

# PERFORMANCE OF 45 NATIVE TREE SPECIES ON DEGRADED LANDS IN SINGAPORE

K. Shono<sup>1,\*</sup>, S. J. Davies<sup>1</sup> & Y. K. Chua<sup>2</sup>

<sup>1</sup>Center for Tropical Forest Science – Arnold Arboretum Asia Program, 1 Nanyang Walk, 637616 Singapore

<sup>2</sup>National Parks Board of Singapore, 1 Cluny Road, 259569 Singapore

Received March 2006

**SHONO, K., DAVIES, S. J. & CHUA, Y. K. 2007. Performance of 45 native tree species on degraded lands in Singapore.** The performance of 45 native tree species, which encompassed a range of early successional to primary forest species, was evaluated in a reforestation planting trial on degraded lands in Singapore. Growth data was obtained from 1640 saplings planted between 1999 and 2004 on seven reforestation plots. Survival rates were greater than 90% across most species. Growth rates of planted saplings were significantly affected by species, site and interaction between species and site. A number of primary forest species performed well in this study. In comparison, many of the secondary forest species had slow to medium growth rates. Of the 45 species tested, 19 had diameter growth exceeding 1 cm year<sup>-1</sup> while seven had growth rates below 0.5 cm year<sup>-1</sup>. This study showed that many primary forest species can grow well in open conditions of deforested sites. The results also emphasized the importance of site-species matching and the region-specific nature of species performance. The approach of interplanting fast-growing native species with primary forest species was shown to be a viable forest restoration method. Continued monitoring will reveal more information on the long-term performance of these planted saplings and native forest development in the restored forests.

Keywords: Tropical reforestation, species selection, native species trial

**SHONO, K., DAVIES, S. J. & CHUA, Y. K. 2007. Prestasi pertumbuhan 45 spesies pokok asli di atas tanah ternyahgred di Singapura.** Prestasi 45 spesies pokok asli yang merangkumi pelbagai jenis pokok daripada spesies sesaran ke spesies hutan primer dinilai dalam satu kajian penghutanan semula di atas tanah ternyahgred di Singapura. Data pertumbuhan diperolehi daripada 1640 anak pokok yang ditanam dari tahun 1999 hingga tahun 2004 di tujuh plot penghutanan semula. Kadar kemandirian melebihi 90% bagi semua spesies. Kadar pertumbuhan anak pokok dipengaruhi oleh jenis spesies, tapak dan saling tindakan antara spesies dan tapak. Sebilangan spesies hutan primer menunjukkan pertumbuhan yang baik dalam kajian ini. Sebaliknya banyak spesies hutan sekunder tumbuh dengan perlahan atau sederhana. Daripada 45 spesies yang dikaji, 19 mempunyai pertumbuhan diameter melebihi 1 cm setahun dan tujuh mempunyai kadar di bawah 0.5 cm setahun. Kajian ini menunjukkan bahawa banyak spesies hutan primer dapat bertumbuh dengan baik di kawasan terbuka di tapak yang terbasmi hutan. Keputusan turut menekankan kepentingan padanan spesies dan tapak serta ciri kawasan tentu bagi prestasi spesies. Pendekatan penanaman selang bagi spesies asli yang cepat tumbuh dengan spesies hutan primer terbukti merupakan kaedah pemulihan yang baik. Pemantauan berterusan akan memberi lebih banyak maklumat tentang prestasi jangka panjang anak pokok ini serta pembangunan hutan asli di hutan yang terpulih.

## INTRODUCTION

Extensive deforestation in the tropics has resulted in the formation of large areas of degraded vegetation that support greatly reduced biodiversity. Between 2000 and 2005, 13 million ha of forest was cleared annually worldwide with most of the deforestation occurring in the tropics (FAO 2005). Tropical deforestation is often followed by conversion of forestlands to agricultural uses mostly to replace land that has

lost productivity due to unsustainable farming practices (Harwood *et al.* 1993). Such degraded lands are subsequently abandoned as wastelands that could potentially regenerate to forest but in areas subjected to intensive anthropogenic effects, the natural successional processes are often very slow because of the degradation of soil resources, recurring disturbance and isolation from intact forests. Numerous studies

\* Author for correspondence. Current address: FAO Regional Office for Asia and the Pacific, 39 Phra Atit Road, Bangkok 10200, Thailand. E-mail: ken.shono@aya.yale.edu

have demonstrated that the establishment of tree plantations on degraded lands can reverse the effects of physical and biological barriers to forest regeneration and initiate the recovery of native forest communities (Lugo 1997, Parrotta *et al.* 1997). Most reforestation projects aim to restore productive capacity of the forest for future timber yield, but integrating short-term economic objectives with long-term biodiversity conservation is becoming increasingly important (Lugo 1997, Lamb 1998, FAO 2001). Due to the incomplete silvicultural knowledge of native tree species, a limited number of exotic timber species, e.g. species of *Acacia*, *Eucalyptus* and *Pinus*, and selected other species such as *Gmelina arborea* continue to be favoured in reforestation projects for their proven ability to grow rapidly on degraded lands (FAO 2001). However, South-East Asia contains some of the most floristically diverse forests in the world and there should be a number of indigenous tree species that are suitable for reforesting degraded lands (Lamb 1994).

Most native species planting trials in South-East Asia have been conducted with trees of the family Dipterocarpaceae (e.g. Adjers *et al.* 1995, 1996, Howlett & Davidson 1996). In addition to their commercial importance, dipterocarps are essential components of lowland forest in the region, typically comprising the greatest portion of the stand basal area and dominating the emergent canopy (Ashton 1988). The large wind-dispersed seeds, typical of the family, have limited dispersal range and, therefore, the dipterocarps are poor colonizers of fragmented landscapes. Human intervention is often required to re-establish dipterocarps on deforested lands devoid of nearby seed trees. Direct planting of dipterocarps and other primary forest species on *Imperata* grasslands have largely been unsuccessful because of slow growth and high mortality arising from their shade and moisture requirements (Otsamo *et al.* 1995). There have been only a few cases of reforestation in South-East Asia using indigenous tree species other than dipterocarps (e.g. Otsamo *et al.* 1996, 1997) and information is scarce on which late-successional species might be suitable for reforesting degraded forestlands.

