0.03)	0.139 (0.03)	8.13 (1.06)
BR	0–20	0.119 (0.01)	1.36 (0.09)[*]	7.09 (0.67)	114.9 (9.6)	1.62 (0.19)	0.30 (0.05)	0.174 (0.02)	0.147 (0.02)	7.89 (0.58)
SA	20–30	0.043 (0.01)	0.41 (0.04)	1.33 (0.24)[*]	65.6 (15.7)	0.50 (0.13)	0.15 (0.07)	0.102 (0.02)	0.106 (0.03)	5.66 (1.47)
BR	20–30	0.056 (0.01)	0.37 (0.05)	2.67 (0.33)[*]	82.6 (7.5)	0.62 (0.19)	0.02 (0.01)	0.094 (0.01)	0.174 (0.03)	5.69 (0.60)

[*] Significant differences ($P < 0.05$) between sites.

months was 4.2% for *D. aromatica* and 5.5% for *S. parvifolia*, with a total of only 78 of 1600 seedlings dying over the 22-month period. Mortality rates did not differ significantly between species, sites, or among planting treatments.

4.3. Diameter and height growth

Soil treatments had a significant affect on diameter and height growth for both species (Table 2), however the response to soil treatments varied between the two sites (Figs. 1 and 2). For *D. aromatica*, there were strong treatment effects in Sampadi, whereas at Balai Ringin there was a strong treatment effect in only one of the two blocks. For *S. parvifolia*, there were strong treatment effects in Sampadi, but not in Balai Ringin.

Nutrient addition significantly enhanced seedling diameter growth rates for both species in Sampadi (Fig. 1). Seedlings with added nutrients had ca. 50% higher relative growth rates than control seedlings. In addition, seedlings in nutrient plus mulch treatments had significantly higher growth rates than seedlings

Table 2
Diameter and height growth increments for seedlings of *D. aromatica* and *S. parvifolia*[a]

Soil treatment	Pot size	Diameter growth (mm per year)		Height growth (cm per year)	
		Sampadi	Balai Ringin	Sampadi	Balai Ringin
D. aromatica					
Control	Big	3.1 (0.17)	3.7 (0.28)	50.5 (2.7)	57.9 (4.1)
Control	Small	3.6 (0.22)	4.3 (0.22)	52.0 (2.2)	68.3 (4.0)
Mulch	Big	4.6 (0.24)	4.4 (0.29)	51.7 (2.5)	51.3 (3.8)
Mulch	Small	3.8 (0.24)	4.5 (0.32)	51.2 (3.3)	61.8 (4.0)
Nutrient	Big	5.2 (0.32)	4.9 (0.24)	60.4 (4.5)	67.6 (3.9)
Nutrient	Small	6.3 (0.28)	5.6 (0.30)	79.2 (4.0)	77.8 (4.1)
Nutrient plus mulch	Big	7.0 (0.35)	4.9 (0.32)	65.5 (3.4)	65.8 (4.3)
Nutrient plus mulch	Small	6.2 (0.27)	5.3 (0.29)	70.3 (3.2)	67.3 (5.0)
S. parvifolia					
Control	Big	4.8 (0.29)	6.9 (0.49)	24.2 (2.1)	69.8 (5.5)
Control	Small	4.4 (0.28)	6.4 (0.63)	24.5 (1.9)	64.8 (6.4)
Mulch	Big	5.0 (0.42)	4.8 (0.35)	26.0 (2.6)	38.9 (3.2)
Mulch	Small	4.8 (0.31)	6.1 (0.37)	26.1 (2.9)	50.8 (3.3)
Nutrient	Big	8.3 (0.40)	5.5 (0.50)	53.6 (2.8)	64.3 (4.4)
Nutrient	Small	8.5 (0.47)	9.3 (0.64)	64.9 (3.6)	85.9 (4.9)
Nutrient plus mulch	Big	10.5 (0.61)	6.4 (0.46)	74.6 (5.9)	69.0 (5.5)
Nutrient plus mulch	Small	10.6 (0.56)	7.1 (0.65)	69.1 (3.7)	75.6 (5.6)

[a] Standard errors are given in parentheses, based on $n = 42-50$. Blocks are pooled for this table, but see Fig. 2 for details of significant block effects for *D. aromatica*.

