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Growth and Site Conditions of *Acacia mangium*, *Acacia* hybrid, *Eucalyptus urophylla*, *Cinnamomum parthenoxylon* and *Erythropholeum fordii* for Livelihood Security of Smallholders in Industrial Tree Planting Programs of Vietnam

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1 Introduction

Vietnam lies in the centre of Southeast Asia and covers a mainland area of about 33 million ha between latitudes 8° and 23° N and longitude 102° 10′ and 109° 24′ E. The length extends 1,650 km between its Southern and Northern extremes. Its width varies between 600 km in its Northern parts to minimum of less than 50 km in its central parts with the Southern parts being about 200 km wide. The country has inland border of about 3730 km, share its border with People's Repub of China in the North with length of 1,150 km, Laos with length of 1,650 km and Cambodia with length of 930 km in the West. Vietnam has a coastline of about 3,260 km from Mong Cai in the North to Ha Tien in Southwest. The territorial sea of Vietnam covers an area of 100 million ha with about 4,000 islands (Con *et al*., 2008).

The total forest area may be divided into natural forests (9.4 million ha) and plantation forest (1.5 million ha). It is particularly noteworthy that area of Vietnam classified as bare and denuded land as substantial as at 8.3 million ha. These denuded lands are concentrated in the Northern uplands areas of the country. Forest cover in Vietnam declined from 44 per cent in the early 1940s to 24 percent by 1983. The decrease in the supply of goods and services from forests has had a profound effect on rural communities and the Nation as a whole. The fundamental causes of rapid deforestation in Vietnam have been by demographic growth, economic growth, an increasing demand for food and export crops and an increasing demand for forest products primarily wood for the pulp and paper industry, for construction and for fuel (Koninck, 1999).

Reforestation is therefore a high priority and the Government is now preparing the Five Million Hectare Reforestation Program (5MHRP) which aims to lift the forest cover of Vietnam back to 43 percent over 10 years. This reforestation is carried out by smallholders rather than government agencies (ACIAR, 2006). In February 2007, the Ministry of Agriculture and Rural Development announced plans to establish 2.4 million hectares of plantations over the next five years in the Northern mountainous region and the plantations are intended to provide raw material for the pulp industry which will produce 700,000 tons of pulp a year in the Northern region of Vietnam once the plantations are established.

Smallholders are involved in plantation timber production through various schemes (Lang, 2007).

Smallholders involved in industrial plantation are mostly self-financed. The expected returns are usually sufficient incentive for plantation maintenance. However, governments have often provided free seedlings to smallholders. In Vietnam, both general policy (the development of a free market) and specific policies and legislation have supported farm-based private plantation forestry. Some 40 percent of the forest area in Vietnam is owned by State Forest Enterprises which historically employed a large workforce. The system is currently being reformed and State forest plantations are gradually being replaced by farm forestry. A concern for State Forest Enterprises is how to provide jobs and livelihoods for its former workers. Leasing out the management of its forests to farmers and entrepreneurs is a common practice in line with corporate social responsibility (Nawir *et al*., 2007).

Smallholder's plantation development has been acknowledged in many circles as a promising land-use option with the potential to increase the socio-economic well beings of rural population and also stabilize the local ecological conditions. Forest resources have played an important role for millions of Vietnamese in assisting the process of poverty alleviation. Smallholders industrial plantations can provide livelihood security to rural communities including employment, fuel wood, fodder and wood for building and everyday uses as well as environmental and amenity benefits (Nawir *et al*., 2007).

Background

Demand for timber and industrial wood fiber in the Asia-Pacific region has increased sharply over the past decade and is expected to continue to grow at a rapid pace for at least the medium term. To a significant degree the region's growing demand for industrial wood has been driven by accelerated GDP growth in China. Between 1997 and 2005, China's imports of wood-based products (including pulp and paper) more than tripled, growing from 40 million cubic meters (m^3) in round wood equivalents (RWE) to 135 million m^3 (RWE) per annum (White *et al*., 2006). Over the next decade, it is expected that regional consumption of wood products will continue to spiral upwards as China and India together, representing just under 50 % of the world's population continue to experience rapid economic growth (White *et al*., 2006, He and Barr, 2004).

Many countries in the region including China, Indonesia, Vietnam, Thailand, Laos and others have responded to the projected increase in industrial wood demand by promoting investments in fast-growing plantation development (Enters and Durst, 2004, Cossalter and Barr, 2005, MARD, 2001). In some countries, governments and wood industries have structured industrial tree-planting initiatives to support large-scale plantation development by state-owned and/or private sector forest enterprises. Increasingly, however, efforts are being made to promote industrial tree-planting by rural smallholders including individual households, village cooperatives and farmer-owned enterprises. These efforts to increase the role of smallholders are reflected in government-led tree-planting programs, international donor projects and initiatives taken by wood-based industries to source a growing portion of their raw materials throughout-grower schemes (Cossalter and Barr, 2005). In some countries, smallholders are also growing trees spontaneously in response to market demand.