In the early 1800s, a significant fraction of Singapore's native lowland dipterocarp forest was cleared to make way for agriculture (Corlett

1991, LaFrankie *et al.* 2005). Farmlands were later abandoned to lalang (*Imperata cylindrica*) grasslands when unsustainable agricultural practices exhausted the soil of productivity. The suppression of fire in the early 1900s allowed the regeneration of secondary forest known as adinandra belukar (named for its dominant species, *Adinandra dumosa*) on these fire-maintained grasslands (Sim *et al.* 1992). Within the secondary forest, in various stages of succession, are patches of open scrubland covered by dense growth of *Dicranopteris linearis* ferns and *Smilax setosa* vines. These areas have apparently remained in this condition for 40 years or more. Fire, the removal of timber from the regenerating forest for firewood and soil factors may have led to the formation of such areas of degraded vegetation (Burkill 1961, Corlett 1991).

Since 1991 the National Parks Board of Singapore has been reforesting these areas of degraded vegetation using native tree species with the principal objective of restoring them to mature secondary forests containing significant primary forest components. Since the main restoration objective is the recovery of biodiversity and other environmental services that forests provide, a wide variety of native tree species was used to test their reforestation potential regardless of their commercial value. To date, around 15 ha have been replanted with more than 17 000 saplings belonging to about 150 species. The forest restoration method combines the staggered planting of primary forest species (Knowles & Parrotta 1995) and the framework species method (Goosem & Tucker 1995, FORRU 2005). Fast-growing native species were interplanted with a diverse range of late-secondary and primary forest species.

The purpose of this study was to examine the reforestation potential of native tree species and to investigate patterns in their performance across various habitats. The main emphasis was in finding a selection of indigenous species with high early growth potential that can quickly restore a closed-canopy forest, and to identify primary forest species that are suitable for open planting on severely degraded lands and will contribute to long-term reforestation success. This study also served to provide baseline data on which long-term monitoring will be based.

## MATERIALS AND METHODS

### Study area

The Republic of Singapore lies at the southern tip of the Malay Peninsula, approximately 137 km north of the equator (1° 14' N, 103° 55' E). The reforestation sites surveyed in this study were located in the Central Catchment Nature Reserve, which includes about 1600 ha of mostly secondary vegetation in the centre of the island, and the Bukit Timah Nature Reserve on a hill adjacent to the Catchment area that contains about 70 ha of primary forest surrounded by regenerating secondary forest and degraded open areas (LaFrankie *et al.* 2005). Much of Singapore is underlain by granite which gives rise to the well-drained ultisols of Rengam series with sandy loam or sandy clay loam texture. Secondary forests in Singapore, within which the study sites are located, have developed on degraded soils following exhaustive agriculture and is known to have very low pH (3.5–4.2 at 0–10 cm) and extremely low concentrations of total N and P (Grubb *et al.* 1994).

The reforestation sites varied in size, planting year, site characteristics and species planted (Table 1). Soils at the reforestation sites were apparently similar in physical characteristics.

The saplings were raised from seeds of native stock, collected as wildlings from the forest, or purchased from tree seedling nurseries in Malaysia. The average size of saplings at the time of planting was 1 cm in diameter and 1.5 m in height. Spacing of approximately 3 m was used between individual saplings, which equates to a planting density of about 1000 saplings per ha. All of the reforestation sites were blanketed by *Dicranopteris* ferns, *Smilax* vines and other weedy vegetation with very few or no residual trees. Prior to reforestation, these target areas were cleared of aboveground plant biomass using grass

cutters. The debris was left *in situ* to decompose. The saplings were placed into planting holes 1.5 times the size of root balls, then the soil was backfilled and firmly packed. Each sapling was watered at the time of planting and also in the next few weeks as needed. The only maintenance operations conducted thereafter was the periodic removal of resprouting *Smilax* vines.

### Data collection and analysis

In this study, growth data obtained from 1640 saplings of 45 species planted on seven plots totalling 2 ha in area were used to evaluate the reforestation potential of native tree species. The seven plots were chosen for their ease of access and availability of records so that the planted saplings could be located. Each site was planted with a different combination of species, depending on sapling availability at the time of planting. However, many of the common species were shared between the sites (Appendix I). Species with less than 10 individuals were excluded from the analysis. For each planted tree, dbh (diameter at breast height) was measured and any damage was noted. Tree heights were measured to the shoot apex on those plots planted after 2002.

All sites were surveyed in 2005. Saplings planted after 2003 were measured at the time of planting or soon after. These measurements were used as the initial planting size for calculating mean annual increments. For those saplings planted prior to 2003, annual growth rates were calculated using the average initial planting size of 1 cm dbh and 1.5 m in height. Saplings with negative growth rates were given annual growth rates of zero. In order to compare growth rates of different species planted on seven different sites at various times, it was assumed that annual growth rates of the planted saplings were constant through the early years of development. This

**Table 1** Site characteristics of each reforestation plot

Plot	1	2	3	4	5	6	7
Year planted	Aug. 2003	Nov. 1999	2000–2001	2001–2002	Sept. 2003	2003–2004	Sept. 2004
Plot area (m <sup>2</sup> )	2162	5000	5116	1500	2775	2775	1300
Slope (degrees)	10	5	Level	29	6	8	Level
Aspect	North	West	-	East	East	North-East	-
Planting density per ha	962	800	1120	1217	1466	1059	740
Dry/wet	Average	Wet	Wet	Dry	Average	Dry	Dry
No. of species planted	18	11	30	16	30	31	15

assumption was unlikely to be true. However, the saplings were relatively close in age and the general pattern observed was that the variation in annual growth rates within species decreased as the plants aged while the mean values remained nearly constant. After the effects of species and sites were accounted for, sapling age was not a significant factor affecting the annual diameter or height growth ( $p > 0.5$ ).