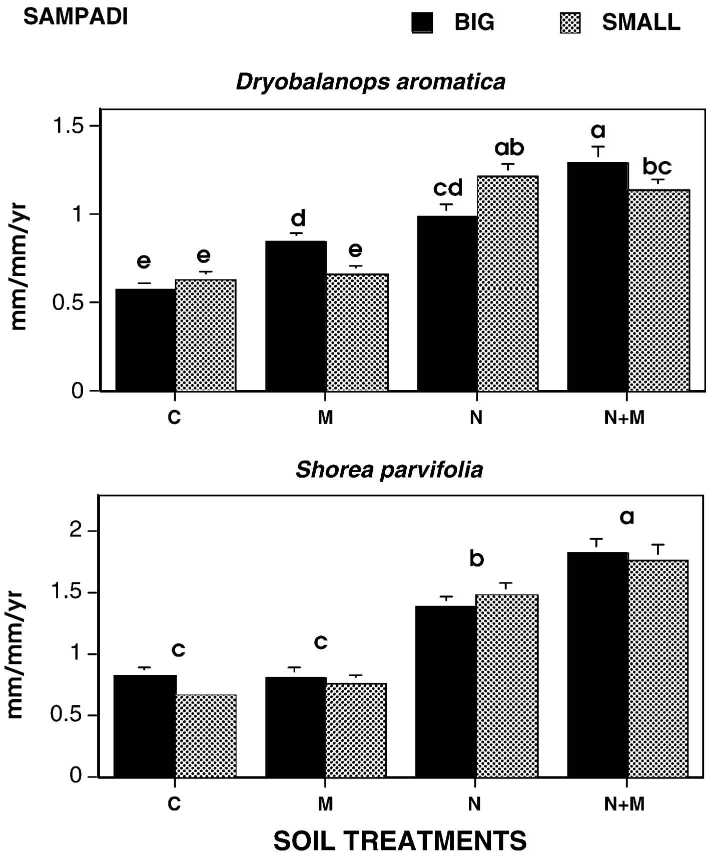

Fig. 1. Mean relative diameter growth rates (+1 S.E.) of seedlings of *D. aromatica* and *S. parvifolia* grown in four soil treatments (C—control, M—mulch, N—nutrient addition, and N + M—nutrient plus mulch addition) and two planting-hole sizes in Sampadi Forest Reserve. N = 42–50 per treatment combination. Note different *y*-axes for the two species. Different letters indicate significant differences ($P < 0.05$) between the means for each species. For *S. parvifolia*, planting-hole size had no effect on growth so different letters indicate significant differences between soil treatments only.

treated with mulch alone. In Balai Ringin, nutrient addition significantly increased seedling growth of *D. aromatica* in block C, but not in block D. In block D there were no treatment effects for this species (Fig. 2). For *S. parvifolia* seedlings at Balai Ringin, nutrient addition had weak and mostly non-significant effects on growth rates (Fig. 2). Although, seedlings planted in small planting-holes grew significantly better with nutrient addition (Fig. 2).

Mulch addition had a much weaker affect on seedling growth than nutrient addition (Figs. 1–3). For *D. aromatica*, diameter growth rates were significantly increased by mulch addition for seedlings grown in large planting-holes at Sampadi, and in block C at Balai Ringin. In both cases, diameter growth was significantly greater in mulch addition treatments than in control treatments, and in nutrient plus mulch treatments than in nutrient-only treatments. Growth of *D. aromatica* in block D was not significantly affected by mulch addition. For *S. parvifolia*, diameter growth of mulch addition plants was not significantly greater than for control plants in either site (Figs. 1 and 2). However, at Sampadi, *S. parvifolia* seedlings given mulch plus nutrients had significantly greater growth rates than for seedlings given nutrients only (Fig. 1). At Balai Ringin there was some evidence of a negative effect of mulch addition on seedling growth for *S. parvifolia*. Seedlings in big planting-holes that were

