Acacia mangium Willd.

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, '*Acacia mangium* Willd.: 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 *Acacia mangium* Willd. 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 research sites under community–company partnerships in South Kalimantan and Riau provinces. In addition, information from large-scale plantations that has been published in several reports is used.

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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Markku Kanninen

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1. Introduction

Acacia mangium Willd., also known as mangium, is one of the most widely used fast-growing tree species in plantation forestry programmes throughout Asia and the Pacific. Its desirable properties include rapid growth, good wood quality and tolerance of a wide range of soils and environments (National Research Council 1983). The recent pressure on natural forest ecosystems in Indonesia inevitably resulted in the use of fast-growing plantation trees, including *A. mangium*, as a substitute to sustain the commercial supply of tree products. Based on trials of 46 species conducted by the Indonesian Ministry of Forestry in Subanjeriji (South Sumatra), *A. mangium* was chosen as the most suitable plantation species for marginal sites, such as alang-alang grasslands (Arisman 2002, 2003).

Indonesia has 67% of the total reported area of *A. mangium* plantations in the world (FAO 2002). Rimbawanto (2002) and Barry *et al.* (2004) reported that around 80% of plantations in Indonesia managed by state and private companies are composed of *A. mangium*. Around 1.3 million ha of *A. mangium* plantations have been established in Indonesia for pulpwood production (Ministry of Forestry 2003). Smallholders also plant *A. mangium*. According to the Ministry of Forestry and the National Statistics Agency (2004), Central Java and East Java have the highest number of *A. mangium* trees planted by smallholders, with these provinces accounting for more than 40% of the total number of *A. mangium* trees planted by households in Indonesia.

2. Description of the species

2.1. Taxonomy

Botanical name: *Acacia mangium* Willd.

Family: Leguminoseae

Subfamily: Mimosoideae

Synonyms: *Rancosperma mangium* (Willd.) Pedley

Vernacular/common names:

Common names in Indonesia: mangga hutan, tongke hutan (Ceram), nak (Maluku), laj (Aru), jerri (Irian Jaya) (Turnbull 1986).

Common names in other countries: black wattle, brown salwood, hickory wattle, mangium, sabah salwood (Australia, England); mangium, kayu SAFODA (Malaysia); arr (Papua New Guinea); maber (Philippines); zamorano (Spain); kra thin tepa, krathin-thepha (Thailand) (Hall *et al.* 1980, Turnbull 1986).

2.2. Botany

Acacia mangium trees are generally large and can grow to a height of 30 m, with a straight bole that may be more than half of the total tree height. Trees with a diameter at breast height (DBH) of more than 60 cm are rare; however, stem diameters of up to 90 cm have been measured in the natural forests of Queensland and Papua New Guinea (National Research Council 1983). On relatively poor sites, the trees may resemble a large shrub or small tree with an average height between 7 and 10 m (Turnbull 1986). The stem has longitudinal furrows. Bark in young trees is smooth (Figure 1) and greenish; fissures begin to develop at 2–3 years. Bark in older trees is rough (Figure 2), hard and fissured near the base, and coloured brown to dark brown (Hall *et al.* 1980).

Figure 1. Bark of young *A. mangium* tree

Figure 2. Bark of old *A. mangium* tree

The leaves of newly germinated juveniles are composed of many leaflets that are similar to those of *Albizia*, *Leucaena* and other species of the subfamily Mimosoideae. After a few weeks, however, juveniles no longer produce these true leaves; instead, the leaf stalk and main axis of each compound leaf flatten and are transformed into a phyllode (Figure 3). The phyllodes are simple and parallel veined, and can be up to 25 cm long and 10 cm wide (Figure 4). Inflorescence is composed of many tiny white or cream flowers in spikes (Figure 5). When in full blossom, the inflorescences resemble bottle brushes (Turnbull 1986). The flower has a mild, sweet fragrance. After fertilisation, the flower develops into a green pod that darkens to blackish-brown at maturity (National Research Council 1983). The seeds are black and shiny with shapes ranging from longitudinal, elliptical and ovate to oblong with a size of 3–5 mm by 2–3 mm. The seeds are attached to the pods (Figure 6) by an orange to red folded funicle.

2.3. Distribution

Acacia mangium originates from the humid tropical forests of north-eastern Australia, Papua New Guinea and the Molucca Islands of eastern Indonesia (National Research Council 1983). Since its successful introduction into Sabah, Malaysia, in the mid 1960s, it has been widely introduced into many countries, including Indonesia, Malaysia, Papua New Guinea, Bangladesh, China, India, Philippines, Sri Lanka, Thailand and Vietnam. In Indonesia, *A. mangium* was first introduced into regions other than the Molucca Islands in the late 1970s as a species for reforestation (Pinyopusarerk *et al.* 1993).