Two-way analysis of variance (ANOVA) was performed to test for the significance of species, site, and species  $\times$  site interaction effect on mean annual growth rates using a linear model. To assess the suitability of various species for reforestation of degraded lands each species was given a composite rating of E (for excellent), G (good), P (poor) and U (unsuitable) based on their growth rates, contribution to floristic and structural diversities, consistency in their performance and other field observations (Appendix 1).

## RESULTS

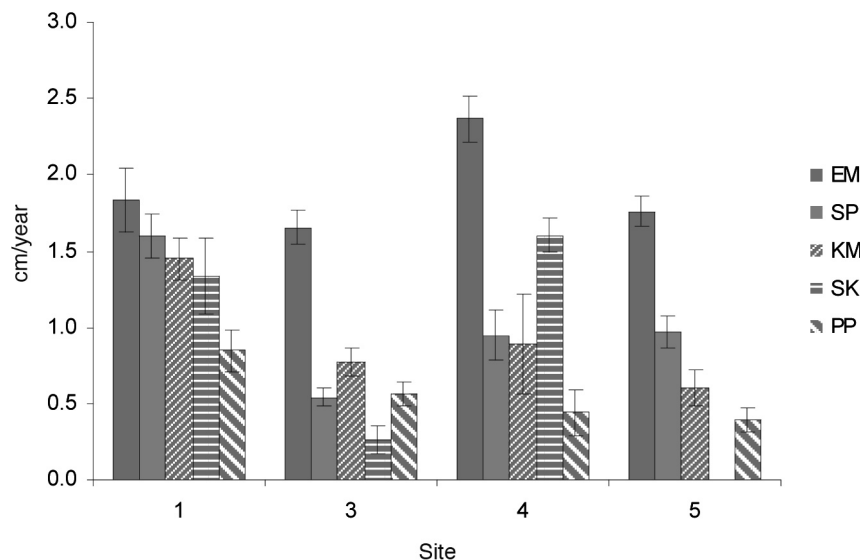
### Survival of planted saplings

On sites 1, 4, 5 and 7 survival rates were  $> 90\%$  for almost all species tested. On the other sites, records were incomplete on how many individuals of each species were planted. However, examination of the spacing between planted trees indicated that overall survival was  $> 90\%$ . The high survival rates were probably due to the large initial planting size of the saplings.

### Factors affecting sapling growth

As predicted growth performance varied significantly among species and site, with a significant species  $\times$  site interaction ( $p < 0.0001$ ). Some species showed great variation in growth rates between sites (e.g. *Sandoricum*) while others maintained relatively constant growth on all sites planted (e.g. *Koompassia*). Due to this difference in species-specific responses, ranking of species was not replicated from site to site, although the general trend was consistent (Figure 1). These growth responses may have resulted from variation in adaptability to specific or multiple limiting factors, such as light levels, water and/or nutrient availability.

Two sites with contrasting habitat characteristics were reforested at about the same time in 2001. Site 5 was located on a hillside in the Bukit Timah Nature Reserve and Site 3, on level ground at the edge of a reservoir in the Central Catchment area. The hill plot had no residual trees while the reservoir plot had a few scattered remnant trees. Four species (*Sandoricum koetjape*, *Pometia pinnata*, *Sindora wallichii* and *Syzygium polyanthum*) were planted at both sites, which enabled a comparison of species performance in relation to site differences in light levels and soil moisture. *Sandoricum koetjape* showed significantly greater growth rates on a dry hill site with full sunlight. This species is drought-tolerant but requires full sunlight for optimal growth. In contrast, *P. pinnata*, which is naturally found on riversides, had significantly greater growth



**Figure 1** Mean annual diameter growth of five species across four different sites. EM = *Elaeocarpus mastersii*, SP = *Syzygium polyanthum*, KM = *Koompassia malaccensis*, SK = *Sandoricum koetjape*, PP = *Pometia pinnata*

on the water-edge site. *Sindora wallichii* also had significantly higher growth rates on the wetter site while *S. polyanthum* showed no site preference (Figure 2).

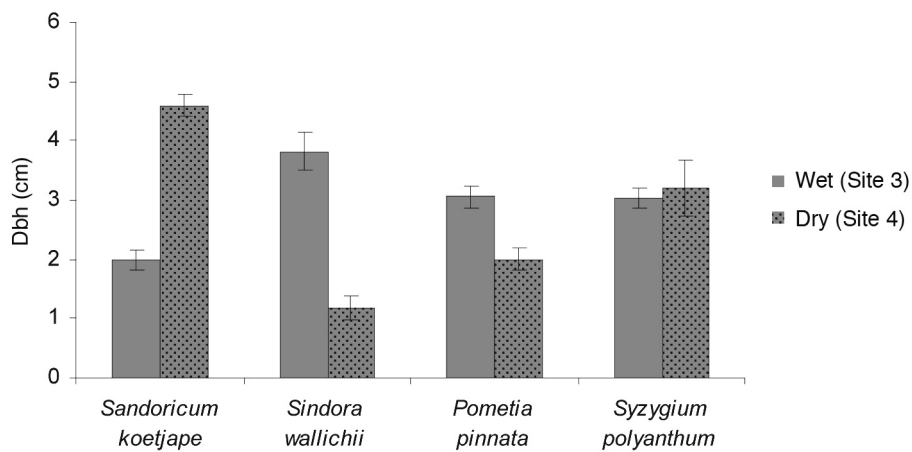
### Dipterocarpaceae

*Dipterocarpus caudatus* and *Hopea nutans* had the highest growth rates among the seven dipterocarp species tested (Figure 3). *Shorea acuminata* and *S. leprosula* were the fastest growing *Shorea* species. Both species had similar annual mean diameter growth, but *S. acuminata* had considerably greater height growth. *Hopea mengarawan* and *Shorea ovalis* did not show good performance