This important transition in the region's forestry sector reflects a growing recognition by government policymakers, development planners, corporate actors and farmers that smallholder tree-planting schemes can potentially offer important 'win-win' outcomes. On the one hand, they can provide wood-based industries with a sustainable supply of raw materials: on the other hand, they can support poverty alleviation by generating new sources of income for large numbers of rural poor. At the same time, such programs can carry significant risks to participating smallholders if they are poorly implemented or do not achieve projected levels of productivity or profitability. Within this context, the question of how to structure smallholder industrial tree-planting initiatives so that they support rural livelihood security and poverty alleviation has emerged as a critical development challenge.

In Vietnam, the government initiated its ‘Five Million Hectare Reforestation Program’ in 1998, with the aim of expanding the nation’s total forest to 14.3 million ha by 2010 (MARD, 2001). The program aims not only to reforest Vietnam but also to address issues of rural poverty and national socioeconomic development. Assuming a shortfall of 12 million m^3 in wood supply by 2010, the program has the objective to establish new plantations on 2 million ha. The Viet Nam Forestry Development Strategy 2006-2020, promulgated by the Prime Minister in February 2007, reasserts the priority given to new tree plantations. The Strategy foresees the establishment of plantations on 1 million ha between 2006 and 2010 and another 1 million ha in 2010-2020 (MARD, 2001). This ambitious goal is based on the assumptions that the demand for timber will more than double from 10 million m^3 in 2005 to 22 million m^3 in 2020 and that Vietnam’s forestry sector will be able to raise US$ 2.8 billion in capital investment from domestic and international sources. In addition, the Strategy suggests concentrating tree plantations in a few regions for developing raw material areas that supply adjacent forest product industries (Pöyry, 2001).

The Reforestation Program is a cornerstone in the forestry reform undertaken by the Vietnamese government with international assistance. The reform comprises two radical departures from past forest management (Sikor, 1998). First, emphasis in forest management and planning has shifted from exploitation to conservation. The Vietnamese government is now committed to maintain the stock of natural forest in Vietnam by limiting its commercial exploitation. It seeks to reduce the pressure on natural forest through rapidly rising investment in tree plantations to meet domestic demands for timber and generate revenues through increasing exports. As a result, the area of new plantations has expanded from 50,000 ha/year to 200,000 ha/year in recent years. Second, the government has promoted a turn towards people-centered forestry (Sunderlin and Thu Ba, 2005). This turn has implied a reassessment of the role played by State Forest Enterprises and efforts to decentralize forest administration.

Over the past decade, the government has allocated more than 3.0 million ha of forestry land to smallholders (Sikor, 2001). It has developed and introduced participatory procedures for land use planning, species site matching and micro-finance arrangements. In a further effort, the Vietnamese government now seeks to upgrade the capacity of district-level extension centers in forestry including the placement of forest extension officers in selected communes. Furthermore, the government has also committed itself to shift the emphasis in policy-making and planning from the national to the provincial level (Chung, 2000).

In Vietnam, the government's program on forest land allocation has conferred 50-year transferable land use rights to more than 3.0 million ha of forestry land to individual households (Tan, 2006). Initial experience on the ground shows, however, that the newly acquired land rights do not automatically translate into benefits for smallholders. There are two major problems that constrain the value of forestry land in many cases. First, the allocation has included large tracts of barren land that local people used for cultivation and animal husbandry before. As a result, allocation as forestry land may have detrimental impacts on local livelihoods as it requires people to abandon other uses of the land. Allocation may also cause conflicts among local people if the new forest owners try to exclude other people asserting previously recognized use rights (Sikor, 2001). Second, land allocation may have shifted property rights from the previously dominant State Forest Enterprises to smallholders, yet it may not hinder those to gain control over the land in other ways. In some areas, Enterprises have hijacked tree-planting projects targeted at smallholders, forcing smallholders to lease their newly acquired land to them for tree plantations.

In Vietnam, commodity markets have become key forces transforming upland livelihoods, social relations and landscapes (Sikor and Vi, 2005). There is a need to better understand the effects of such changes on marginalized groups, including women as they often drive increased social and economic inequality. A related problem in Vietnam's forestry sector is that the government seeks to curb illegal logging by exercising tight controls on the nation's timber trade. This does not necessarily reduce the volume of trade: however, it does provide opportunities for some well-positioned actors to extract high rents from the buying and selling of timber. As To and Sikor (2006) have identified, Vietnam's wood markets are far from competitive and a relatively small number of local elites, traders and government officials reap most of the benefits. In this way, there are potential opportunities to increase smallholder incomes if steps can be taken to improve access to timber markets.

