



***Swietenia macrophylla* King**

Ecology, silviculture and productivity

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Preface

Smallholders in Indonesia have long been actively planting trees on private or community land. Various actors have encouraged this activity with the aim of improving local livelihood security, environmental sustainability and industrial wood supply. Such tree-planting efforts are generally successful, but they are often undertaken without technical assistance. Farmers often lack the necessary technical capacity and knowledge regarding proper management. The most common management activity is harvesting products, with other management practices less frequently implemented. As a result, the quality and quantity of products may not be fulfilling their potential. The productivity of smallholder plantations can be improved by enhancing smallholders' management knowledge and skills including species selection (site matching), silvicultural management to produce high-quality products, and pest and disease management. There is thus a need for manuals on ecology and silvicultural management of the selected tree species planted by smallholders in Indonesia.

This manual, '*Swietenia macrophylla* King: ecology, silviculture and productivity', is one of a series of five manuals produced as part of the research project 'Strengthening rural institutions to support livelihood security for smallholders involved in industrial tree-planting programmes in Vietnam and Indonesia'

coordinated by CIFOR. This project was funded by Germany's Advisory Service on Agriculture Research for Development (BMZ/BEAF), through the Gesellschaft für Internationale Zusammenarbeit (GIZ) for a 3-year period (2008–2010).

This manual gathers as much information as possible on *Swietenia macrophylla* King from available resources, with a focus on Indonesian sites. However, in terms of growth and yield (productivity), the availability of data for this species, particularly from smallholder plantations, is generally limited. Efforts have been made to collect inventory data from a research site in Ranggung village, Takesung Subdistrict, Tanah Laut District, South Kalimantan. In addition, we have used growth data for older stands collected by staff of the Forestry Research and Development Agency of the Indonesian Ministry of Forestry.

The manual has been translated into Indonesian and modified slightly to meet smallholders' needs. The authors believe this manual will benefit smallholders and organisations involved in implementing tree-planting programmes.

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1. Introduction

Swietenia macrophylla King, also known as big-leaf mahogany, is a tropical tree species native to Central and South America. *Swietenia macrophylla* has a wide natural distribution, extending from Mexico to Bolivia and central Brazil (Lamb 1966). However, large areas of former *S. macrophylla* forests have been converted to other uses, or the remaining forests are few (Shono and Snook 2006). The depletion of *S. macrophylla* populations has led to concern for the future of the species and its commercial trade. In 2002, *S. macrophylla* was listed in Appendix II (species that may face extinction if trade is not controlled) of the Convention on International Trade in Endangered Species of Wild Fauna and Flora (CITES) (Grogan and Barreto 2005).

The largest plantations of *S. macrophylla* have been reported in South and Southeast Asia and the Pacific region. A significant proportion of the total area, most remarkably in Indonesia and the Philippines, was intended for protection of slopes and water catchments and may not be productive. In addition, *S. macrophylla* is widely used for avenue planting in some Asian countries including Indonesia, India and Sri Lanka. According to Mayhew and Newton (1998), the earliest recorded introduction of *S. macrophylla* into any country is to Indonesia in 1870 with seeds from India. It was then planted as an ornamental and cultivated in plantations in Java between 1897 and 1902.

Swietenia macrophylla has since become a promising tree species for industrial plantations as well as for reforestation and afforestation in Indonesia. The total plantation area of *S. macrophylla* in Indonesia was about 54 000 ha in the mid 1990s, according to Perum Perhutani (1995). The number of smallholder *S. macrophylla* plantations is increasing, particularly in Java and Kalimantan, because of the species' high-quality wood used for furniture and cabinet making. According to a report by the Ministry of Forestry and the National Statistics Agency (2004), Central Java and West Java have the highest number of *S. macrophylla* trees planted by smallholders, with these two provinces accounting for 60% of the total number of *S. macrophylla* trees planted by households in Indonesia.

2. Description of the species

2.1. Taxonomy

Botanical name: *Swietenia macrophylla* King

Family: Meliaceae

Subfamily: Swietenioideae

Synonyms: *Swietenia belizensis* Lundell, *Swietenia candollei* Pittier, *Swietenia krukovii* Gleason, *Swietenia macrophylla* King var. *marabaensis* Ledoux et Lobato, *Swietenia tessmannii* Harms.

Vernacular/common names:

Common names in Indonesia: mahoni (all parts of Indonesia)

Common names in other countries: bara mahauni, bara-mahagoni, mahagni (Bangladesh); mahogany, big- or large-leaved mahogany, bastard mahogany, Brazilian mahogany tree, Colombian mahogany tree, Dominican mahogany, Honduras mahogany, Mexican mahogany tree, Peruvian mahogany tree, Spanish mahogany, West Indian mahogany (England); acajou du Honduras, acajou du Venezuela, acajou étranger (France); Echtes mahagoni (Germany); mogano (Italy); cheria mahogany (Malaysia); mahok, mahonie (Netherlands); mogno (Portugal); caoba, caoba de Honduras, caoba de Santo, caoba del Atlántico, caoba hondureña, domingo, (Spain); mahokkani-baiyani, mahokkani-bailek (Thailand); gi[as]I ng[uw]ja (Vietnam) (Agroforestry Tree Database; Soerianegara and Lemmens 1993).