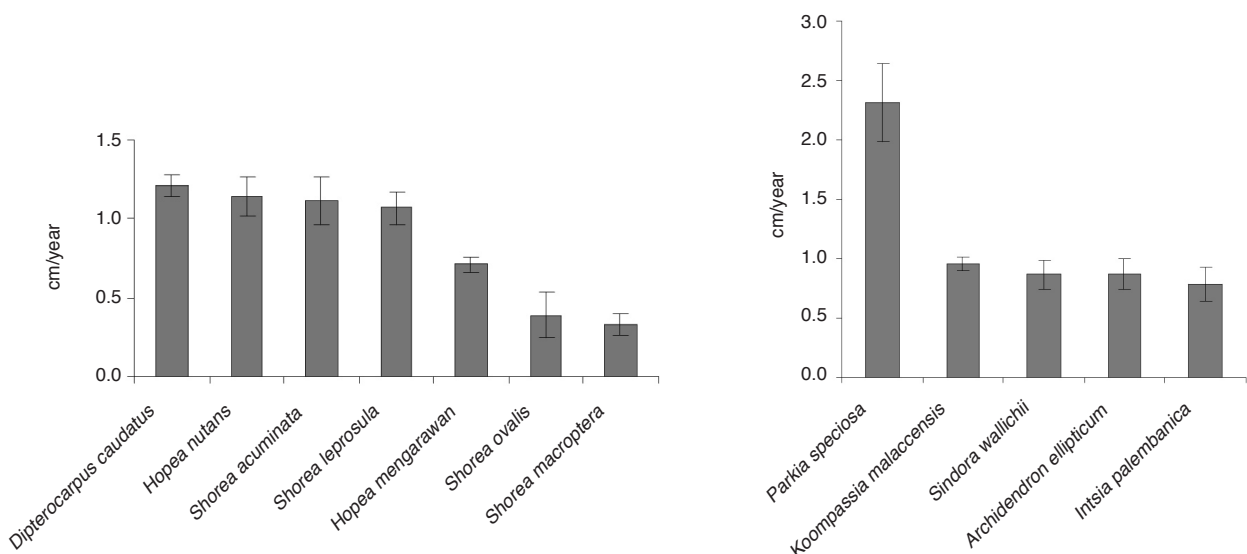
while *S. macroptera* exhibited minimal growth as they were out competed by faster-growing species soon after planting.

### Legumes

*Parkia speciosa* had the greatest mean annual diameter and height growth of all 45 species included in this study (Figure 4). *Sindora wallichii* varied widely in performance between individuals, even between those planted under similar conditions in the same plot. On Site 5, the fastest growing individuals of *Sindora wallichii* achieved heights of 6–7 m and diameters of 5–6 cm in two years, while the slower-growing trees



**Figure 2** Mean diameter of four species in wet (Site 3) and dry (Site 4) sites, four years after planting



**Figure 3** Mean annual diameter growth of dipterocarps

**Figure 4** Mean annual diameter growth of legumes

hardly showed any growth increments from the initial planting size. *Koompassia malaccensis* and *Archidendron ellipticum* were found to be promising with steady mean annual growth rates of nearly 1 cm in dbh and over 1 m in height. The planted saplings were apparently vigorous and healthy. *Intsia* is a slow-growing tree (Appanah & Weinland 1993, Mohd *et al.* 2005) and in this study, it had the least growth rate among the legumes tested.

### Secondary forest species

Among the secondary forest species, *Litsea elliptica*, *Elaeocarpus mastersii* and *Syzygium lineatum* showed consistently vigorous growth although *E. mastersii* tended to branch low and have a bushy form when planted in the open. *Camptosperma auriculatum* had adequate dbh growth but poor height growth (Figure 5). Other *Syzygium* species and *Cinnamomum iners* had average performance. Several dominant species of successional forests in Singapore were shown to be unsuitable for reforestation where initial fast growth rate is preferred. *Rhodamnia cinerea* was one of the slowest growing trees planted. *Adinandra dumosa* also performed poorly where they were planted (results not shown). *Fagraea fragrans* had slow growth rate and an unusually high mortality rate of 50% on Site 1 and the surviving individuals appeared to be unhealthy.

### Other species

*Canarium littorale* and *Sandoricum koetjape* were hardy species capable of tolerating exposure to full sunlight and occasional droughts. *Dyera costulata* was also a consistent performer with mean annual diameter growth of 1.15 cm. Many individuals achieved heights of 10 m within five years of planting. *Lithocarpus ewyckii* also showed high potential. The stems of *Alstonia angustiloba* were often broken by long-tailed macaques and were also susceptible to attacks by defoliating ants on some plots, although they grew extremely well at other sites. Interestingly, naturally established *Alstonia* seedlings were common in the reforestation plots and those seemed to grow much more vigorously than the planted saplings. Other species found to be unsuitable for reforestation due to slow growth rates included *Strombosia javanica*, *Pouteria obovata*, *Aquilaria malaccensis*, *Gonystylus confusus* and *Lepisanthes rubiginosa*.