Figure 3. Juvenile leaves of *A. mangium* seedling
(Photo: M. Kallio)

Figure 4. Phyllodes of *A. mangium*

Figure 5. Inflorescence of *A. mangium*

Figure 6. Mature blackish-brown *A. mangium* pods

Table 1. Wood density of *A. mangium*

Wood density (kg/m^3)			Moisture content	Reference
Low	Medium	High	(%)	
500	–	600	–	Abdul-Kader and Sahri (1993)
450	530	690	15	Lemmens *et al.* (1995)
530	610	660	15	Oey (1964)

2.4. Ecological range

Acacia mangium is well adapted to a wide range of soils and environmental conditions. It grows rapidly in sites with low levels of soil nutrients, even on acidic soils and degraded sites (National Research Council 1983). It performs well on lateritic soils, i.e. soils with high amounts of iron and aluminium oxides (Otsamo 2002). However, it is intolerant of saline conditions and shade. In shade, *A. mangium* grows to be stunted and spindly (National Research Council 1983). The species is a pioneer that can naturally regenerate in disturbed sites. Gunn and Midgley (1991) reported that the species occurs in abundance after forest disturbance, along roads and following slash-and-burn agriculture in Indonesia and Papua New Guinea.

The species is typically found in the tropical lowland climatic zone characterised by a short dry period of 4 months (Eldoma and Awang 1999). Altitudinal range of the species is from just above sea level to about 480 m above sea level. However, the species can grow at elevations as high as 800 m (Hall *et al.* 1980, Atipanumpai 1989). The total annual rainfall of the areas where *A. mangium* grows varies from 1000 mm to more than 4500 mm with a mean annual rainfall between 1446 and 2970 mm. In the species' natural range, the mean minimum temperature is approximately 12–16 °C and the mean maximum temperature is approximately 31–34 °C (National Research Council 1983). The species does not grow continuously throughout the year; growth seems to slow or cease in response to the combination of low rainfall and cool temperatures (Turnbull 1986). Dieback occurs if the trees are exposed to a severe period of drought or prolonged frost. Pan and Yang (1987) reported high mortality of 5-year-old *A. mangium* trees after being exposed for a long period to low temperatures of about 5–6 °C with cold rain.

2.5. Wood characteristics

Acacia mangium wood is diffuse and porous. The sapwood of *A. mangium* is narrow and light coloured. Its heartwood is medium-brown, hard, strong and durable in well-ventilated situations, although not in ground contact (National Research Council 1983). The grain is straight to shallowly interlocked; the texture is fine to medium and even. The wood density varies, ranging from 450 to 690 kg/m^3 at 15% moisture content (Table 1). The rates of shrinkage are fairly low to moderate at 1.4–6.4% (Abdul-Kader and Sahri 1993). The specific gravity of *A. mangium* grown in timber plantations is more commonly between 0.4 and 0.45, whereas that from natural stands is normally about 0.6 (National Research Council 1983).

2.6. Uses

The *A. mangium* wood is suitable for pulp, paper, particle board, crates and woodchips. It also has potential for sawn timber, moulding, furniture and veneers. As it has a calorific value of 4800–4900 Kcal/kg, the wood can be used for firewood and charcoal. The leaves can serve as forage for livestock. Fallen branches and dead leaves can be used for fuel. Non-timber uses include adhesive and honey production. The sawdust provides good-quality substrate for edible mushrooms (Lemmens *et al.* 1995).

The trees are useful for shade, ornamental purposes, screening, boundaries and windbreaks; they are also used in agroforestry and erosion control (National Research Council 1983). Many farmers choose to plant the species to improve soil fertility of fallowed field or pastures. The trees have an ability to overcome strong competition from aggressive weeds, such as *Imperata cylindrica*; they can also fix atmospheric nitrogen and produce a rich harvest of litter, which increases soil biological activity and rehabilitates the physical and chemical properties of the soil (Otsamo *et al.* 1995). *Acacia mangium* trees can also be used as fire breaks as trees with diameters of 7 cm or more are commonly fire resistant (National Research Council 1983).

3. Seed production

3.1. Seed collection

Acacia mangium starts to flower and produce seeds 18–20 months after planting (National Research Council 1983). The flowering and fruiting seasons differ according to geographical location. For example, in Australia, the major peak of flowering occurs between March and May with fruits maturing from late September to December (Sedgley *et al.* 1992). In Indonesia, fruits ripen earlier, in July, and in Papua New Guinea they ripen in September (Turnbull 1986). In general, fruits mature 5–7 months after the flowering period (Table 2).

The fruits are ready for harvesting when they change to dark brown and begin to crack open. Harvesting is done by clipping the fruits from the trees with pruning poles. Ideally, fruits are harvested before they are fully open (Bowen and Eusebio 1981 *in* Adjers and Srivastava 1993), although pods with hanging seeds remain available on the trees for several weeks.

3.2. Seed preparation

The pods of *A. mangium* should be processed as soon as possible after collection. Many techniques are used to separate *A. mangium* seeds from their pods. Seeds can be extracted manually after sun-drying for several days (24–48 hours) until the pods turn brown/black and split. The drying temperature should remain below 43 °C to avoid loss of seed viability (FAO 1987). Seeds can also be separated from the pods after drying by turning them for 10–15 minutes in a cement mixer with heavy wooden blocks. Another method is to put the dry pods into sacks and then beat them in a mechanical thresher. The seeds are then sieved clean of pod debris and winnowed by hand or machine to remove chaff. There are about 80 000–110 000 cleaned seeds per kg (National Research Council 1983).