2.2. Botany

Swietenia macrophylla is a large deciduous tree with an umbrella-shaped crown (Figure 1), frequently



Figure 1. Five-year-old *S. macrophylla* trees of characteristic shape, planted by a smallholder in South Kalimantan



Figure 2. Bark of 15-year-old *S. macrophylla* tree



Figure 3. The brown fruit of *S. macrophylla*



Figure 4. *S. macrophylla* capsule showing the internal arrangement of winged seeds



Figure 5. The seeds of *S. macrophylla*

reaching heights of over 30 m and diameter at breast height (DBH) of more than 1.5 m. However, heights of 40–60 m and diameters of 2.5–3.5 m were reported before the population was extensively logged (Lamb 1966). The trunk is straight and cylindrical, slightly grooved, with well-developed spurs. The crown of young trees is narrow, but old trees have a broad, dense and highly branched crown. The open, rounded crown has thick, rising branches and thick, dense foliage. The outer bark of older trees (Figure 2) is scaly, shaggy, deeply longitudinally furrowed and brownish-grey to reddish-brown, and the inner bark is red-brown or pinkish-red. The leaves are usually paripinnate, sometimes imparipinnate, 12–45 cm long, and are made up of 3–6 pairs of lanceolate or ovate leaflets. The leaflets are asymmetrical, 5–12 cm long and 2–5 cm wide, with a whole margin and an acute or acuminate apex (Soerianegara and Lemmens 1993; Schmidt and Jøker 2000).

The flowers are unisexual, 0.5–1.0 cm in length, and are borne in large, branched inflorescences including both male and female. The fruits (Figure 3) are capsular, oblong or ovoid, 11.6–38.7 cm in length, 6.7–12.0 cm in diameter and light grey to brown with 4–5 valves. Each fruit contains 22–71 developed seeds (Figure 4). The seeds are samaroid (Figure 5), bulky at their base, 7–12 cm long and 2–2.5 cm wide including the wing (Soerianegara and Lemmens 1993).

2.3. Distribution

Swietenia macrophylla grows naturally in Belize, Bolivia, Brazil, Colombia, Costa Rica, Ecuador, El Salvador, Guatemala, Honduras, Mexico, Nicaragua, Panama, Peru and Venezuela. However, it is nearly extinct in Ecuador, Colombia, Panama and Costa Rica; close to commercial extinction in Bolivia; declining in Mexico, Belize and Brazil; and in severe decline in Guatemala, Peru, Nicaragua and Honduras

(Lugo 2002). The species has been extensively planted mainly in Southern Asia and the Pacific including India, Indonesia, Philippines and Sri Lanka (Soerianegara and Lemmens 1993). It has also been introduced into West Africa.

2.4. Ecological range

Swietenia macrophylla can tolerate a wide range of soils and environmental conditions. Within its natural range, it has been found on alluvial soils, volcanic soils, heavy clays, lateritic soils and soil derived from limestone, granite and other sedimentary, igneous or metamorphic rock formations (Whitmore 1992). In tropical America, *S. macrophylla* is amongst the pioneer species reoccupying degraded agricultural land (Mayhew and Newton 1998). In the Philippines, this species is reported to be very wind firm (resistant to cyclones) (Soerianegara and Lemmens 1993). In plantations in Java, trees can grow on very poor soils but perform best on deep, fertile, well-drained soils with a pH of 6.5–7.5.

At present, *S. macrophylla* is widespread throughout the tropics, found naturally in both tropical dry and tropical wet forest types. Within its ecological range, the optimum annual rainfall is between 1000 and 2500 mm with a dry period of 0–4 months (Lamb 1966). In Amazonian Ecuador and Peru, annual rainfall in this species' area has been reported at

3800 mm (Whitmore 1983). The reported optimum natural development for this species is under tropical dry forest conditions with an annual precipitation of 1000–2000 mm, a mean annual temperature of 24 °C and a potential evapotranspiration ratio of 1–2 (Lamb 1966). In Indonesia, *S. macrophylla* grows at elevations of 0–1500 m above sea level, in areas with a mean annual temperature of 20–28 °C, with the range in the coldest and warmest months being 11–22 °C and 22–30 °C, respectively (Soerianegara and Lemmens 1993).

2.5. Wood characteristics

Swietenia macrophylla is a rather soft, medium-weight timber. The heartwood is reddish or pinkish, the colour darkening with age to a deep red or brown; the sapwood is usually yellowish. It has an attractive appearance, can be worked easily with hand tools and has excellent finishing qualities and dimensional stability (Martawijaya *et al.* 2005). It polishes well and does not crack or bend, making it valuable for the manufacture of quality furniture. The timber is valued particularly for its colour and workability. The wood density is in the range of 485–850 kg/m³ at 15% moisture content (Table 1). The grain of the wood is interlocked, sometimes straight, with a fine to moderately coarse texture (Soerianegara and Lemmens 1993). The surface is glossy, and the timber is often nicely figured because of the irregular grain (Figure 6).

Table 1. Wood density of *S. macrophylla*

Low	Wood density (kg/m ³)		High	Moisture content (%)	References
	Medium				
530	610		670	15	Oey (1964); Martawijaya <i>et al.</i> (2005)
485	–		840	12	Soerianegara and Lemmens (1993)
560			850	15	Mayhew and Newton (1998)
–	500		–	–	Fearnside (1997)
560	–		720	15	World Biodiversity Databases



Figure 6. *S. macrophylla* timber



Figure 7. Items made of *S. macrophylla* timber: (a) door pane, (b) cupboard, (c) flooring and (d) urn

2.6. Uses

Swietenia macrophylla is suitable for large-scale timber production plantations because of its excellent timber quality. The wood can be used for construction materials, plywood (veneer), high-grade furniture and cabinet making. It is also suitable for panelling, framing, flooring, automobile bodies, interior trim of boats, radio and phonograph cabinets, bodies of musical instruments, mouldings and other ornaments (Figure 7).