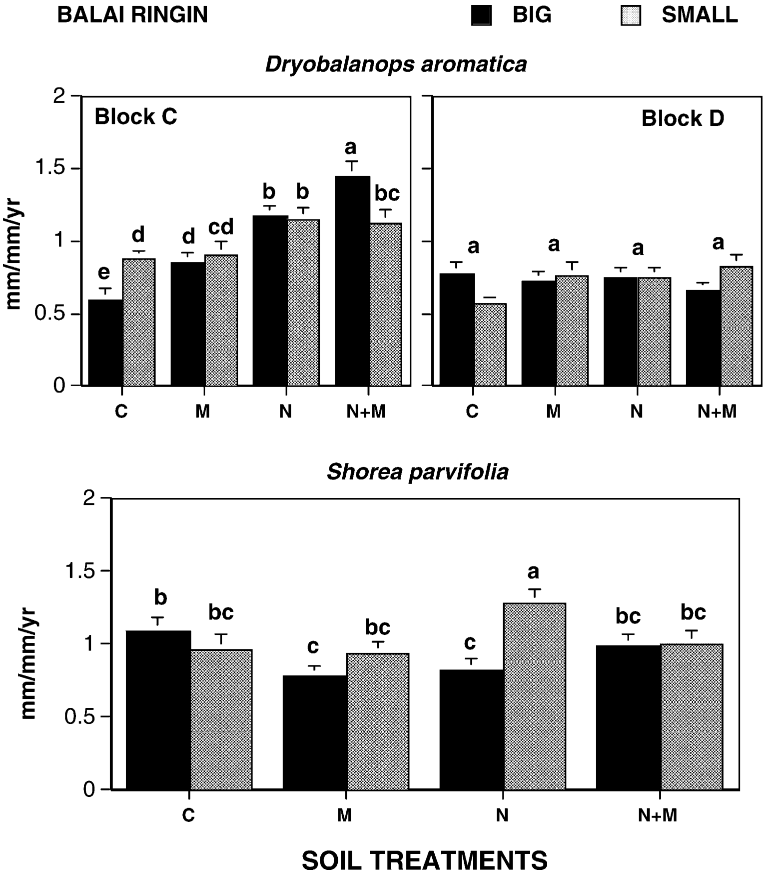

Fig. 2. Mean relative diameter growth rates (+1 S.E.) of seedlings of *D. aromatica* ($n = 19–25$ per treatment combination) and *S. parvifolia* ($n = 45–50$) grown in four soil treatments (C—control, M—mulch, N—nutrient addition, and N + M—nutrient plus mulch addition) and two planting-hole sizes in Balai Ringin Protected Forest. Due to significant block effects the two blocks are illustrated separately for *D. aromatica*. Different letters indicate significant differences ($P < 0.05$) between the means for each species. For *D. aromatica* in block D, planting-hole size had no effect on growth so different letters indicate significant differences between soil treatments only.

given mulch grew significantly worse than control plants, and seedlings planted in small planting-holes that were given nutrients plus mulch performed significantly worse than plants given nutrients alone (Fig. 2).

Planting-hole size did not have a consistent significant effect on seedling growth rates in either species (Figs. 1 and 2). For *D. aromatica* at Sampadi, plants in small holes had significantly higher growth rates than plants in big holes for nutrient-added plants, but significantly lower growth rates for plants given mulch or nutrients plus mulch (Fig. 1). There were also significant planting-hole size effects on *D. aromatica* growth in block C at Balai Ringin (Fig. 2). However, again there was no consistent trend, with control plants doing better in small holes, and nutrient plus mulch plants doing better in big holes. Planting-hole size did not significantly affect the growth of *S. parvifolia* seedlings, except under one soil treatment (nutrient-added) at Balai Ringin where plants in small holes performed better (Fig. 2).