3.3. Seed storage and viability

Storing the seeds of *A. mangium* is relatively easy. Once the seeds are dried (to 6–8% moisture content) and placed in an airtight container, they maintain a germination of 75–80% for several days (National Research Council 1983). Good storage protects the seeds from high temperatures, light and excessive oxygen. FAO (1987) recommends storing *A. mangium* seeds in sealed, air-tight containers in a refrigerator at a temperature of 0–5 °C. Supriadi and Valli (1988) *in* Adjers and Srivastava (1993) recommend using clean jerrycans or small jars that can be closed tightly. According to Evans (1982), *A. mangium* has long seed viability under almost any conditions if seeds are kept dry and free from insect and rodent damage.

Before sowing, seeds should be placed in boiling water for 30 seconds, and then cooled by soaking in cold water for 2 hours. Germination may begin after 1 day and continue for 10–15 days (Adjers and Srivastava 1993).

4. Propagation and planting

4.1. Sowing

Seeds may be sown in seedbeds and transplanted 6–10 days after sowing. However, the recovery rate using this method is only about 37%. Sowing in germination trays and transplanting the seedlings 6–10 days later, when the radicle emerges, leads to more than 85% recovery (Adjers and Srivastava 1993). Another option is direct sowing in containers followed by transplanting to maintain 1 seedling per container. As direct sowing reduces the cost of seedling production and has minimal risk of root deformation, it is commonly preferred by many tree growers (Adjers and Srivastava 1993). This method requires good-quality seeds with a high germination percentage. FAO (1987) recommends

Table 2. Flowering and fruiting periods of *A. mangium* in selected countries

Country	Flowering	Fruiting	Reference
Australia	March–May	September–December	Sedgley *et al.* (1992)
Papua New Guinea	April–July	September–November	Turnbull (1986)
Indonesia	January–March	July	Turnbull (1986)
Malaysia	January	June–July	Sedgley *et al.* (1992)
Taiwan	October–November		Kiang *et al.* (1989) *in* Adjers and Srivastava (1993)
Thailand	September		Kijkar (1992) *in* Adjers and Srivastava (1993)
Central America		February–April	CATIE (1992) *in* Adjers and Srivastava (1993)

placing several seeds in each container: 3 seeds per container if the germination is 30–50%; 2 seeds per container if the germination is 51–80%; and 1 seed per container if the germination is more than 81%. Direct sowing should be carried out under a shading net, as only light shade is suitable for *A. mangium*. In Indonesia, nets transmitting 50% light have been extensively used (Supriadi and Valli 1988 *in* Adjers and Srivastava 1993). Seeds should be covered after sowing. Suitable materials such as coarse, washed sand, crushed rock or gravel prevent damping-off, allow rapid emergence of the cotyledon and provide good air exchange and water drainage (FAO 1987).

4.2. Preparation for planting out

Adequate moisture and a suitable source of fertilisers are essential for good seedling growth in the nursery. Excessive watering can result in watery seedlings, whereas insufficient watering can lead to stunted seedlings (FAO 1987). The watering schedule will depend on the temperature, rainfall, air humidity, evapotranspiration, wind velocity, tree size and substrate. NPK fertiliser is generally applied 10 days after transplanting and twice weekly in the nursery (Adjers and Srivastava 1993). After applying fertiliser, light watering is necessary to wash any fertiliser residue off the leaves.

Seedlings are usually retained in the nursery for 12 weeks or until they have attained a height of 25–40 cm (Figure 7). Srivastava (1993) recommends 2 root prunings and hardening off of the seedlings before planting out. In low-phosphorus soils, *A. mangium* seedlings fertilised with 30 g/tree of phosphorus showed significant increase in growth compared with seedlings that were not fertilised (Lemmens *et al.* 1995).

4.3. Planting

Seedlings are planted manually during the rainy season on freshly prepared sites, on which the recommended spacing has been marked out. Seedlings are planted in contour lines on slopes and in straight lines on flat areas. After its polythene bag is removed, each seedling is carefully placed into a planting hole of about 13 cm in diameter and 20 cm in depth (Srivastava 1993). See Section 5.2 for fertilisers used during planting.

Figure 7. Nursery and seedling production of *A. mangium* in Riau, Sumatra

Spacing in plantations depends on the intended uses and soil fertility. Initial spacing can vary from 2×2 m to 4×4 m. For chipwood and fuelwood production where form may not be important, seedlings should be planted at wider spacing to produce multi-leaders and heavier branches, which may result in higher volume (Srivastava 1993), although it may increase harvesting costs. Dense planting for the production of saw logs reduces the incidence of large branches and the inherent risk of fungal infections (Weinland and Zuhaidi 1991 *in* Srivastava 1993). In Indonesia, a spacing of 3×3 m is commonly used in both large-scale and small-scale *A. mangium* plantations (Figures 8–9).

5. Plantation maintenance

5.1. Weeding

Weeding in *A. mangium* plantations is recommended to remove climbers, creepers and vines, but less harmful weeds can be left in the field to maintain lateral competition. The first weeding should be done 2 months after planting out, according to Udarbe and Hepburn (1987) *in* Srivastava (1993). The number of follow-up weedings will vary for each site. In areas where *Imperata* has a strong hold, weeding should be done frequently; for example, the area surrounding each seedling is often cleared at 1.5, 3 and 5 months, and weeds between rows are slashed at the third month (National Research Council 1983). In Indonesia, weeding around *A. mangium* is usually done 3–4 times in the first and second years after planting (Ministry of Forestry and Estate Crops 1999).