Swietenia macrophylla also has great potential for reforestation and afforestation, particularly for improving soil. In the Philippines, the tree species is recommended for revegetation of scrubland and denuded areas (Soerianegara and Lemmens 1993). In Indonesia, it is also used in agroforestry systems, for example in Java with maize, upland rice and cassava, and in our study village in South Kalimantan with cassava, corn, peanuts and pumpkin.

3. Seed production

3.1. Seed collection

Swietenia macrophylla is propagated from seeds. The best outcomes can be achieved by using seeds from a mother tree in excellent form and health. Seed production fluctuates considerably from year to year. The fluctuation may reflect variation in flowering phenology, or failure of pollination or fertilisation (Mayhew and Newton 1998). Flowering and fruiting regularly occur annually from 10 to 15 years of age. Flowering and fruiting seasons differ according to geographical location. For example, in the central and

northern parts of South America, the tree blooms from April to June, and the fruits ripen from January to March of the following year (Schmidt and Jøker 2000). In Indonesia, the flowering months are usually between July and September and the fruiting season is between December and February. Flowering usually takes place when trees are leafless or just coming into new leaf shortly before the rainy season. The fruits ripen during the dry season, when the trees begin to lose part of their foliage and the warm air dries the fruits and promotes dehiscence (Mayhew and Newton 1998).

The fruits are preferably collected from the ground immediately after seed fall or from the trees just before they open by climbing the trees or using poles with metal hooks to cut down the seeds. Fruits should be harvested from the tree towards the middle or the end of the fruiting season. When the fruits are ripe, the pericarp changes to a light coffee colour just before the valves open and release the seeds.

3.2. Seed preparation

Mature dry fruits or dry seeds (capsules) collected from the forest floor can be stored for some days in sacks without significant deterioration. Unripe capsules may need to be dried out first to encourage them to open. The capsules can be dried in the sun. Alternatively, capsules can be placed on a rack over electric lamps at a temperature of 38°C for 36–48 hours to encourage them to open. The length of time required for drying depends on the ripeness of the capsule and ambient temperature and humidity. The fruits will split open when dried for 1–4 days, depending on maturity, after which the seeds are

Table 2. Flowering and fruiting periods of *S. macrophylla* in selected countries

Country*	Flowering	Fruiting
Central and northern South America	April–June	January–March
Southern South America	September–October	July–August
British Virgin Is. and Puerto Rico	May–June	September–October
Costa Rica	March–April	December–January
Solomon Islands		June–September
Philippines	March–June	December–March
Indonesia	July–September	December–February

* Source: Schmidt and Jøker (2000) for countries other than Indonesia

easily released by gentle shaking or raking of the fruits. Seed wings are removed by hand to facilitate handling and to reduce volume. The wing is broken 1 cm above its base, and the seeds without wings are placed in a container (Mayhew and Newton 1998).

3.3. Seed storage and viability

The viability of fresh *S. macrophylla* seeds is around 80–90%, although that for stored seeds can vary (Mayhew and Newton 1998). The seed viability also varies with size. For example, Chinte (1952) in Mayhew and Newton (1998) reported that large seeds have a 12% higher germination rate and produce healthier, faster-growing seedlings with better developed root systems than small seeds. Mayhew and Newton (1998) stated further that in general, *S. macrophylla* seed will not retain an acceptable level of viability if stored at room temperature and in humid conditions for more than about 3 months. Seeds of *S. macrophylla* are susceptible to chilling damage below about 16 °C when they are moist. If they are to be refrigerated they have to be dried first. It has been reported that dried seeds refrigerated to 2–8 °C and maintained at constant humidity maintain viability for more than a year. If seeds are dried to a moisture content of 5% or less, deep freezing (at –20 °C) will maintain a high viability for at least 2 years and possibly many decades (Mayhew and Newton 1998).

4. Propagation and planting

4.1. Sowing

The seeds are sown in a bed of light sand in furrows or holes 3–7 cm deep. Germinating seeds should be under shade and kept moist. The sowing density may vary depending on the desired size of the planting stock and whether or not transplanting is intended.

As reported by Neil (1986) and Bauer (1987) in Mayhew and Newton (1998), to obtain seedlings of 30–60 cm in height, a square spacing of 10–15 cm is commonly recommended, and to obtain seedlings of 100 cm in height, a spacing of 20×30 cm is suggested.

Swietenia macrophylla can also be sown in containers. Raising stock in containers may give a more fibrous root system and better results after planting out, but the cost may be high. Container planting stock may be more suitable for dry planting sites whereas bare-rooted stock are suitable for wet sites or sites that are subject to very strong winds (Soerianegara and Lemmens 1993).

4.2. Preparation for planting out

Good maintenance of *S. macrophylla* seedlings is essential for the production of healthy and fast-growing plants (Figure 8). Weeding should be conducted in the nursery in every 2–4 weeks until the seedlings are ready to be planted out. Chemical weeding is not possible in *S. macrophylla* as the seedlings are very sensitive to herbicide. Nurseries should also be thoroughly watered before seedlings are lifted to avoid straining or breaking the small fibrous roots (Busby 1967 in Mayhew and Newton 1998). Lifting and subsequent preparation of bare-rooted stock must take place as close to the planting date as possible to minimise the risk of desiccation. Root pruning in the nursery helps to create a more fibrous root system. Root pruning should be carried out about 4 weeks before lifting, but should not be done whilst seedlings are flushing (Mayhew and Newton 1998).