2 Statement of problems

Much of the natural forest in the mountainous parts of Vietnam was logged and cleared for shifting cultivation during the 1960s, 1970s, and 1980s (FAO, 2006). The Vietnamese government is currently carrying out a large scale "reforestation" program. Smallholders plant a wide range of tree species. Much of the planting taking place today in Vietnam is of fast growing trees aimed at producing raw material for the pulp and paper industry or woodchips. It is estimated that 24 million people living in or near forest lands and nearly eight million people spend much of their time for their livelihood security.

Poverty is fundamentally a real problem in Vietnam, with 90 percent of the poor living in rural areas and with incidence of poverty being much higher in rural areas than in urban ones (World Bank, 2002). Poverty in Vietnam will be mainly rural for the foreseeable future (ADB *et al*., 2003). For this reason, short-to medium-term poverty alleviation efforts will have to be heavily focused on forest (Glewwe *et al*., 2002). Forest resources have served and will serve the goal of poverty alleviation.

And also Vietnam's environmental policy puts much emphasis on the objective of restoring forest ecosystems, protecting ecological environments, conserving biodiversity in particular species indigenous to that country (FSIV and JICA, 2003). This reforestation is carried out by smallholders rather than by the government. Smallholders are involved in plantation timber production through various schemes (Lang, 2007).

In general tree plantations are successful but proper research on silvicultural and management aspects of fast growing species and also native species i.e. site index, stand density, growth rate in different ages, etc are still needed.

3 Objectives

The study will concentrate on both fast growing species grown by smallholders for pulp and paper industries in rural areas and native species. The main objective of this study is to provide vital information on the growth of some exotic and native species. The major objectives of this study are:

(1) to compare stand structure and stand density for different age classes of exotic and native species,

(2) to develop a site index system and site classes for the selected species with special reference to site conditions in Vietnam,

(3) to investigate wood production potential of smallholders for pulp and paper industry.

4 Materials and methods

4.1 Study Areas

4.1.1 Binh Dinh Province

Binh Dinh is located in the key economic zone of the central part which is a coastal Province in the Southern part of the central region of Viet Nam. It borders Quang Ngai Province in the North, Phu Yen Province in the South, Gia Lai Province in the West and South China Sea in the East. It is 1065 km South of Hanoi and 649 km North of Ho Chi Minh City.

Binh Dinh has an area of 6025 km^2 of land. Its population is 1545,300 with the density of 256 people per km^2 (census of the year 2004). Binh Dinh is divided into 11 administrative units including Quy Nhon as its capital and state-approved second classed city and ten other districts. They are An Lao, Vinh Thanh,Van Canh as three mountainous districts; Tay Son and Hoai An as midland district: and Hoai Nhon, Phu My, Phu Cat, An Nhon and Tuy Phuoc as flat areas. At a lower administrative level the Province is divided into 157 smaller units of commune, residential wards and small towns.

Binh Dinh has high humid tropical climate with prevalent winds. This weather is suitable for the cultivation of tropical trees and crops. The annual average temperature is between 26˚and 28˚C and the average annual rainfall is between 1,700 and 1,800 millimetres.

Con River is the longest river of the Province. Besides there are other smaller and shorted rivers including Kon, Lai Giang, La Tinh and Ha Thanh.

There are 30 different types of soil in the Province with 71,000 hectares of silty soil. An approximate of 117,000 hectares is used for agriculture. 202,700 hectares is forestry land with 154,400 hectares of natural rain forest. There are more than 195,000 hectares of marginal land which are potentially good for either agricultural of forestry development.

The coast line of Binh Dinh is 134 km^2 with three river mouths including Quy Nhon, De Gi and Tam Quan with Thi Nai Lagoon and several others. The sea water is suitable for the growth of rich varieties of marine livestock. This is a good potential for the development of the aquaculture industry.

4.1.2 Phu Tho Province

Phu Tho's area is 3465 km^2 with 10 administrative divisions comprising Viet Tri City, Phu Tho Town and 8 districts including Phong Chau, Doan Hung, Thanh Ba, Ha Hoa, Song Thao, Tam Thanh, Thanh Son and Yen Lap. The population is 1,302,700 inhabitants of which urban population accounts for 15%, rural population accounts for 85%. The average population density is 3706 per km^2 except Viet Tri City, in which it is 21,042 per km^2. The elevation is between 60-100 m asl. Low hills occupied mainly in the area and the slope varies from 10 to 35%. The total area is 3465 km^2. There are three large rivers running through the Province. They are the Red, Lo and Da rivers with a total length of 200 km.