Figure 8. Two-year-old *A. mangium* trees planted with a spacing of 3×3 m in smallholder plantations in South Kalimantan

Figure 9. Three-year-old *A. mangium* trees planted with a spacing of 3×3 m in large-scale plantations in South Sumatra

5.2. Fertilising

On most sites, *A. mangium* trees have shown little response to fertiliser and *A. mangium* plantations are usually not fertilised (National Research Council 1983). However, 100 g of rock phosphate is usually placed in the hole at the time of planting, and on extremely poor soils. Simpson (1992) *in* Srivastava (1993) reported that application of suitable fertilisers in adequate amounts (e.g. 100 kg/ha N, 50 kg/ha P and 50 kg/ha K) has great potential to increase early growth of *A. mangium*. Depending on soil and other site conditions, the type and amount of fertiliser may vary. For example, in South Kalimantan, K appears to be a limiting factor to growth, and in Malaysia, P appears to be the most important nutrient (Srivastava 1993).

5.3. Replanting

A survival count usually takes place 1 month after planting. Replanting is usually done for any dead seedlings. Replanting normally takes place in the rainy season at 1–2 months after planting. Srivastava (1993) reported a generally high survival of *A. mangium* after planting; on favourable sites it can reach more than 90%.

5.4. Singling and pruning

Acacia mangium seedlings grown in fairly open conditions and on good sites often develop multiple leaders (Figure 10). In addition, the species has a poor self-pruning ability. Therefore, singling and pruning are necessary in an early stage of stand development if the aim is to maintain full growth potential and produce good-quality timber (Mead and Speechly 1991). However, singling and pruning are usually done only in plantations where the objective is to produce quality saw or veneer logs. Singling usually starts at 4–6 months after planting before the trees form heartwood. Pruning begins after the first year of establishment (Srivastava 1993). Pruning is usually done in Year 2 up to 2–3 m, in Year 3 up to 5 m, and in Year 4 up to 7 m. The branches should be pruned before reaching 2 cm in diameter to avoid fungal infections, especially heart rot (Srivastava 1993). In agroforestry systems, branches are usually pruned regularly to prevent competition with agricultural crops.

5.5. Thinning

The decision whether to thin for *A. mangium* plantations is based primarily on product objectives. If pulpwood production is the sole objective, there is no restriction on product size and thinning is therefore not necessary. Thinning is necessary only when the trees are grown to produce sawn timber and veneers. Krisnawati (2007) found that the need for thinning varies according to stand density and site quality. She recommends the first thinning to be performed when trees are aged between 2 and 4 years, depending on site index and stand density. At these ages, the stands in her study had a mean tree height of approximately 9 m. This result is in agreement with those stated by Mead and Speechly (1991) and Mead and Miller (1991), who found that the first thinning in *A. mangium* plantations should be done when trees are 9 m tall (trees reach this height at approximately 2 years of age at a spacing of

3×3 m). The optimal number of thinnings during a rotation increases as initial stand density increases. In most cases, only a single thinning is optimal. In cases where conducting multiple (2) thinnings is the optimal management option, the second thinning is conducted 2 years after the first thinning. Optimal single thinning regimes involve removal of 30–60% of stems, and optimal multiple thinning regimes always remove 50% of the stems. Optimal intensity of thinning is heavier in stands of higher stand density. For high-density stands, 60% thinning is generally optimal, whereas for medium-density stands optimal thinning intensity is about 40–50% (Krisnawati 2007).

5.6. Control of pests and diseases

In general, *A. mangium* is relatively free from serious diseases and pests (Mead and Miller 1991). Surveys to evaluate diseases in tropical Acacia plantations have concluded that heart rot, root rot and phyllode rust (i.e. fungal infections of heartwood, roots and leaves, respectively) are the main threats (Old *et al.* 2000). Heart rot does not kill trees, but the quality of wood decreases; the wood becomes whitish, spongy or fibrous and is surrounded by a dark stain. Heart-rot fungi are wound basidiomycete parasites that enter trees through injuries and branch stubs (e.g. caused by pruning) and do not preferentially attack living tissue. Root-rot disease is a decay of roots caused by various basidiomycete pathogens, which attack living root tissue and may result in tree death or symptoms of crown decline. The disease is spread by contact of a diseased root or infested woody debris with a healthy root. Phyllode rust is caused by a fungus distorting the growing points in nursery plants and young plantations. An epidemic leading to premature leaf shedding occurred in 15-month-old trees in Sumatra and South Kalimantan (Old *et al.* 2000).

Figure 10. Multi-stemming tendency of *A. mangium* trees

Some groups of insects have been reported to attack *A. mangium*. Insects that may attack nursery seedlings include plant bugs, grasshoppers and bagworms, which cause various types of damage (Nair and Sumardi 2000). *Captotermes curvignathus* (termite), feeding on young seedlings' roots or stems near the ground and penetrating to the heartwood, is reported to kill 10–50% of saplings in plantations in Sumatra in their first years (Wylie *et al.* 1998 *in* Nair and Sumardi 2000). The borer *Xystrocera festiva* attacks *A. mangium* in agroforestry plantations in East Java and in industrial plantations in South Sumatra, in which up to 11% have been infested (Matsumoto 1994). These insect attacks can be controlled using insecticidal spot treatment (Old *et al.* 2000).