The seedlings can be planted in the field when they are about 50–100 cm tall, when they are sufficiently strong and not tender and their fresh shoots have a chance to mature and harden (Figure 9). To increase



Figure 8. *S. macrophylla* seedlings in a smallholder's nursery in South Kalimantan



Figure 9. *S. macrophylla* seedlings ready for planting out



Figure 10. Five-year-old *S. macrophylla* trees planted at a spacing of 4×5 m by a smallholder in South Kalimantan. Ground vegetation is *Brachiaria decumbens* grass, which provides good fodder for cattle

the survival rate at the planting site, the seedlings should be handled carefully and roots kept moist. Some methods include wrapping the roots of the bundles in dry grass and soaking, putting bundles in wet sacks and putting individual plants in polythene bags, which are in turn placed in wet sacks to keep them cool (Lamb 1966). Bundles, bags or sacks should then be kept in the shade until planting out.

4.3. Planting

All weeds should be cleared from the planting sites. The use of close spacing can shade the ground and thus reduce the growth of weeds. Close spacing will also serve to reduce the development of vigorous lateral branches. Spacing for planting *S. macrophylla* is usually 2–3 m. Planting *S. macrophylla* amongst trees such as *Paraserianthes falcataria* and *Manglieta glauca* that are already a few years old can create mild shade for the *S. macrophylla*, minimising lush growth of terminals and laterals (Soerianegara and Lemmens 1993). Wider spacing of about 4–5×4–5 m is also commonly applied by smallholders in South Kalimantan and Java in order to obtain multiple yields by intercropping the *S. macrophylla* trees with cassava, corn, peanut, pumpkin and other agricultural crops. As we observed in our study village in South Kalimantan, *Brachiaria decumbens* grasses are often planted under *S. macrophylla* trees to provide fodder for cattle (Figure 10).

5. Plantation maintenance

5.1. Weeding

Weeding is required to ensure maximum growth and survival of seedlings. Some weeds commonly found in young *S. macrophylla* plantations are *Imperata cylindrica* Beauv., *Clibadium surinamense* L., *Melastoma malabathricum* L. and *Merremia umbellata* Hallier (Nazif and Pratiwi 1989). Weeds that are as tall as or taller than the seedlings should be removed. During the first 2 years after planting, weeding and hoeing should be done 4 times every 6 months (Directorate of Industrial Plantation Forests 1990, Mindawati and Tata 2001). Either line weeding (along the rows of main species) or ring weeding (in a 1-m diameter around the seedling) is recommended. To prevent the regrowth of weeds, cut grass is placed as mulch around the seedlings (Directorate of Industrial Plantation Forests 1990).

5.2. Fertilising

Fertilising *S. macrophylla* seedlings may reduce susceptibility to shoot borer damage by altering the chemical composition of the apical shoots and/or enhancing tolerance by improving vigour (Mayhew and Newton 1998). In Indonesia, fertilisers are usually applied after planting at a dose of 75–100 g NPK (chemical fertiliser) per plant in a ring around the seedlings (Directorate of Industrial Plantation Forests 1990, Suharti *et al.* 1990, Mindawati and Tata 2001). In our study village in South Kalimantan, farmers often use organic fertiliser from animal waste.

5.3. Replanting

Replanting can be done twice during the rotation. The first replanting normally takes place in the rainy season at 1 month after planting to replace any dead seedlings and the second one is at the end of the second year. In large-scale plantations, further replanting may be necessary if the survival rate is less than 70% (Directorate of Industrial Plantation Forests 1990).

5.4. Pruning

Pruning consists of removing dead or non-productive branches from the lower trunk to encourage the production of clear wood (Figure 11). It also reduces the risk of disease and pest infestations (e.g. shoot borer). Pruning is usually done for the first 3 years (Directorate of Industrial Plantation Forests 1990);

this is expected sufficient to reduce the threat of shoot borer as the moth usually attacks young trees only. The best time for pruning is just before the rainy season. Sometimes *S. macrophylla* trees have 2 or 3 stems during early growth at 6–9 months. In this case, pruning and singling should be done by removing the co-dominant stem. If the trees are not singled, the stem density might be too high. In addition, multiple stems usually become tall and slender, and thus can easily be broken by rain or wind (Soerianegara and Lemmens 1993).

5.5. Thinning

The principal objective of thinning is to improve the growth of remaining trees with an acceptable form for the final crop. Trees selected for thinning should consist of diseased or pest-infested trees, deformed or poorly shaped trees and suppressed trees. Selective removal of damaged trees may help ensure that seeds produced by the final crop are genetically less susceptible or more tolerant to attack.

Krisnawati *et al.* (2010) developed thinning scenarios for *S. macrophylla* plantations and suggested that the time of the first thinning should be around 5–10 years, depending on site quality and initial stand density. The number of thinnings required in a rotation also varies depending on initial density and site quality. The interval period between thinnings is 5–10 years. In the scenarios proposed by Krisnawati *et al.* (2010), multiple thinnings are suitable only in



Figure 11. Three-year-old *S. macrophylla* trees in a smallholder plantation in South Kalimantan that have been pruned to maintain the stem form

stands planted at closer spacings (3 m × 3 m – 2 m × 3 m). For stands with high initial planting density (spaced at 2 m × 3 m), four thinnings in a rotation is recommended to obtain high timber volume at the end of the rotation. For intermediate initial density stands (spaced at 3 m × 3 m), two–three thinnings appears to be essential for obtaining high timber volume, while in a wide spacing (4 m × 4 m) one thinning option is suitable. The intensity of thinning suggested by Krisnawati *et al.* (2010) should be heavier in the first thinning (45–55% of the standing trees removed) for high initial density in order to maintain high growth rates and shorten the rotation length. The intensity of subsequent thinnings should then be reduced gradually to 25–30%. For stand of low initial density (spaced at 4 m × 4 m) the suitable thinning intensity is about 30–43%.