Phu Tho has a monsoon tropical climate with a cold winter and hot summer: the average annual rainfall is 1,800 mm, the mean temperature ranges from 22.2˚C to 26.5˚C with an average of 22.9˚C. The relative humidity ranges from 75% to 88% with an average of 83% (Trieu, 2008).

The gold red ferralitic soil appears on degraded rock such as clay schist, Mica and Gnai schist making up about 33 percent of the total Province's soil areas. This is a type of mountain soil at average height of 100 m. As a thick layer of soil, good humidity reservation and high fertile rate relevant for long-term industrial planting are very popular.

The mountain ferralitic soil group makes up 30 percent of the natural areas and exists in sloping mountain on the thin layer surface of soil. It is suitable for forest planting and re-planting.

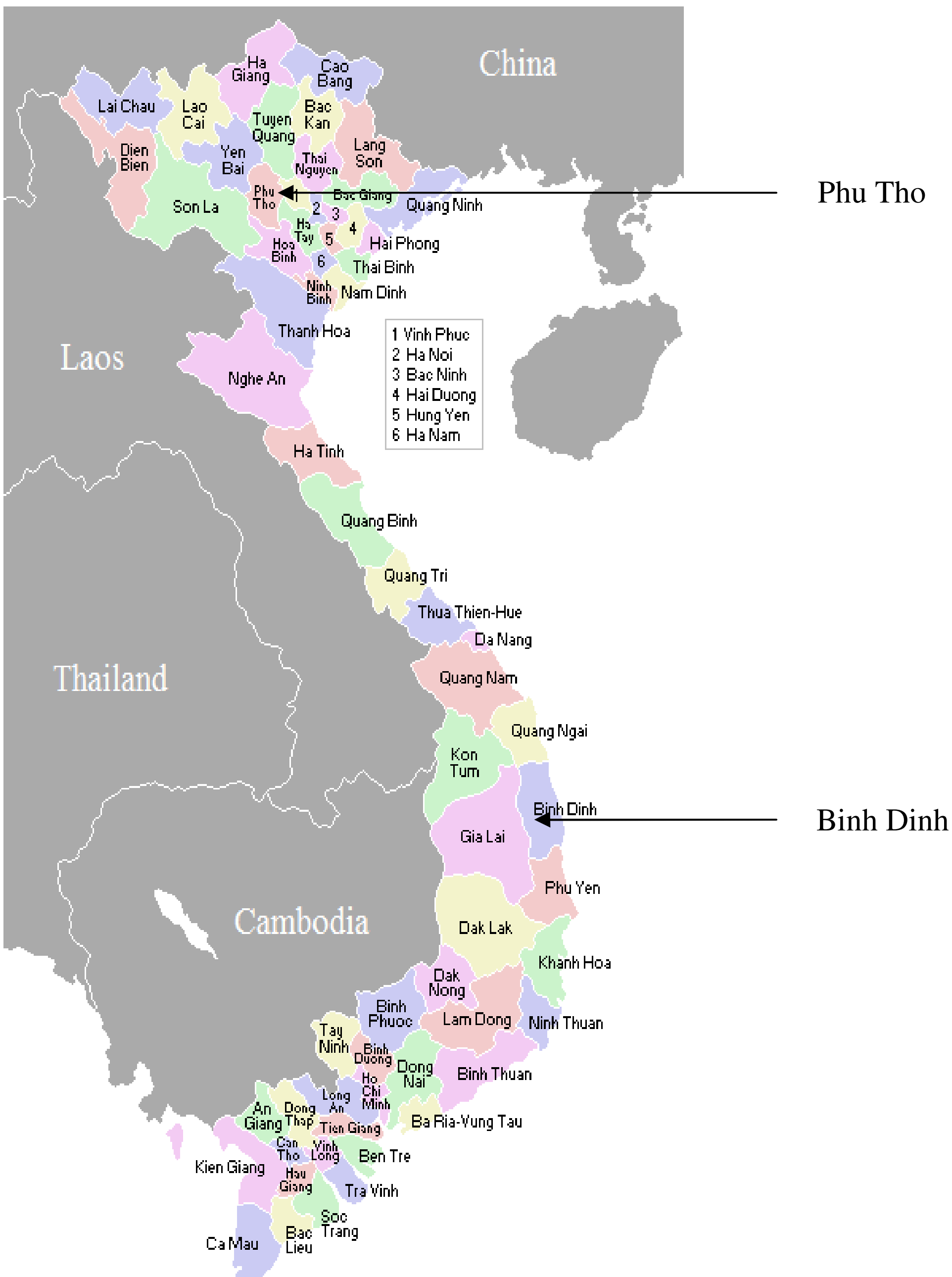


Figure 4.1: Study Area: Bin Dinh and Phu Tho Provinces in Vietnam

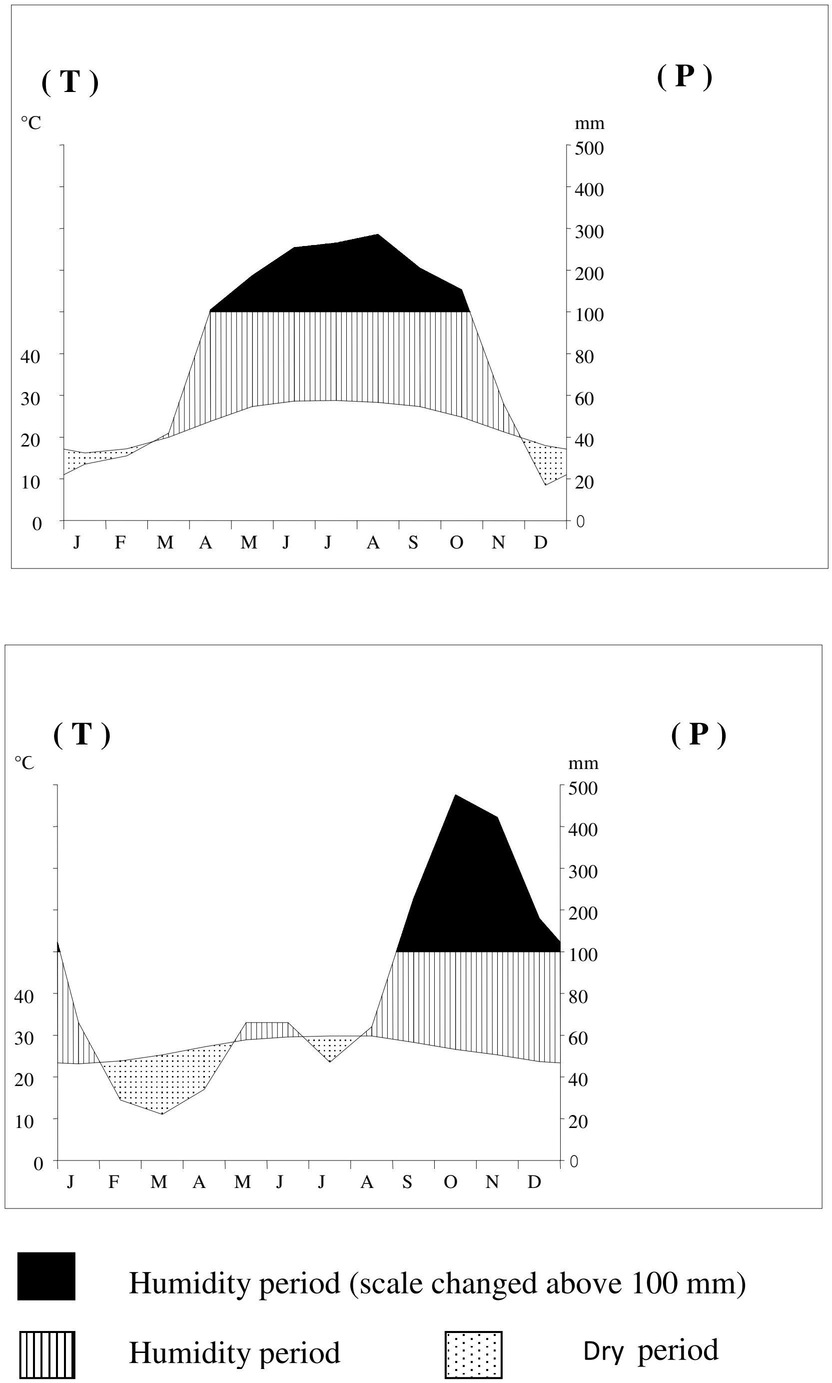


Figure 4.2: Mean rainfall (P) and mean temperature (T) of the study areas Binh Dinh Province (Quy Nhon city, 51-71) above and Phu Tho Province (Viet Tri city, 35-33) below, Van *et al.*, 2000.

4.2 Data collection

4.2.1 Selection of stands and sample plots

The data concerning the required stands was gathered, namely: age, species, and size and site condition by visiting the local commune office of the Binh Dinh and Phu Tho Provinces. The five main species are *Acacia* hybrid*, Acacia mangium, Eucalyptus urophylla*, *Cinnamomum parthenoxylon* and *Erythropholeum fordii*.