Height growth showed similar patterns to diameter growth for each species, however allocation patterns differed between the species with *D. aromatica* having taller and more slender stems than *S. parvifolia* (Fig. 3).

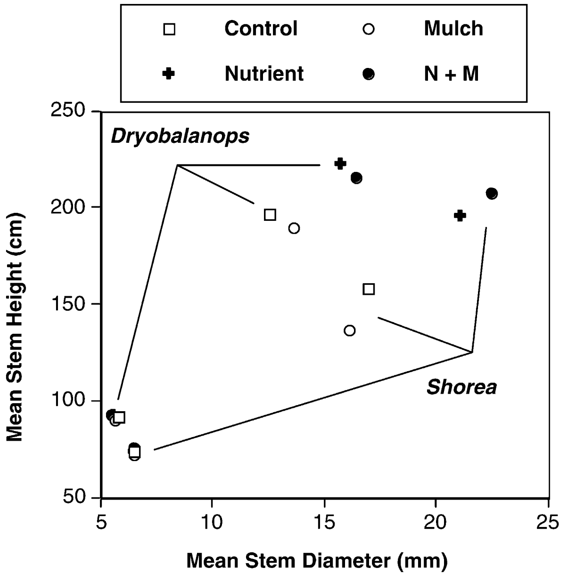

Fig. 3. Mean initial and final height vs. diameter for seedlings of *D. aromatica* and *S. parvifolia* grown in four soil treatments (N + M—nutrient plus mulch addition) to illustrate different allocation patterns between the species. Means are based on $n = 181-198$.

5. Discussion

5.1. Survival

Survival rates of >94% over 2 years are exceptionally high for dipterocarp plantation experiments. Most other studies involving planting dipterocarps in logged and degraded forests have reported substantially higher mortality rates. For example, Suhaili et al. (1998) found seedling mortality rates of 39% for *D. aromatica* and 22% for *S. parvifolia* over the first 6 months in degraded land in Peninsular Malaysia. In several other dipterocarp plantation studies in Southeast Asia, mortality rates have been 20–50% in the first few years and sometimes even higher (Ang, 1991; Adjers et al., 1995; Ang and Maruyama, 1995; Adjers et al., 1996; but see Raja Barizan, 1996).

Since none of the treatments applied in this experiment significantly affected mortality rates, environmental conditions other than those manipulated in the experiment must have had a large impact on survival. During the first 12 months of the experiment there were only 2 months at each site that had less than 150 mm of total rainfall, with a minimum of 97 mm in July 2000 at Balai Ringin. Furthermore, there was more than 200 mm of rain in each of the first 4 months after planting at both sites (maximum 920 mm in January 2000 at Sampadi). In degraded forests and in open areas, a combination of increased run-off and higher light levels may lead to increased water stress on planted seedlings (Malmer, 1992). Although planting the seedlings in lines within regenerating secondary forest may have provided partial shade for the dipterocarp seedlings and thereby helped avoid soil water stress, high mortality rates have been observed in other line-planting studies (Adjers et al., 1995). It seems most likely that the high survival rates in this experiment were due to a highly favorable soil water environment.

5.2. Nutrient addition

Nutrient addition had the strongest affect on seedling growth of the treatments applied in this experiment. Positive responses to soil nutrient addition have been found in other field experiments in aseasonal Southeast Asia (e.g., Nussbaum et al., 1995b), however very few species have been tested for a nutrient response and these studies have been done in only a few areas. The broad-spectrum NPK fertilizer used in this experiment followed the standard application of the SFD in their reforestation program. More detailed field studies which manipulate fertilizer composition and quantity are required for dipterocarp plantations in Southeast Asia. This information is likely to have significant impact on the silvicultural success and economic viability of dipterocarp plantations (Kollert et al., 1996).