6. Growth and yield

6.1. Growth rates

Information on growth rates of *A. mangium* trees, in terms of mean diameter and mean height, taken from various sources under different conditions (site, age and spacing), is summarised in Table 3. In general, mean diameter increases fairly rapidly up to 15 cm in stands less than 3 years old. Growth rates slow noticeably after the fifth year, and diameter begins to level off at around 25 cm by the age of 8 years. Height growth shows the same trends as diameter. In the first 2–3 years, height increases moderately up to 10–15 m and then increases sharply up to 25 m at about 5 years, after which the height levels off.

Growth rate, as listed in Table 3, varies considerably with site, age and spacing. Comparisons can be made on the basis of the mean annual increment (MAI) values. The MAI for diameter ranges from 1.4 to 7.3

Table 3. Diameter at breast height (D), height (H) and mean annual increments (MAI) of DBH and height for *A. mangium* trees of different ages at several sites in Indonesia

Location, site	Age (years)	Spacing (m×m)	Mean DBH (cm)	D MAI (cm/yr)	Mean height (m)	H MAI (m/yr)	Reference
Sodong, S. Sumatra	1	3×3	6.9	6.9	4.8	4.8	Hardiyanto *et al.* (2004)
Toman, S. Sumatra	1	4×2	5.9	5.9	4.7	4.7	Hardiyanto *et al.* (2000)
Baserah, Riau	1	3×2	7.3	7.3	4.3	4.3	Nurwahyudi and Tarigan (2004)
Baserah, Riau	1.5	3×2	9.6	6.4	8.6	5.7	Nurwahyudi and Tarigan (2004)
Sodong, S. Sumatra	2	3×3	12.8	6.4	11.6	5.8	Hardiyanto *et al.* (2004)
Toman, S. Sumatra	2	4×2	12.3	6.2	9.4	4.7	Hardiyanto *et al.* (2000)
Jorong, S. Kalimantan[a]	2	3×3	5.2	2.6	3.9	2.0	Krisnawati and Kallio (2009)
Subanjeriji, S. Sumatra	2.5	3×3	10.9	4.4	7.66	3.1	Heriansyah *et al.* (2008)
Baserah, Riau	2.6	3×2.5	11.0	4.2	10.2	3.9	Krisnawati and Kallio (2009)
Baserah, Riau[a]	2.6	3×2.5	12.7	4.9	10.5	4.0	Krisnawati and Kallio (2009)
Maribaya, W. Java	3	3×2	7.2	2.4	7.3	2.4	Miyakuni *et al.* (2004)
Toman, S. Sumatra	3	4×2	14.0	4.7	14.8	4.9	Hardiyanto *et al.* (2000)
Baserah, Riau	3.1	3×2.5	12.7	4.1	10.5	3.4	Krisnawati and Kallio (2009)
Baserah, Riau[a]	3.3	3×2.5	14.3	4.3	11.8	3.6	Krisnawati and Kallio (2009)
Baserah, Riau[a]	4.3	3×2.5	16.8	3.9	15.1	3.5	Krisnawati and Kallio (2009)
Baserah, Riau	4.5	3×2.5	19.8	4.4	15.6	3.5	Krisnawati and Kallio (2009)
Baserah, Riau	5 (R1)	3×2	15.8	3.2	22.4	4.5	Siregar *et al.* (2008)
Baserah, Riau	5 (R2)	3×3	18.1	3.6	24.8	5.0	Siregar *et al.* (2008)
Tenjo, W. Java	5	3×2	16.0	3.2	15.1	3.0	Miyakuni *et al.* (2004)
Sodong, S. Sumatra	5 (R2)	3×2	19.3	3.9	25.2	5.0	Hardiyanto and Wicaksono (2008)
Sodong, S. Sumatra	5.5	3×3	17.9	3.3	17.4	3.2	Heriansyah *et al.* (2008)
Toman, S. Sumatra	6 (R2)	4×2	18.2	3.0	23.4	3.9	Hardiyanto and Wicaksono (2008)
Tenjo, W. Java	8	3×2	21.1	2.6	18.5	2.3	Miyakuni *et al.* (2004)
Toman, S. Sumatra	8.5	2×4	17.4	2.0	15.9	1.9	Heriansyah *et al.* (2008)
Toman, S. Sumatra	9 (R1)	4×2	17.7	2.0	22.0	2.4	Hardiyanto and Wicaksono (2008)
Sodong, S. Sumatra	10 (R1)	3×2	14.1	1.4	24.0	2.4	Hardiyanto and Wicaksono (2008)
Maribaya, W. Java	10	3×2	27.8	2.8	25.1	2.5	Miyakuni *et al.* (2004)
Bd. Anyar S. Sumatra	10.5	2×4	15.0	1.4	19.2	1.8	Heriansyah *et al.* (2008)

a Plantations under company–community partnership; R1: 1st rotation; R2: 2nd rotation.

cm/year. High DBH MAI values (more than 4 cm/year) are recorded for stands less than 3 years old, after which the diameter MAI values generally decline towards 1.5–2 cm/year. The MAI for height ranges from 1.8 to 5.8 m/year, and high values of height MAI (more than 4 m/year) have been recorded for stands less than 3 years old, although a height MAI of more than 4 m/year has also been reported in older stands in several sites in Riau (Siregar *et al.* 2008) and in South Sumatra (Hardiyanto and Wicaksono 2008). As with diameter MAI, height MAI drops, declining towards 2–2.5 m/year. Growth generally declines rapidly after 8 years.