Table 4.1: Data collection in the Binh Dinh and Phu Tho Provinces

Province	Species	No of stands	No of plots	Min (Age)	Max (Age)
Binh Dinh	*Acacia* hybrid	42	89	1	6
	Eucalyptus urophylla	25	57	1	5
Phu Tho	*Acacia mangium*	49	104	1	7
	Eucalyptus urophylla	51	110	1	5
	Cinnamomum parthenoxylon	12	25	2	17
	Erythropholeum fordii	21	45	2	23

All the plantations are owned by smallholders in both Provinces. The information and topographic maps have been taken from the Forest Department. All sample stands (see in table 4.1) were selected with topographic maps by consulting and asking of the heads of communes and villages. The stand was subdivided in two parts by cutting the longest diagonal into two by a perpendicular bisector. In each of the two parts of the stand one plot center was determined randomly. When the stand was so big that more than two plots were allocated, more than one plot was selected per sub-stand.

A fixed circular plot was laid out to encompass sample trees on which observations were done. A high number of trees per hectare lead to a smaller plot size and a low density to a larger one. A standard rule of thumb, achieving an average of about 20 trees per plot was used. Often the plots have been made larger to get more data. All plots are temporary ones and their size ranged from 78.5 to 315 m^2 and their spacing varied 2 x 2, 2.5 x 2, 1.5 x 2, 1 x 3, 2 x 3. For native species, wider spacing 2.5 x 3, 4 x 3, 3 x 3 was found and their sizes varies 78.5 to 1256.6 m^2, see in figure (4.3).

For exotic species, sample plots were selected within the project area (two communes from Phu Tho and Binh Dinh Provinces), see table (4.1). But for native species, sample plots both outside and inside of the research communes were selected only in the Phu Tho Province because of the rare plantation of native species, see table (4.1). In the Binh Dinh Province, native species plantations were not assessed due to the lack of information.