There was significant variation in the response to nutrient addition between the two sites used in the study. Both species responded strongly to nutrient addition at Sampadi, however at Balai Ringin *S. parvifolia* did not respond to nutrient addition and *D. aromatica* responded in only one of the two blocks. Balai Ringin has more clay-rich soils with slightly higher soil-nutrient levels than Sampadi, but both sites have relatively low soil-nutrient status for tropical soils (Grubb et al., 1994), and variation in soil fertility does not seem to explain the lack of growth response at Balai Ringin. Seedling growth rates in control treatments, with no nutrient or mulch addition, were higher for both species at Balai Ringin than at Sampadi, which might reflect the higher soil fertility at Balai Ringin. However, growth of nutrient-added plants was much higher for both species at Sampadi, suggesting that growth remained limited by some undetermined factor at Balai Ringin. It is possible that the nutrients applied at Balai Ringin were not received by plants, resulting in no nutrient responses. Phosphorus may have been be more quickly adsorbed in the clay soils at Balai Ringin than in the more sandy soils at Sampadi (Lawrence and Schlesinger, 2001). Tissue nutrient analysis is required to assess whether the seedlings received the nutrients in both sites. This would also enable a more critical assessment of the nature of nutrient limitation for these species (Webb et al., 2000).

5.3. Mulch and planting-hole size

Mulch addition significantly improved the growth of both *D. aromatica* and *S. parvifolia* at Sampadi. However, the effect was much weaker than the soil-nutrient effect and it was not consistent among treatments; e.g., plants of *S. parvifolia* given mulch did not grow better than control plants, but mulch plus nutrient plants grew better than mulch-only plants. At Balai Ringin the effect of adding mulch was even weaker, and for *S. parvifolia* there were some treatments where mulched plants grew more slowly than control plants. Mulching is thought to enhance seedling survival and performance in plantations by suppressing weeds, aiding in soil moisture retention, and by providing a source of nutrients through decomposition (Davies, 1988; Evans, 1996). However, several studies have found no effect or a negative effect of mulching (Gupta, 1991; Truax and Gagnon, 1993; Nussbaum et al., 1995b). Nussbaum et al. (1995b) attributed a negative response to mulching in dipterocarp seedlings to soil waterlogging in the rooting zone. Our results suggest that the effects of mulching vary among both sites and species, and that more detailed assessment of the actual effect of mulching on seedling resource availability is required before prescriptions for dipterocarp species can be made.

Planting-hole size did not consistently affect seedling growth of *D. aromatica* or *S. parvifolia* in this experiment. Increased planting-hole size might benefit seedling performance through reduced compaction in a larger soil volume surrounding the roots, increased infiltration and hence water availability, or through decreased root competition in the early stages of establishment. We argued above that climatic conditions through the course of this experiment were extremely favorable, and that the seedlings were unlikely to have suffered water stress. Whether larger planting-hole sizes benefit seedlings during periods of water stress remains to be tested. In logged forest in Sabah, Pinard et al. (1998) found no significant difference in growth between seedlings with a trench dug around the seedling to exclude root competition and untrenched seedlings. They interpreted this to mean that root competition was not a significant influence on early seedling growth. Root competition may have been unimportant in the experiment presented here also, however a more detailed assessment of rooting profiles in large and small planting-hole seedlings is required to assess this.

5.4. Conclusions

This experiment demonstrated that nutrient availability strongly limits the growth of two dipterocarp species when planted in a nutrient-poor, post-shifting cultivation, secondary successional site in Sarawak. Mulching may positively or negatively affect seedling growth, depending on other site conditions. Planting-hole size had a relatively minor effect on seedling growth. An important implication of this study is that the results of planting experiments may often be specific to the particular site and environmental conditions in which the study is conducted. Experimental studies across a wider range of sites, in which resource availability and fluxes are carefully measured, are required for the development of protocols for planting dipterocarp species. Such research is essential if the recent initiatives by Malaysia and other Southeast Asian countries to expand the area of dipterocarp plantation forests are to be successful.

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