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 in the plots. Quantifying the relationship between tree height and diameter is therefore necessary to predict heights of the remaining trees. Siregar and Djaingsastro (1988) investigated the relationship between diameter at breast height (D) and total height (H) for young *A. mangium* (< 2 years) growing in an experimental site in Lampung and developed the following simple model:

$$H\text{ (cm)} = -8.4052 + 120.0915\ D\text{ (mm)}$$

This model may not be reliable for estimating heights for older *A. mangium* trees because early height (as used to develop the model) may be erratic and is often determined by factors other than site quality, such as initial stocking level, planting stock quality and planting technique. In addition, the use of DBH alone as a predictor variable for estimating total tree height may restrict the model's usefulness only to the stands where the data were gathered. The height–diameter relationship may vary from stand to stand, and even within the same stand, as the relationship within a stand may not be constant over time and the development of tree height may take longer on poor-quality sites than on good-quality sites. Krisnawati *et al.* (2010a) developed a generalised height–diameter model that can account for variability in site and stand conditions. The model includes stand variables (i.e. stand age (A) and site quality (S)), in addition to diameter at breast height (D):

$$H = 1.3 + 12.16 \exp\left(-3.45 D^{-0.855} - \frac{2.82}{A} + 0.0565 S\right)$$

The proposed model allows for the variability in heights within diameter classes depending on stand age and site index, and therefore provides more realistic height predictions across varying stands than models that include diameter only. Inclusion of the additional stand variable significantly improves height predictions compared with when diameter only is used. The model possesses the following characteristics: (1) height increases at a decreasing rate as a given DBH increases, (2) height increases at a decreasing rate for a given DBH as age increases and (3) height increases for a given DBH and age as site index increases (Figure 11).

6.3. Stem volume estimation

Several stem volume models for *A. mangium* in different regions in Indonesia have been developed in previous studies (Table 4). The models were estimated from diameter at breast height (D) alone or in combination with total tree height (H), or from the length of bole measured to a specified minimum top diameter, such as 4 cm (Sumarna and Bustomi 1986, Wahjono *et al.* 1995) or 7 cm (Bustomi 1988, Wahjono *et al.* 1995, Krisnawati *et al.* 1997). These models were used to construct stem volume tables, either one-way tables in which volumes are given for a particular DBH, or two-way tables that provide estimates for a DBH against a range of height measurements. However, these models were developed using data from a narrow range of ages (mostly 5 years old) and with a fixed diameter limit, which may not be sufficient for estimating volume for older or younger trees and inflexible if the merchantability standard changes.

The volume estimates for a tree with a DBH of 20 cm, derived using different estimation models as listed in Table 4, are given in Table 5.

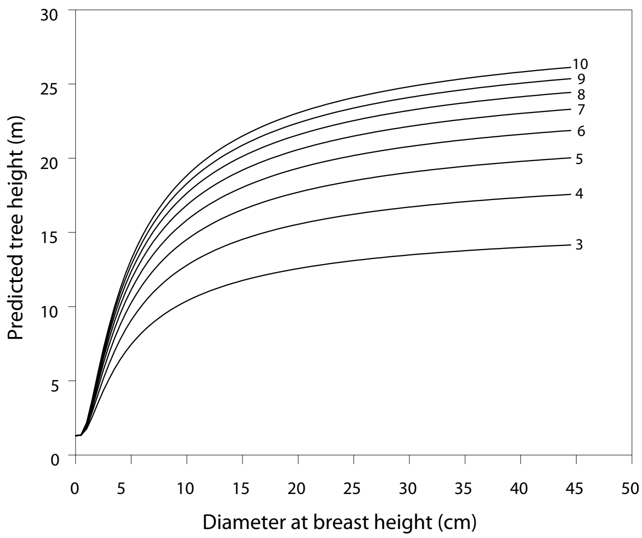
Table 4. Several stem volume models developed for *A. mangium* in Indonesia

Location, site	Age sample	N sample	Equation form	Reference
Subanjeriji, South Sumatra	3, 5, 7	103	$V_c = 0.1217D^{2.4697}$ $V_4 = 0.1537D^{2.4247}$	Sumarna and Bustomi (1986)
Balikpapan, East Kalimantan	5–6	131	$V_7 = 0.7952D^{1.8873}$ $V_7 = 0.0396D^{1.6536} H^{1.2432}$	Bustomi (1988)
Labuhan Batu, North Sumatra	5	105	$\log V_4 = -2.9325 + 1.7915 \log D$ $\log V_4 = -3.6381 + 1.4918 \log D + 0.8143 \log H$ $\log V_7 = -3.0173 + 1.8485 \log D$ $\log V_7 = -3.7641 + 1.5314 \log D + 0.8618 \log H$	Wahjono *et al.* (1995)
Bogor, West Java	5	46	$\log V_c = -3.3211 + 1.9899 \log D$ $\log V_c = -3.7805 + 1.8509 \log D + 0.62 \log H$ $\log V_7 = -3.3955 + 2.0767 \log D$ $\log V_7 = -3.7216 + 1.978 \log D + 0.4401 \log H$	Krisnawati *et al.* (1997)