5.6. Control of pests and diseases

The most destructive pest in *S. macrophylla* plantations is the shoot-borer *Hypsipyla robusta*. Attacks are most often noticed on saplings and pole-size trees when terminal shoots show symptoms of dieback, which ultimately result in malformed trees. The larvae bore into the growing shoots of saplings, destroying the terminal bud and causing growth retardation and stem forking. Often, multiple leaders are formed. According to Morgan and Suratmo (1976), in Java young trees 3–6 years old and 2–8 m tall were the most severely attacked by shoot borer. This finding is supported by Suratmo (1977), who observed that about 90% of 3-year-old trees (2.5 m tall) were affected compared with only 5% of trees 14 years old and 13 m tall. Older trees are not susceptible to attack. At present, there is no effective method to control this insect. Extensive pruning until 3 years after planting may reduce the threat of shoot borer. Planting of trees repellent to the moth along the plantation border or in a mixed stand has also been suggested to prevent the arrival of moths for egg laying. In preliminary trials, planting of *Acacia mangium* around a *S. macrophylla* plantation prevented *H. robusta* infestation (Matsumoto *et al.* 1997). Interplanting neem (*Azadirachta indica*) with *S. macrophylla* also reduced shoot-borer attacks (Suharti *et al.* 1995). These preliminary results suggest the potential of this method, but more critical large-scale trials are necessary to examine the effectiveness and feasibility of these methods. Minor pests observed in experimental plantings include the leaf-feeding

caterpillar *Attacus atlas* (Lepidoptera, Saturniidae) and the leaf cutter bee *Megachile* sp. (Hymenoptera, Megachilidae) (Matsumoto 1994).

The only disease noted in *S. macrophylla* is bark rot, which occurs at the base of the trunk. A lesion appears in the middle of the rainy season, spreads rapidly from the bottom upwards and often kills the trees by the end of the season. The lesion always appears on the stem surface facing the water flow along the slope and it is assumed that the pathogen arrives through water and enters through wounds. The causative organism remains unidentified (Soerianegara and Lemmens 1993).

6. Growth and yield

The ability to predict the growth and yield potential of *S. macrophylla* plantations is of considerable importance for plantation planning. However, relatively little reliable experimental data covering periodic stand measurement until the end of rotation are available. The information on growth and yield presented here is based on preliminary data of young *S. macrophylla* stands (up to 5 years old) collected from 76 temporary sample plots established in smallholder plantations in South Kalimantan and some data from 6 permanent plots (covering an age range of 5–10 years) collected by Susila and Njurumana (2005) in *S. macrophylla* plantations in Nusa Tenggara. For older stands, information was taken from 36 permanent sample plots spreading over several sites in Java, which were collected by Forest Research Institute and used by Wulfin (1949) and updated by Suharlan *et al.* (1975) to develop preliminary stand yield tables for mahogany (combining both *S. macrophylla* and *S. mahagoni* species).

6.1. Growth rates

Predictions of mean DBH and height for age have been reported for some young *S. macrophylla* plantations in Indonesia (e.g. Susila and Njurumana 2005). Susila and Njurumana (2005) reported that *S. macrophylla* trees in 5–9-year-old stands growing in the plantations of Sumbawa (West Nusa Tenggara) had a mean diameter of 16.6 cm and a mean height of 12 m. In a site in Kupang (East Nusa Tenggara), *S. macrophylla* trees in stands of 6–10 years old were reported to have a mean diameter of 13.2 cm and a

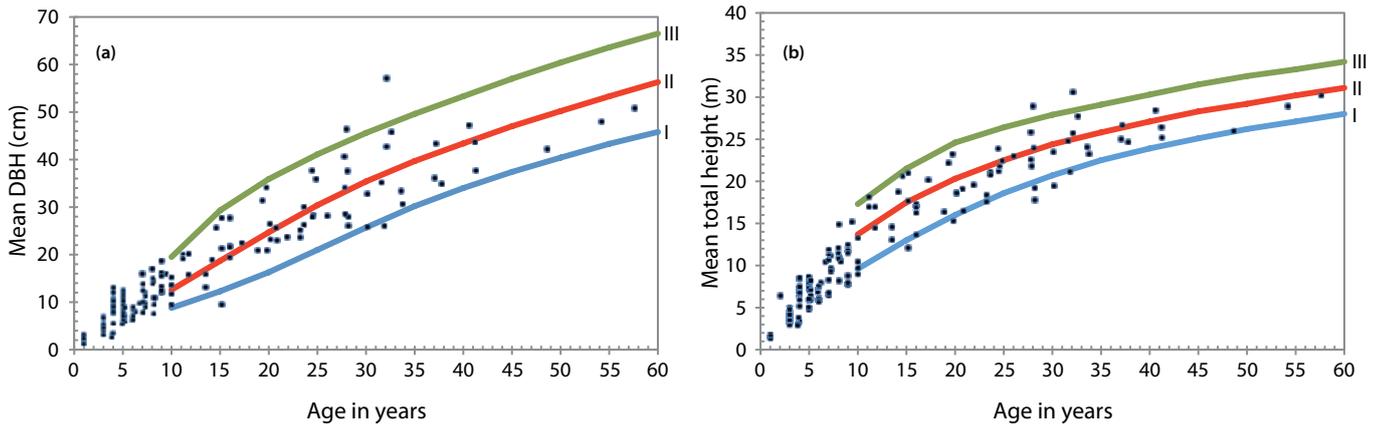


Figure 12. The relationships between age and diameter (a) and age and height (b) of *S. macrophylla* taken from measurements of temporary plots in South Kalimantan and permanent plots in Java and Nusa Tenggara (points: mean values of the plots, lines: values taken from the yield table developed by Wulfing (1949)). Roman numerals indicate site quality class with a low class number indicating poor site quality.