### DISCUSSION

The use of larger seedlings enhanced survival in competition with the weedy vegetation and resulted in high survival rates across most species and sites. However, the use of 1.5 m saplings for forest restoration is unusual and smaller

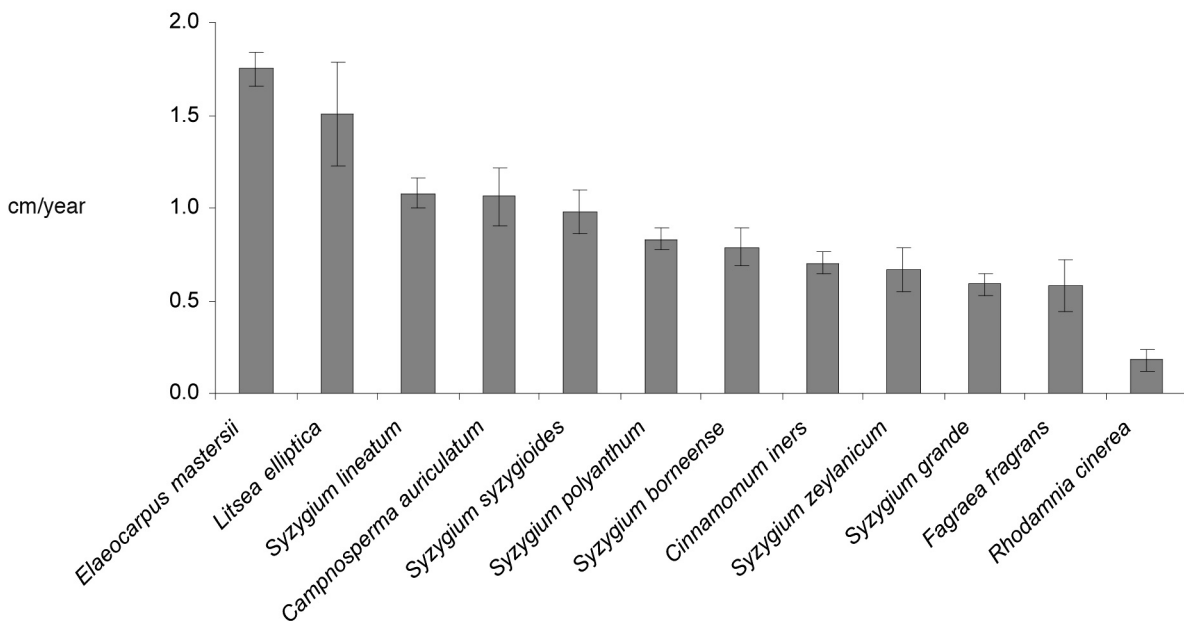


Figure 5 Mean annual diameter growth of secondary forest species

seedlings should be tested in future experiment to assess the magnitude of difference in survival rates.

Growth rates of individual saplings are affected by a combination of factors that include edaphic conditions, light availability and competition. Although we could not control nor quantify the significance of these factors, definite patterns in comparative growth rates among species emerged from this study.

It is generally recognized that dipterocarps require shade and moisture for germination and establishment. Once established, however, the seedlings grow faster in open conditions and may require light gaps to grow successfully into the canopy (Sasaki & Mori 1981, Ashton 1983, Denslow 1987). This study demonstrated that dipterocarp species vary in their tolerance to exposure during early stages of development. *Shorea leprosula* is known to be capable of fast initial growth and benefit from full open conditions (Appanah & Weinland 1993, Symington *et al.* 2004). It has been shown to be the most suitable *Shorea* species for reforestation in several studies (Mohd *et al.* 2005, Adjers *et al.* 1996, Otsamo *et al.* 1996, Howlett & Davidson 1996); so their superior performance in this study was not surprising. *Shorea acuminata* and *Hopea nutans* are both naturally abundant on hills in the Malay Peninsula (Symington *et al.* 2004) and their fast growth rates on exposed sites are probably due to their drought tolerance. *Dipterocarpus caudatus* performed well in this study despite negative findings for other *Dipterocarpus* species (*D. cornutus* and *D. kunstleri*) on abandoned agricultural land in Peninsular Malaysia (Adjers *et al.* 1996). It has been reported that *S. ovalis* failed to grow satisfactorily and developed galls when exposed to full sunlight (Appanah & Weinland 1993). Studies have reported slow growth and low survival of *S. macroptera* in open planting (Ang & Maruyama 1995) and under the light canopy cover of *Paraserianthes* (Otsamo *et al.* 1996). Their poor performance in this study confirmed that these are not suitable species for open planting and need to be established by later enrichment planting. Two native *Shorea* species not included in this study, *S. parvifolia* and *S. curtisii*, may be useful for reforestation and should be included in future planting trials. *Shorea parvifolia* shares many characteristics with *S. leprosula* but have more tolerance of shade (Appanah & Weinland

1993). *Shorea curtisii* is the dominant canopy species in Bukit Timah hills and is relatively fast-growing in the natural forest (LaFrankie *et al.* 2005).

Legumes play an important role in restoring soil fertility because of their nitrogen fixing properties (Lamb & Tomlinson 1994). The fact that some of the legumes performed well on these degraded sites with extremely low N and P concentrations could be because their elevated leaf nitrogen concentrations resulted in greater carbon assimilation capacity as was shown for pioneer species on early successional sites in Latin America (Ellsworth & Reich 1996). *Parkia speciosa* displayed exceptional growth rates in this study. It was also described as one of the best candidates for plantation species by Appanah and Weinland (1993). Another *Parkia* species, *P. roxburghii*, was found to be the best performing native species in a planting trial in Kalimantan, Indonesia (Otsamo *et al.* 1997). *Parkia speciosa* is common in secondary forests of Singapore where they were once planted around villages. This species offers promise for utilization in future reforestation for its fast growth and relative ease in propagation. In addition, *Parkia speciosa* provides an important non-timber forest product in the form of its edible seeds, making it a multi-purpose reforestation species. *Koompassia* is a big forest tree that reaches up to 55 m in height (Corner 1940). It is generally considered slow-growing, but it showed good growth rates and tolerated the open conditions.