All models were developed for over-bark volumes

Table 5. Volume estimates of a sample tree with DBH of 20 cm, from different volume models

DBH (cm)	H (m)	Top diameter	Volume (m³)	Reference
20	–	Clear bole	0.199	Sumarna and Bustomi (1986)
20	–	4 cm	0.219	Sumarna and Bustomi (1986)
20	–	7 cm	0.227	Bustomi (1988)
20	16	7 cm	0.176	Bustomi (1988)
20	–	4 cm	0.250	Wahjono *et al.* (1995)
20	16	4 cm	0.192	Wahjono *et al.* (1995)
20	–	7 cm	0.244	Wahjono *et al.* (1995)
20	16	7 cm	0.184	Wahjono *et al.* (1995)
20	–	Clear bole	0.185	Krisnawati *et al.* (1997)
20	16	Clear bole	0.237	Krisnawati *et al.* (1997)
20	–	7 cm	0.202	Krisnawati *et al.* (1997)
20	16	7 cm	0.241	Krisnawati *et al.* (1997)



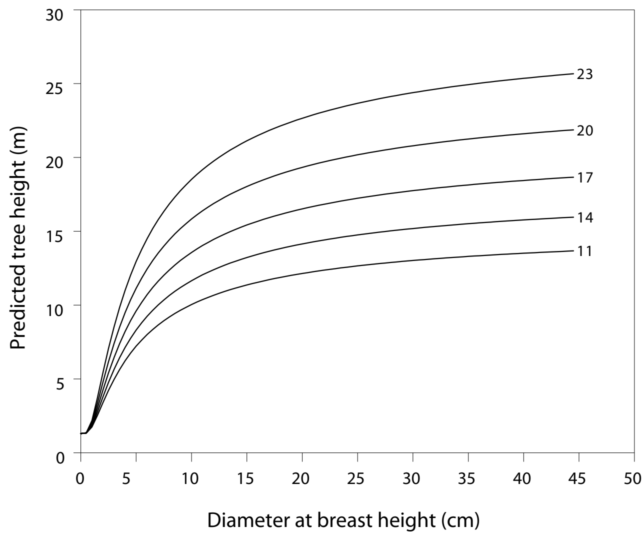


Figure 11. Predicted total tree heights for different ages at a given site index of 20 m (left) and predicted total tree heights for different site index classes at a given age of 6 years (right) based on the model developed by Krisnawati *et al.* (2010a)

Krisnawati *et al.* (2010b) developed a more flexible model for *A. mangium* plantations using 209 sample trees from South Sumatra. The model covers a wider range of ages (2–9 years) and allows prediction of merchantable volume at any specified upper stem diameter (*dob* for over-bark diameter or *dub* for under-bark diameter) based on only easily measurable parameters such as diameter at breast height (*D*) and height (*H*). The model was derived from a compatible estimation system of stem volume and taper models in which the stem volume calculated using a volume model will be equal to that computed by integration of the stem taper model from the ground to the top of the tree. They developed models for estimating both over-bark volume (*Vob*) and under-bark volume (*Vub*) as follows:

$$Vob = 0.0000636D^{1.736}H^{-1.2786}\left(H^{2.352} - \left(0.326dob^{3.479}D^{-3.019}H^{2.224}\right)\right)$$

$$Vub = 0.0000542D^{1.778}H^{-1.2426}\left(H^{2.286} - \left(0.445dub^{3.555}D^{-3.161}H^{2.209}\right)\right)$$

6.4. Biomass estimation

Biomass as a unit of yield may be a more important measure than volume as it allows comparisons to be made between different crops as well as among different tree components (e.g. stems, branches, barks, leaves). For example, in agroforestry systems, the amount of leaves or litter that can be used for fodder is more appropriately measured in terms of biomass than in volume. However, estimation of tree biomass involves much time and effort. Several studies have reported aboveground biomass estimates for *A. mangium* under different conditions (age and site) in Indonesia (Table 6). The total biomass estimated for a stand of 3-year-old *A. mangium* is significantly higher in Riau than that in West Java. The same trends apply for the stands aged 5 and 10 years old. The proportion of aboveground biomass components for *A. mangium* is about 55–80% stems, 10–22% branches, 7–10% bark and 2–9% leaves.

Several authors have developed allometric equations for estimating biomass of different components of *A. mangium* trees as well as total biomass using DBH as a parameter (Table 7).

6.5. Rotation

According to Lemmens *et al.* (1995), the common rotation age for *A. mangium* plantations for pulpwood production is 6–8 years after planting and that for sawn timber production is 15–20 years after planting. A study conducted by Krisnawati (2007), which used a simulation approach based on a dynamic programming algorithm to determine optimal rotation age and thinning strategies for *A. mangium* plantations under a range of initial planting spacings and site qualities, found that the optimal rotation age for pulpwood production is about 7–8 years, except for poorer sites (site index 11 m) with wide spacing (4×4 m), in which regimes without thinning delayed the optimal rotation age to 9 years.