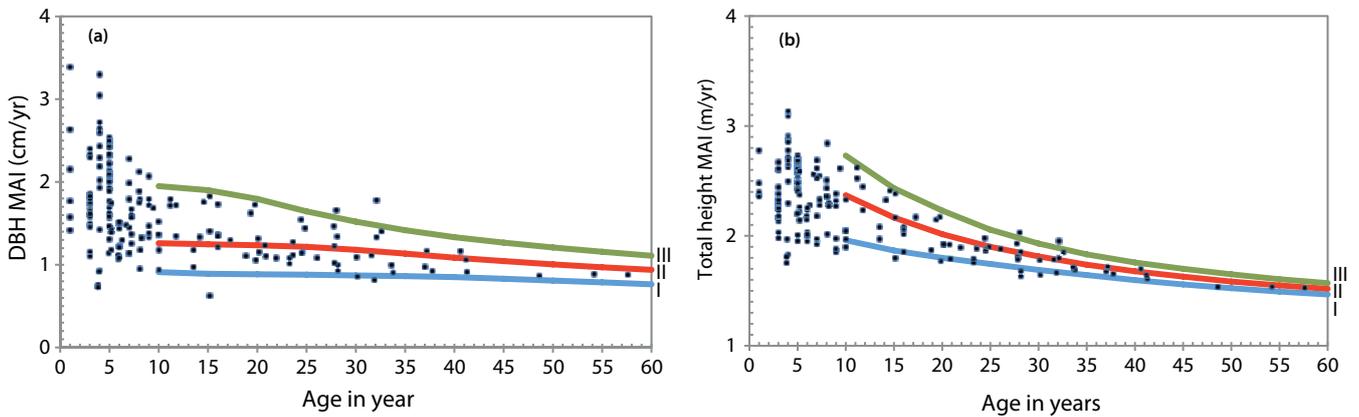


Figure 13. Mean annual increment (MAI) in diameter (a) and height (b) of *S. macrophylla* trees. Data from measurements of temporary plots in South Kalimantan and permanent plots in Java and Nusa Tenggara (points: MAI values of the plots, lines: values taken from the yield table developed by Wulfing (1949)). Roman numerals indicate site quality class with a low class number indicating poor site quality.

mean height of 9.6 m. Our recent study in Tanah Laut (South Kalimantan) recorded that *S. macrophylla* trees growing in small farms have a mean diameter ranging from 2.8 to 13.2 cm with a maximum diameter of 21.0 cm for trees younger than 5 years old. The mean height of the corresponding stands ranges from 2.9 to 8.7 m with a maximum value of 11.8 m. The range of mean diameter from trees older than 10 years growing in several plantation sites in Java is 9.4–57.1 cm with a mean value of 29.3 cm. The oldest of these stands was 57.6 years. The wide variations in mean diameter and height as reported in these studies are due to the differences in site quality and management practices. The growing conditions in Nusa Tenggara are reported to be much drier than those in South

Kalimantan. In addition, some *S. macrophylla* trees in South Kalimantan have been found to grow slowly, particularly in stands with dense ground vegetation and poor site quality.

The relationships between mean diameter and age and between height and age of *S. macrophylla* taken from all available data are shown in Figure 12. The diameter at breast height (DBH) generally increases up to 10–20 cm in trees younger than 10 years old. Growth rates slow noticeably after 10 years, and both diameter and total height begin to level off after 30 years (Figure 13).

6.2. Height–diameter relationship

Height and diameter are essential inventory measures for estimating tree volume. However, measurement of tree height is difficult and costly. Consequently, height is measured for only a subset of trees. Quantifying the relationship between tree height and diameter is therefore necessary to predict heights of the remaining trees. Despite the importance of height–diameter models in forest plantation management and planning, relatively little information is available on the height–diameter relationship for *S. macrophylla* plantations.

Using measurement data collected from 721 *S. macrophylla* trees in smallholder plantations in Tanah Laut District, South Kalimantan, we investigated the relationship between total tree height (*H*) and diameter at breast height (*D*) of *S. macrophylla*. Six non-linear models were tested: Chapman–Richards, Curtis, exponential, Gompertz, Korf and Patterson. Of these, the Chapman–Richards model best fit the data. The functional form of the selected model was:

$$H = 1.3 + b_0 (1 - \exp(-b_1 D))^{b_2}$$

The results of fitting the selected model, including non-linear least squares estimates of the parameters, the standard error (SE), *t*-statistic, *p*-value, the root mean squared error (RMSE) and the adjusted coefficient of determination, are presented in Table 3. The model produced relatively low RMSE (about 0.8 m) and explained a relatively high proportion of the total variation in observed values of the tree height, accounting for 87.2%. However, care should be taken when using the model for older trees as the model was developed based on data from young trees only (mostly less than 5 years old with diameters less than 20 cm; only a few trees in the sample had larger diameter). The relationship between height and diameter of *S. macrophylla* is presented in Figure 14.

6.3. Stem volume estimation

The estimation of the volume of an individual tree is a necessary step in estimating the stand volume. Stem volume equations were produced for *S. macrophylla* in Indonesia by Wahjono and Sumarna (1987). They developed stem volume models to estimate stem volume up to the first branch (clearbole volume, *V_c*) and stem volume up to 7 cm in diameter (thickwood volume, *V₇*) by relating stem volume to DBH and volume to DBH (*D*) and total height (*H*) together using log–log relationships:

$$\begin{aligned} \log V_c &= -0.5157 + 2.1623 \log D \\ \log V_c &= -1.007 + 2.0086 \log D + 0.6156 \log H \\ \log V_7 &= -0.7618 + 2.3704 \log D \\ \log V_7 &= -0.8956 + 2.3280 \log D + 0.1699H \end{aligned}$$

The models were developed based on data collected from 114 *S. macrophylla* sample trees grown in state-owned plantations in Jember District, East Java. The range of the diameter used to develop the models was 25–59 cm and the height range was 9–22 m. The models have been used to produce single (DBH only) and double (both DBH and height) entry volume tables.