*Dyera costulata* is an emergent canopy tree that requires full sunlight for optimal growth. It grows well in the open and has been successfully planted in lalang grasslands (Appanah & Weinland 1993). The results from this study confirmed its suitability as reforestation species. *Sandoricum koetjape* and *Canarium littorale* are promising species for planting on exposed slopes as they benefit from full sunlight and can tolerate water stress. *Sandoricum koetjape* has been utilized successfully for urban planting as a wayside tree. Other indigenous tree species used as roadside trees may also be suitable for reforestation. In a native species planting trial on eroded hillsides in Hong Kong, early successional species performed better than the later successional species (Hau & So 2002). Such pattern could not be detected in this study as many of the secondary forest species had mediocre to poor performance. Given their

frequent occurrence as regeneration in restored forests (Shono *et al.* 2006), there is little point in investing time and effort to propagate and plant these slower-growing secondary forest species.

This study provides an adequate amount of information needed to generate a preliminary list of species that are suitable and unsuitable for reforestation, which was previously unknown. Under certain reforestation objectives, the approach of inter-planting fast growing native species with exposure-tolerant primary forest species offers an effective restoration method. Using native species is ecologically more sound and the method restores a greater portion of the floristic diversity with the initial planting. The understorey can later be enriched with species that require shade for establishment.

Results from this study indicate that many native, late-successional species are able to tolerate the climatic and edaphic conditions of open degraded sites and can be utilized in restoration of such landscapes. Species selection is obviously one of the most important decisions to make in designing a reforestation project. Species performance is often region and site specific (Carpenter & Nichols 2002, Hau & So 2002, this study). Species choice decisions should be based on field trials and reflect existing knowledge of natural history and habitat requirements for each species. In addition, consideration should be given to the ecological functions they serve in restoring the forest ecosystem, such as provision of food source and habitat for wildlife. Restoration planting consisting of fast-growing species that can quickly establish a canopy and large-seeded primary forest species lacking in natural regeneration will ensure that the restored forest have the floristic diversity and provide habitat heterogeneity to support a diverse community of rainforest plants and animals.

Continued monitoring of the reforestation sites surveyed in this study will allow for evaluation of long-term performance of planted trees and native forest development in the reforested sites. Further studies are recommended to identify additional native species suitable for reforestation and to examine how specific physical and biological factors limit the growth of various tree species on degraded sites.

## ACKNOWLEDGEMENTS

We thank S. Chan and S. Lum for facilitating and supporting this research project. We are grateful for the field assistance by P. Huang, the National Parks Board staff, volunteers and students from the United World College of South-East Asia. We also thank the National Parks Board for the permission to carry out this research and for providing logistical support. This study was jointly initiated and conducted by the Center for Tropical Forest Science – Arnold Arboretum Asia Program and the National Parks Board, Singapore.

## REFERENCES

- ADJERS, G., HADENGGANAN, S., KUUSIPALO, J., NURYANTO, K. & VESA, L. 1995. Enrichment planting of dipterocarps in logged-over secondary forests: effect of width, direction and maintenance method of planting line on selected *Shorea* species. *Forest Ecology and Management* 73: 259–270.
- ADJERS, G., HADENGGANAN, S., KUUSIPALO, J., NURYANTO, K. & VESA, L. 1996. Performance of ten dipterocarp species in restocking logged-over forest areas subjected to shifting cultivation. *Journal of Tropical Forest Science* 9(2): 151–160.
- ANG, L. H. & MARUYAMA, Y. 1995. Survival and early growth of *Shorea platyclados*, *Shorea macroptera*, *Shorea assamica*, and *Hopea nervosa* in open planting. *Journal of Tropical Forest Science* 7: 541–557.
- APPANAH, S. & WEINLAND, G. 1993. *Planting Quality Timber Trees in Peninsular Malaysia—Review*. Forest Research Institute of Malaysia, Kepong.
- ASHTON, P. S. 1983. Dipterocarpaceae. *Flora Malesiana (Series J)* 9: 237–252.
- ASHTON, P. S. 1988. Dipterocarp biology as a window to the understanding of tropical forest structure. *Annual Review of Ecology and Systematics* 19: 347–370.
- BURKILL, H. M. 1961. Protection of wild life on Singapore Island. Pp. 152–164 in Wyatt-Smith, J. & Wycherley, R. P. (Eds.). *Nature Conservation in Western Malaysia*. Malayan Nature Society, Kuala Lumpur.
- CARPENTER, F. L. & NICHOLS, J. D. 2002. Variable success of native trees planted on degraded pasture in Costa Rica. Pp. 51–64 in Sim, H. C., Appanah, S. & Durst, P. B. (Eds.). *Proceedings of an International Conference on Bringing Back the Forests: Policies and Practices for Degraded Lands and Forests*. 7–10 October 2002. Kuala Lumpur, Malaysia. Food and Agriculture Organization of the United Nations, Bangkok.
- CORLETT, R. T. 1991. Plant succession on degraded land in Singapore. *Journal of Tropical Forest Science* 4: 151–161.
- CORNER, E. J. H. 1940. *Wayside Trees of Malaya*. Government Printer, Singapore.