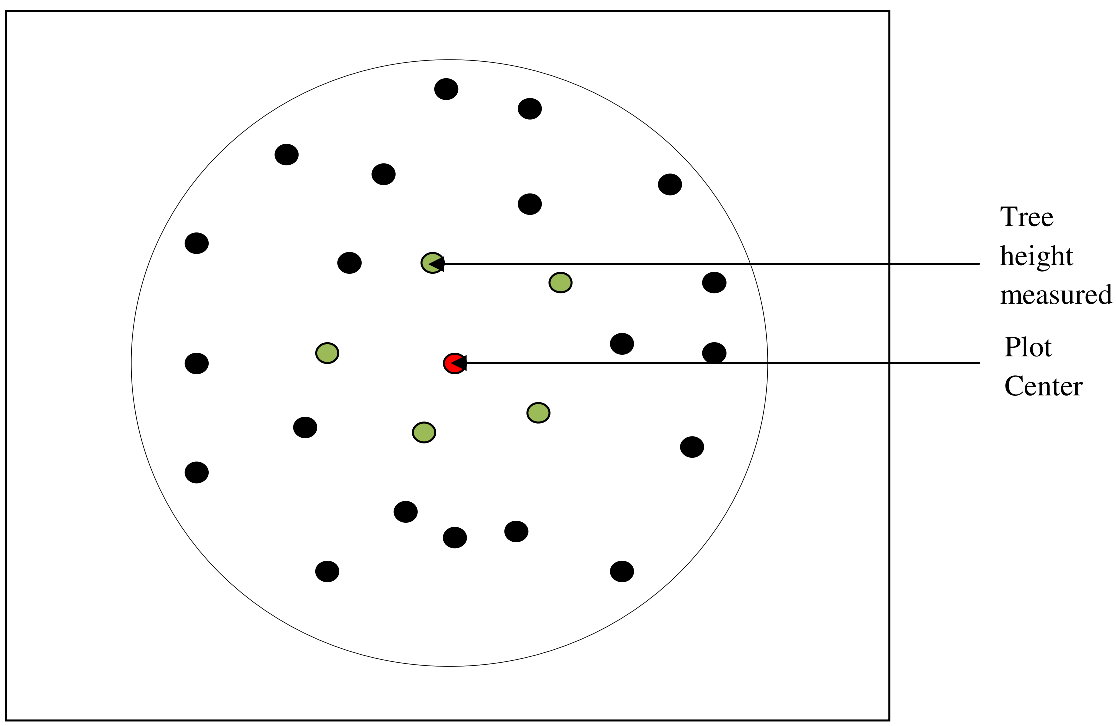


Figure 4. 3: Round Shape of sample plot with single trees cross sectional area

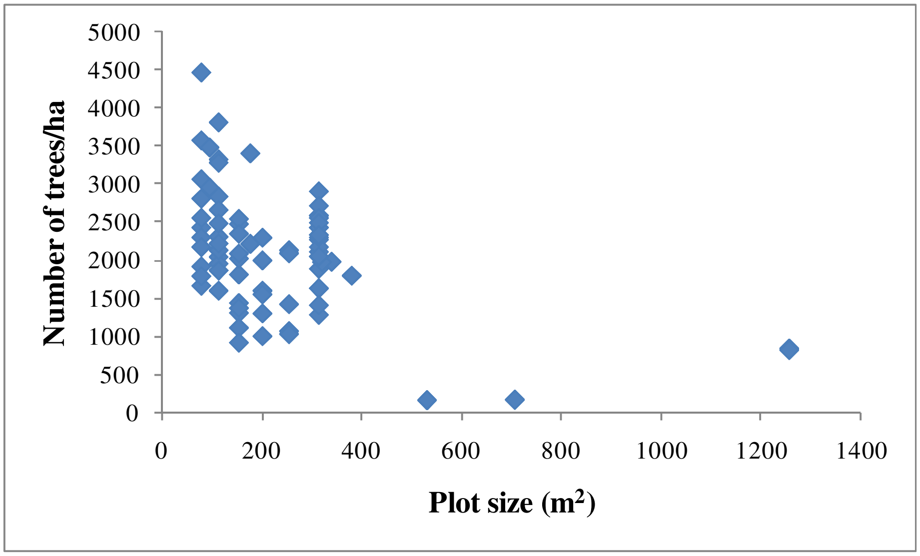


Figure 4.4 Estimated trees per hectare with respective plot size.

*Because of coppice rotation of *Eucalyptus urophylla*, some plots have a large number of trees.

The measurements, diameter, total tree height, stem quality and overall tree condition had been taken. The height of the five nearest trees to the sample points were measured with electronical hypsometer and telescope stick. The remaining trees were estimated using the Prodan function that is the best fitted function for height-diameter relationship: see in table (6.4). The diameter at breast height (1.3 m above ground) of all trees in each plot was measured using diameter tape. Further on natural regenerating trees were counted as far as they occurred. In addition to the pure plantation, plot related data: spacing, elevation, slopes, aspect at the plot centre and the accessibility and adjacent land uses has been recorded.

The raw data from the field plots was entered into an Excel spreadsheet. After then, it was transferred to various formats according to the softwares used. The major software used in the analysis was Statistica (STATISTICA FOR WINDOWS, 9.1) and for the diameter distribution, XL stat, 2011 software developed by Kolvach Computing Services, Anglesey, Whales was used.

5 Ecology and Silviculture of selected species

5.1 Ecology and Silviculture of *Acacia* hybrid

5.1.1 Description of the Species

Taxonomy

Botanical name: *Acacia* hybrid

Family: Fabaceae

Sub-family: Mimosoideae

Venacular/ Common names in Vietnam: Keo lai

Morphological characteristics

The *Acacia* hybrid is a medium sized tree which is similar in appearance to *Acacia mangium*. The tree is capable of reaching a height of 8–10 m and a diameter at breast height of 7.5–9.0 cm within 2 years.

The morphological traits of the hybrids (flower colour, pod aspect, leaf shape and size, bark aspect and wood density) are generally an even mixture between those of the *Acacia mangium* and *Acacia auriculiformis,* its pure parent species (Chiae, 1993). However, the *Acacia* hybrid differs from *Acacia auriculiformis* and *Acacia mangium* in several ways. When *Acacia* hybrid is young, the bark is greenish white, similar to the bark of *Acacia auriculiformis*. As it ages, the bark turns greenish brown or brown, eventually becoming as smooth as the bark of *Acacia auriculiformis,* with slightly scaly, shallow furrows at the foot of the tree (Lapongan, 1987, Rufeld, 1987, Pinso and Nasi, 1991, Kijkar, 1992, Kha, 1996). The hybrid's branching behaviour differs from *Acacia mangium* and *Acacia auriculiformis* in that the tree has many small, light branches that can be easily pruned. Similarly, its main stem, though not as straight as that of *Acacia mangium*, is much straighter than the main stem of *Acacia auriculiformis*. Unlike the stem of *Acacia mangium*, that of the *Acacia* hybrid has no angles or ribs (Darus and Ghani, 1989, Kijkar, 1992). Its phyllode is about 4–6 cm wide and 15–20 cm long, with four veins similar to those of *Acacia mangium*, with the vein on the outer edge of the crescent difficult to see. Flowers come out in July and August and again in November and December. *Acacia* hybrid begins to set flowers at about 3 years. The flowers are creamy to whitish and arranged in a straight, or slightly bent, 8–10 cm spike. Since male flowers in the hybrid are usually situated towards the bottom of the spike, less than 3% of the inflorescences produce fruits (Kijkar, 1992). The pod (fruit) is usually very curly and twists like the pods of all Acacia species. The pods mature in about 3 months (Ibrahim, 1993). A pod holds 5–9 seeds. The seed is about 0.3 x 0.4 cm, and about half of it is attached to the pod by a yellowish red funicle.