The development of total wood volume of *S. macrophylla* trees growing in small farms in South Kalimantan and the thickwood and clearbole volume models of Wahjono and Sumarna (1987) are presented in Figure 15. As expected, the different top diameter specifications resulted in variation in the volume estimates. The graph shows that Wahjono and Sumarna’s (1987) models predict higher clearbole and thickwood volumes than do total stem volumes reported for smallholder plantations in South Kalimantan. These higher estimates are not surprising as the data used to develop Wahjono and Sumarna’s models came from sample trees in state-owned plantations that have been well managed, whereas smallholder plantations typically are less well maintained.

Table 3. Parameter estimates, standard errors and related fit statistics of the height–diameter model for *S. macrophylla* plantations

Parameter	Estimate	SE	t	Pr ≥ t	RMSE	R ² adj
<i>b</i> ₀	12.399160	0.3647	34	< 0.0001	0.803	0.8718
<i>b</i> ₁	0.105376	0.0073	14.44	< 0.0001		
<i>b</i> ₂	1.790226	0.1032	17.34	< 0.0001		

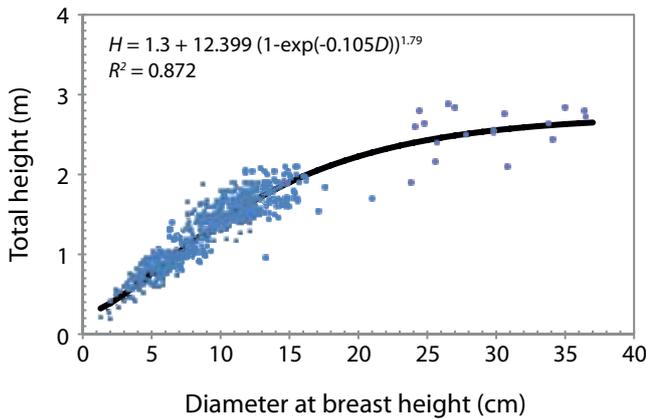


Figure 14. The relationship between height and diameter of *S. macrophylla* developed using measurement data from smallholder plantations in South Kalimantan (points: measured values, solid line: model)

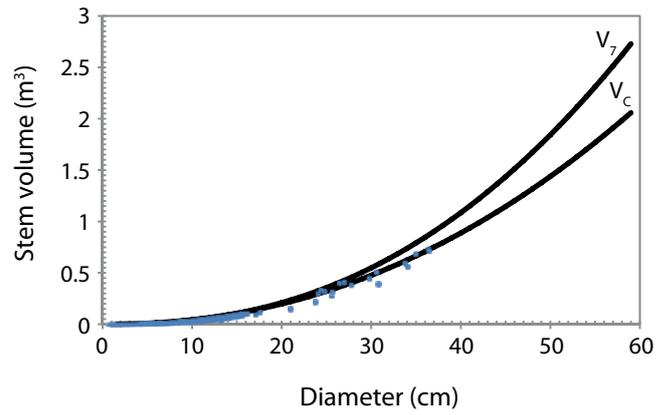


Figure 15. Merchantable (V_c) and thickwood (V_7) volumes against tree DBH for *S. macrophylla* plantations based on Wahjono and Sumarna's (1987) model, overlaid with total stem volume measured from small farms in South Kalimantan (points: measured values, lines: model).

Table 4. Aboveground biomass estimation models for each tree component and associated statistical information for *S. macrophylla* (Adinugroho and Sidiyasa 2006)

Component	Model	R ²	SE	PRESS
Stem	$B_{\text{stem}} = 0.044 D^{2.61}$	94.7	0.063	0.13
Branch	$B_{\text{branch}} = 0.00059 D^{3.46}$	83.5	0.157	0.76
Twig	$B_{\text{twig}} = 0.0027 D^{2.42}$	65.6	0.179	1.07
Stump	$B_{\text{stump}} = 0.022 D^{1.96}$	65.6	0.145	0.68
Leaf	$B_{\text{leaf}} = 0.0138 D^{1.93}$	70.0	0.129	0.54
Total	$B_{\text{total}} = 0.048 D^{2.68}$	95.8	0.057	0.10

D = diameter at breast height (cm); B = biomass of each component (kg)

6.4. Biomass estimation

The aboveground biomass estimation for *S. macrophylla* has been reported by Adinugroho and Sidiyasa (2006). They developed allometric equations to provide a method for estimating aboveground biomass using a sample of 30 *S. macrophylla* trees grown in state-owned plantations in Cianjur, West Java. The range of the DBH of the sample trees was 14.3–36.9 cm and the range of the total tree height was 8.5–25.8 m. The 30 trees were felled, and after felling, each tree was divided into 5 components: stem, branch, twig, stump and leaf. Total tree biomass was calculated as the sum of biomass of each tree component. Their study tested 9 different models, including both linear and non-linear models, for each tree component using DBH, height and a combination of both as independent variables; ultimately, only

the DBH model was selected as the DBH is easy to measure accurately in the field. The best-fitting model in each case was selected based on R², standard error and PRESS (predicted residual sum of squares). The best-fit equations developed in their study for the different components of *S. macrophylla* trees are given in Table 4.