For sawn timber production, depending on initial spacing and site quality, optimal rotation was found to be between 11 and 17 years (Krisnawati 2007). Three management options may be suggested: (1) planting trees at a wide spacing (e.g. 4×4 m and 3×4 m) and no thinning; (2) planting trees at a closer spacing (e.g. 3×3 m and 3×4 m) and accepting a somewhat longer rotation to obtain a product of desirable size; or (3) planting trees at a closer spacing

Table 6. Biomass estimates (t/ha) of *A. mangium* stands at different ages

Location, site	Age (years)	Stem	Branch (+twig)	Bark	Leaf	Total	Reference
Baserah, Riau	1	5.2	1.7	3.7	1.7	12.3	Siregar *et al.* (2008)
Sodong, South Sumatra	1	6.32	5.97	1.21	3.64	17.2	Hardiyanto *et al.* (2004)
Toman, South Sumatra	1.2	5.5	5.54	1.78	4.84	17.7	Hardiyanto *et al.* (2004)
Baserah, Riau	2	22.4	8.6	3.7	3.3	38.0	Siregar *et al.* (2008)
Toman, South Sumatra	2	20.85	14.73	4.02	6.84	46.1	Hardiyanto *et al.* (2004)
Subanjeriji, S. Sumatra	2.5	27.1	10.4	a	6.7	44.2	Heriansyah *et al.* (2008)
Baserah, Riau	3	85.2	22.3	11.9	2.4	121.8	Siregar *et al.* (2008)
Maribaya, W. Java	3	13.9	2.4	a	1.9	18.2	Heriansyah *et al.* (2008)
Baserah, Riau	4	107.1	15.0	14.5	4.9	141.5	Siregar *et al.* (2008)
Baserah, Riau	5	123.6	14.0	12.0	4.8	154.4	Siregar *et al.* (2008)
Sodong , S. Sumatra	5					169.6	Hardiyanto and Wicaksono (2008)
Tenjo, W. Java	5	29.8	8.3	a	2.4	40.5	Heriansyah *et al.* (2008)
Sodong , S. Sumatra	5.5	82.1	23.8	a	4.2	110.1	Heriansyah *et al.* (2008)
Toman , S. Sumatra	6					135.2	Hardiyanto and Wicaksono (2008)
Baserah, Riau	7	106.9	26.3	11.9	5.4	150.5	Nurwahyudi and Tarigan (2004)
Tenjo, W. Java	8	40.1	11.7	a	1.8	53.6	Heriansyah *et al.* (2008)
Toman, S. Sumatra	8.5	112.0	17.5	a	4.3	133.8	Heriansyah *et al.* (2008)
Subanjeriji, S. Sumatra	9	105.12	23.44	12.88	3.96	145.4	Ihwanudin (1994) *in* Siregar *et al.* (1999)
Subanjeriji, S. Sumatra	9	124.7	46.6	14.2	4.1	189.5	Hardiyanto *et al.* (2000)
Maribaya, W. Java	10	71.9	10.3	a	1.4	83.6	Heriansyah *et al.* (2008)
Sodong, South Sumatra	10	162.2	56.4	17.7	4.7	241.1	Hardiyanto *et al.* (2004)
Bd. Anyar, S. Sumatra	10.5	129.2	16.4	a	2.4	148.0	Heriansyah *et al.* (2008)

a Bark included in the stem

Table 7. Several allometric equations developed to estimate biomass of *A. mangium*

Location, site	Age sample	N sample	Equation form	Reference
Bogor, West Java	8	26	Total: $W = 0.1876D^{1.131}$	Hiratsuka *et al.* (2003)
Benakat, South Sumatra	6			
Madang, PNG	6			
Sonbe, Vietnam	7			
Toman, South Sumatra	6	16	Stem: $W = 0.0116D^{3.0294}$	Hardiyanto and Wicaksono (2008)
			Bark: $W = 0.0104D^{2.4651}$	
			Branch: $W = 0.0712D^{2.21179}$	
			Leaf: $W = 2.1195D^{0.515}$	
Sodong, South Sumatra	5	16	Stem: $W = 0.0009D^{3.9677}$	Hardiyanto and Wicaksono (2008)
			Bark: $W = 0.0022D^{2.9229}$	
			Branch: $W = 0.0486D^{2.2592}$	
			Leaf: $W = 0.1204D^{1.448}$	

and thinning to keep trees growing at an acceptable rate (e.g. 2×3 m and 2×2.5 m). In state-owned plantations in Java, the economic rotations for *A. mangium* have been defined as being around 8 years for pulpwood production and around 15 years for saw-log production, according to a decree by the director of Perum Perhutani (Decree No. 378/Kpts/Dir/1992; Perum Perhutani 1995).

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This manual gathers information on the ecology and silviculture of *Acacia mangium* Willd. with a focus on Indonesia. It also includes growth and yield data from published sources and collected from sites under community–company partnerships in South Kalimantan and Riau provinces. This manual is one of five manuals that guide smallholder tree planting of five selected tree species in Indonesia. The other four species are: *Aleurites moluccana* (L.) Willd.; *Anthocephalus cadamba* Miq.; *Paraserianthes falcataria* (L.) Nielsen; and *Swietenia macrophylla* King. Smallholders in Indonesia have planted trees on private or community land for a long time. Various actors have encouraged this activity to improve local livelihoods, environmental sustainability and industrial wood supply. These efforts have been generally successful, but they are often undertaken without technical assistance. 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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