- DENSLOW, J. S. 1987. Tropical rain forest gaps and tree species diversity. *Annual Review of Ecology and Systematics* 18: 431–451.
- ELLSWORTH, D. S. & REICH, P. B. 1996. Photosynthesis and leaf nitrogen in five Amazonian tree species during early secondary succession. *Ecology* 77(2): 581–594.
- FAO. 2001. *Global Forest Resources Assessment 2000*. FAO Forestry Paper 140. Food and Agriculture Organization of the United Nations, Rome.
- FAO. 2005. *Global Forest Resources Assessment 2005. 15 Key Findings*. Food and Agriculture Organization of the United Nations, Rome.
- FORRU (Forest Restoration Research Unit). 2005. *How to Plant a Forest: The Principles and Practice of Restoring Tropical Forests*. Biology Department, Science Faculty, Chiang Mai University, Chiang Mai.
- GOOSEM, S. P. & TUCKER, N. I. J. 1995. *Repairing the Rainforest—Theory and Practice of Rainforest Re-establishment in North Queensland's Wet Tropics*. Wet Tropics Management Authority, Cairns.
- GRUBB, P. J., TURNER, I. M. & BURSLEM, D. F. R. P. 1994. Mineral nutrient status of coastal hill dipterocarp forest and adinandra belukar in Singapore: analysis of soil, leaves and litter. *Journal of Tropical Ecology* 10: 559–577.
- HARWOOD, R. R., CARTER, M. E., GOMAZ, R., GLIESMAN, S. P., GOMEZ-POMPA, A., HARDIN, L. S., HILL, W. A., LAL, R., LEVINE, G., LUGO, A. E., POWER, A. G., RUTTAN, V. W., SANCHEZ, P. A., SERRAO, E. A. & WRIGHT, P. C. 1993. *Sustainable Agriculture and the Environment in the Humid Tropics*. National Research Council, National Academy Press, Washington DC.
- HAU, C. H. & SO, K. Y. 2002. Using native tree species to restore degraded hillsides in Hong Kong, China. Pp. 179–190 in Sim, H. C., Appanah, S. & Durst, P. B. (Eds.). *Proceedings of an International Conference on Bringing Back the Forests: Policies and Practices for Degraded Lands and Forests*. 7–10 October 2002. Kuala Lumpur, Malaysia. Food and Agriculture Organization of the United Nations, Bangkok.
- HOWLETT, B. E. & DAVIDSON, D. W. 1996. Dipterocarp seed and seedlings performance in secondary logged forests dominated by *Macaranga* spp. Pp. 256–266 in Appanah, S. & Khoo, K. C. (Ed.) *Proceedings Fifth Round-Table Conference on Dipterocarps*. Chiang Mai, Thailand, 7–10 November 1994. Forest Research Institute Malaysia, Kepong.
- KNOWLES, O. H. & PARROTTA, J. A. 1995. Amazonian forest restoration: an innovative system for native species selection based on phenological data and field performance indices. *Commonwealth Forestry Review* 74: 230–243.
- LAFRANKIE, J. V., DAVIES, S. J., WANG, L. K., LEE, S. K. & LUM, S. K. Y. 2005. *Forest Trees of Bukit Timah: Population Ecology in a Tropical Forest Fragment*. Simply Green, Singapore.
- LAMB, D. 1994. Reforestation of degraded tropical forest lands in the Asia-Pacific region. *Journal of Tropical Forest Science* 7(1): 1–7.
- LAMB, D. 1998. Large-scale ecological restoration of degraded tropical forest lands: the potential role of timber plantations. *Restoration Ecology* 6(3): 271–279.
- LAMB, D. & TOMLISON, M. 1994. Forest rehabilitation in the Asia-Pacific region: past lessons and present uncertainties. *Journal of Tropical Forest Science* 7(1): 157–170.
- LUGO, A. E. 1997. The apparent paradox of reestablishing species richness on degraded lands with monocultures. *Forest Ecology and Management* 99: 9–19.
- MOHD, Z. H., NOR, A. A., MOHAMAD, A. A., SUHAILI, R. & NIK, M. M. 2005. Growth and survival performances of indigenous tree species 72 months after planting in Negeri Sembilan. Presented at the Symposium on Tropical Rainforest Rehabilitation and Restoration. Kota Kinabalu, Sabah. 26–28 July 2005.
- OTSAMO, A., ADJERS, G., HADI, T. S., KUUSIPALO, J., TUOMELA, K. & VUOKKO, R. 1995. Effect of site preparation and initial fertilization on the establishment and growth of four plantation tree species used in reforestation of *Imperata cylindrica* (L.) Beauv. dominated grasslands. *Forest Ecology and Management* 73: 271–277.
- OTSAMO, R., ADJERS, G., HADI, T. S., KUUSIPALO, J. & OTSAMO, A. 1996. Early performance of 12 shade tolerant tree species interplanted with *Paraserianthes falcataria* on *Imperata cylindrica* grassland. *Journal of Tropical Forest Science* 8(3): 381–394.
- OTSAMO, A., ADJERS, G., HADI, T. S., KUUSIPALO, J. & VUOKKO, R. 1997. Evaluation of reforestation potential of 83 tree species planted on *Imperata cylindrica* dominated grassland—a case study from South Kalimantan, Indonesia. *New Forests* 14(2): 127–143.
- PARROTTA, J. A., TURNBULL, J. W. & JONES, N. 1997. Catalyzing native forest regeneration on degraded tropical lands. *Forest Ecology and Management* 99: 1–7.
- SASAKI, S. & MORI, T. 1981. Growth response of dipterocarp seedlings to light. *Malayan Forester* 44(2&3): 319–345.
- SHONO, K., DAVIES, S. J. & CHUA, Y. K. 2006. Regeneration of native plant species in restored forests on degraded lands in Singapore. *Forest Ecology and Management* 237: 574–582.
- SIM, J. W. S., TAN, H. T. W. & TURNER, I. M. 1992. Adinandra belukar: an anthropogenic heathforest in Singapore. *Vegetatio* 102: 125–137.
- SYMINGTON, C. F., ASHTON, P. S. & APPANAH, S. 2004. *Foresters' Manual of Dipterocarps*. Barlow, H. S. (Ed.). Malayan Forest Records No. 16. Forest Research Institute of Malaysia, Kepong.