The proportions of aboveground biomass of the *S. macrophylla* components are shown in Figure 16. The largest amount of biomass was found in the stem (73%), followed by the branch (17%), stump (5%), leaf (3%) and twig (2%). The biomass expansion factor for *S. macrophylla* was 1.36 when calculated to the total tree height and 2.16 when calculated to the merchantable height (Adinugroho and Sidiyasa 2006).

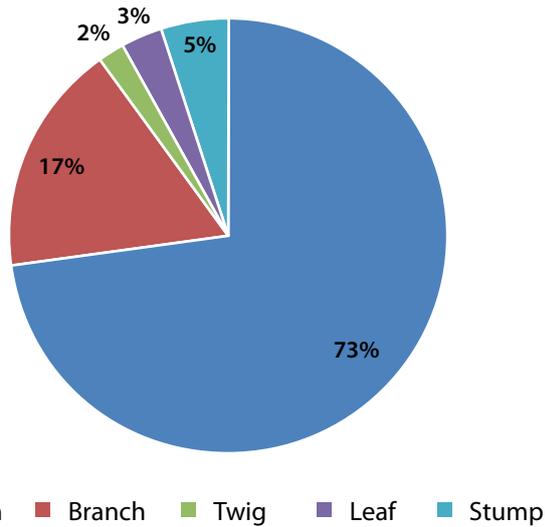


Figure 16. Proportion of aboveground biomass component for *S. macrophylla*

6.5. Productivity

Swietenia macrophylla plantations in Indonesia are predicted to reach a maximum volume mean annual increment (MAI) of 38.1 m³/ha/year in 15 years in the best sites, producing up to 572 m³/ha over the rotation and in medium-quality sites, a volume MAI of 19.7 m³/ha/year can be attained in 25 years, producing up to 493 m³/ha (Wulfing 1949). If the rotation is set to 30 years, stands growing in moderate sites can attain a mean height of 24.4 m and a mean diameter of 35.4 cm, producing a basal area of 30 m²/ha and total volume including thinning is 583 m³/ha. This value is much higher than that reported by Suharlan *et al.* (1975) who predicted the total volume of 439 m³/ha for the same age (30 years) and site quality (moderate site). According to the scenarios proposed by Krisnawati *et al.* (2010) total timber volume (including thinning) yielded over the rotation of 15–30 years of age was between 200.5 and 501.6 m³/ha with a mean annual volume increment of 7.7–19.3 m³/ha/year.

6.6. Rotation

Previously reported rotation lengths for *S. macrophylla* plantations were variable. Fattah (1992) reported that in the state-owned plantations in Java,

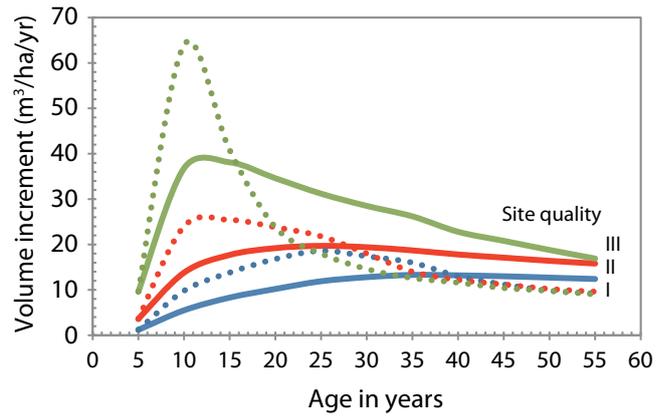


Figure 17. Volume MAI (solid lines) and Current Annual Increment (CAI) (dashed lines) against age by site quality for *S. macrophylla* plantations. Graphs were drawn from preliminary yield tables (Wulfing 1949) with a low class number indicating poor site quality.

the economic rotation for *S. macrophylla* plantations was defined to be around 30–50 years. In private farms of *S. macrophylla* plantations in the Philippines, Rodriguez (1996) suggested the harvesting time could be around 15–20 years of age. A longer rotation (up to 60 years) has also been reported in other country in Puerto Rico (Bauer and Francis 1998).

The desired rotation length may be guided by the time taken for the stands to reach their maximum mean annual volume increment (MAI) in volume. Wulfing (1949) and Suharlan *et al.* (1975) constructed a preliminary stand yield table for a combined species of *S. macrophylla* and *S. mahagoni* for high initial stand density (spaced at 2 m × 3 m or closer) in Indonesia and predicted that these plantation will reach the maximum mean annual volume increment at sometime between 15 and 50 years, depending on site quality (Figure 17). Other report suggested that on average site, the maximum mean annual volume increment will be reached at around 35 years (Pandey 1983). This prediction is supported by Krisnawati *et al.* (2010) who estimated the feasible rotation length for *S. Macrophylla* plantations in Indonesia is around 15–30 years of age, depending on site quality and initial stand density.

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This manual gathers information on the ecology and silviculture of *Swietenia macrophylla* King, with a focus on Indonesia. It also includes growth and yield data from published sources, collected from smallholders' farms in the research sites in South Kalimantan province, and collected previously by the Forestry Research and Development Agency of Indonesia. This manual is one of five manuals that guide smallholder tree planting of five selected tree species in Indonesia. The other four species are: *Acacia mangium* Willd.; *Aleurites moluccana* (L.) Willd.; *Anthocephalus cadamba* Miq.; and *Paraserianthes falcataria* (L.) Nielsen. Smallholders in Indonesia have planted trees on private or community land for a long time. Various actors have encouraged this activity with the aim of improving local livelihoods, environmental sustainability and industrial wood supply. Since farmers often lack technical capacity and management know-how, the quality and quantity of products may not be optimal. Productivity of smallholder plantations can be improved by enhancing smallholders' management knowledge and skills, including species selection based on site matching, silvicultural management to maximise product quality, and pest and disease management.

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