**Appendix 1** Performance summary of planted species and overall score (E = excellent, G = good, P = poor, U = unsuitable) based on growth rates, ecological value and other relevant field observations

Species	N	M.A.I. diameter (cm)	SE	N	M.A.I. height (cm)	SE	Sites planted	Successional status	Overall score	Remarks
<i>Parkia speciosa</i>	18	2.32	0.33	19	212.5	13.8	1, 5, 6	SP	E	Excellent initial growth
<i>Cratogeomys cochinchinense</i>	11	1.96	0.36	11	154.3	18.1	5, 6	S	G	Common secondary forest species
<i>Elaeocarpus masterei</i>	93	1.75	0.09	84	165.4	6.5	1, 3, 4, 5, 6, 7	S	G	Tends to branch low and becomes bushy
<i>Litocarpus euydii</i>	12	1.73	0.23	-	-	-	3	P	G	-
<i>Cleistanthus malaccensis</i>	10	1.62	0.09	-	-	-	3	P	G	-
<i>Streblus elongatus</i>	10	1.60	0.20	9	120.0	20.0	6	SP	E	Food source for wildlife
<i>Litsea elliptica</i>	16	1.51	0.28	18	110.4	14.1	5, 6	S	G	Common secondary forest species
<i>Canarium littorale</i>	21	1.50	0.16	18	102.2	14.1	1, 3, 5	P	E	-
<i>Neolisea zeylanica</i>	11	1.34	0.09	-	-	-	3	SP	G	-
<i>Dipterocarpus caudatus</i>	48	1.21	0.07	-	-	-	3	P	E	Best performing dipterocarp tested
<i>Hopsea nutans</i>	20	1.14	0.12	20	157.1	13.4	5	P	G	-
<i>Dyera costulata</i>	101	1.13	0.05	42	105.0	9.3	1, 2, 3, 4, 5, 6, 7	P	E	Consistent performance
<i>Sandoricum koetjape</i>	68	1.12	0.10	53	150.0	8.2	1, 3, 4, 7	P	E	Tolerant to drought and exposure
<i>Shorea acuminata</i>	14	1.12	0.15	14	118.5	16.0	4	P	E	Best performing Shorea tested
<i>Syzygium lineatum</i>	88	1.08	0.08	45	112.1	8.9	1, 2, 3, 4, 5, 6	S	G	Common secondary forest species
<i>Shorea leprosula</i>	43	1.07	0.10	43	71.7	9.1	1, 4, 5, 7	P	E	Tolerates exposure
<i>Campnosperma aviculatum</i>	12	1.06	0.16	12	62.2	17.3	1, 4	S	G	Good diameter growth, poor height growth
<i>Embliza officinalis</i>	23	1.01	0.08	-	-	-	3	S	G	-
<i>Pentace triptera</i>	15	1.00	0.15	8	110.7	21.2	2, 6	SP	G	-
<i>Syzygium syzygioides</i>	23	0.98	0.12	23	80.9	12.5	5	S	G	Food source for wildlife
<i>Gnetum gnemon</i>	50	0.97	0.08	44	74.4	9.0	1, 3, 4, 6, 7	SP	P	Performance variable
<i>Koompassia malaccensis</i>	78	0.96	0.06	47	108.3	8.7	1, 2, 3, 4, 5, 7	P	E	N-fixing, canopy emergent
<i>Sindora wallichii</i>	71	0.87	0.12	58	96.4	7.9	3, 4, 5, 6	P	G	Growth highly variable between individuals
<i>Archidendron elliptica</i>	22	0.87	0.13	22	109.1	12.8	4, 5	S	G	N-fixing
<i>Syzygium polyanthum</i>	120	0.83	0.06	79	91.6	6.7	1, 2, 3, 4, 5, 6	S	P	Common secondary forest species
<i>Cratogeomys formosum</i>	31	0.81	0.08	28	104.6	11.3	1, 2, 5	S	P	Common secondary forest species
<i>Intsia palembanica</i>	19	0.79	0.14	23	61.6	8.3	5, 6	P	G	N-fixing, canopy emergent, storable seeds
<i>Syzygium borneense</i>	20	0.79	0.10	-	-	-	3	S	P	-
<i>Garcinia atrovirens</i>	42	0.71	0.05	10	59.8	19.0	2, 3, 5	P	P	-
<i>Hopsea mengarawan</i>	40	0.71	0.05	-	-	-	3, 6	P	P	-
<i>Cinnamomum iners</i>	83	0.70	0.06	24	77.3	12.2	1, 3, 5, 6	S	P	-
<i>Carallia brachialata</i>	20	0.69	0.05	-	-	-	3, 5	SP	P	Common secondary forest species
<i>Syzygium zeylanicum</i>	14	0.67	0.12	14	38.0	16.0	1, 7	S	U	-
<i>Syzygium grande</i>	26	0.59	0.06	-	-	-	3, 7	S	U	Abundant in natural regeneration
<i>Fagraea fragrans</i>	14	0.58	0.14	12	64.8	17.3	1, 3, 5	S	U	High mortality, common
<i>Lepisanthes rubiginosa</i>	27	0.53	0.06	27	112.0	11.5	5, 6	P	P	-
<i>Aquilaria malaccensis</i>	11	0.52	0.11	13	67.5	16.6	4, 6	P	P	-
<i>Pometia pinnata</i>	107	0.52	0.05	88	43.9	6.4	1, 3, 4, 5, 6, 7	P	P	Prefers moist habitat
<i>Pouteria obovata</i>	48	0.45	0.05	45	49.2	8.9	1, 5	P	P	-
<i>Strombosia javanica</i>	30	0.44	0.12	31	49.5	10.8	5, 6	P	U	-
<i>Shorea ovalis</i>	11	0.39	0.14	9	16.0	20.0	2, 5, 7	P	P	Not suitable for open planting
<i>Shorea macroptera</i>	12	0.33	0.07	-	-	-	2, 3	P	P	Not suitable for open planting
<i>Gonystylus confusus</i>	12	0.27	0.04	-	-	-	3	SP	U	Variable performance
<i>Alstonia angustiloba</i>	59	0.23	0.05	53	19.8	8.2	1, 3, 5, 6, 7	SP	U	Common secondary forest species
<i>Rhodamnia cinerea</i>	16	0.18	0.06	12	44.9	17.3	5, 6	S	U	-

M.A.I. indicates mean annual increment and are followed by standard errors (SE).

Successional status: S denotes species typical of secondary forests, P are primary forest species, and SP are species found both in secondary and primary forests.