Distribution

Acacia is a large genus with over 1,300 species widely distributed throughout the tropics and subtropics. Most species are found in the southern hemisphere and the main centre of diversity is located in Australia and the Pacific. Within the Indonesian region alone, 29 native or naturalised species occur, and several more have been introduced, mainly in the mountain regions of Java. Most of the timbers producing species are found in New Guinea. The *Acacia* hybrid grows in China, Indonesia, Malaysia, Thailand and Vietnam (Rufled, 1987, Kijkar, 1992, Kha, 1996). In the late 1970s, natural hybridisation between *Acacia mangium* and *Acacia auriculiformis* was first reported in Sabah, Malaysia (FAO, 1982). *Acacia mangium* was identified as the female parent and *Acacia auriculiformis* the male parent of the natural *Acacia* hybrid (Le *et al*., 1993). *Acacia* hybrid is found where mean annual temperatures are 12–35 °C, annual precipitation is 1,200–1,850 mm and elevation is 50–350 m (Vozzo, 2002).

Ecological range

The species grows on sandy-loam or sandy-clay soil: however, it also thrives on lateritic crude soils (Somyos, 2003). The planting sites in Vietnam are at 8°–22° N, and an altitude of 5–500 m. With regards to climatic conditions, mean annual rainfall is 1,500 –2,500 mm, and mean annual temperature is 23–28 °C. *Acacia* hybrid plantations are being established in the ecological range between latitude 17 °S, longitude 145.5 °E) in north Queensland, Australia, and near Kuala Lumpur (latitude 3 °N, longitude 102 °E) and Tawau (latitude 4 °N, longitude 118 °E) in Malaysia (Sedgley *et al*., 1992).

Wood characteristics

The wood density of the *Acacia* hybrid is the product of an equal input from the *Acacia mangium* and *Acacia auriculiformis*. *Acacia* hybrid is similar to those of *A. mangium*, although the hybrid has a slightly higher wood density (0.455 g / cm^3) (Kha, 1996). The physical and mechanical properties of the hybrids, such as shrinkage, moisture absorption, slide and split resistance and the static bending and rupture strength, are a mixture of the properties displayed by the parents. The root system of the hybrids has been found to be deeper than either of the parents and therefore they are rarely blown down by strong winds (IUFRO, 2000).

An important feature of *Acacia* hybrid is its higher pulping potential and the fact that the paper produced from it has a better mechanical strength. Its pulling and folding strength is markedly superior to paper produced from *Acacia mangium* or *Acacia auriculiformis*. The folding resistance, before and after bleaching, of paper produced from *Acacia* hybrid is 790–1,300 times, whereas *Acacia mangium* is 305–440 times and *Acacia auriculiformis* is 417–820 times. The cellulose content of *Acacia* hybrid wood is also markedly higher than that of *Eucalyptus urophylla*, *Eucalyptus camaldulensis* and some native tree species such as *Styrax tonkinensis* and *Manglietia glauca*. These properties make the wood of *Acacia* hybrid very suitable for paper production. *Acacia* hybrid has 2–4 times more rhizobium nodules (in weight and number) than its parent species. This improves the capability of *Acacia* hybrid for soil improvement (Kha, 1996).

Uses

Acacia hybrid wood is used for construction, boat building, furniture and cabinet making and veneering. It also makes excellent particle board. The pulp is easy to bleach to a very bright colour and is excellent for paper making. The tree is also used for firewood, and is occasionally planted for erosion control, as a firebreak or for ornamentation. The leaves may also be used as forage for cattle (PROSEA, 1993).

The establishment of *Acacia* hybrid plantations in rural areas creates employment opportunities for poor households, which had hitherto only been possible on large scale forestry plantations. Higher wages than those provided by farms, as well as the opportunity for unskilled labourers to acquire new competencies, make such plantations an attractive prospect. These new skills afford people new employment opportunities in the growing, harvesting, transport and processing sectors of wood production. The disadvantage is that this work can be largely seasonal and some of the processing jobs may be available to skilled labourers only, at least initially.

Acacia hybrid plantations have the potential to provide several environmental benefits. In parts of central Vietnam, fast growing *Acacia* hybrids have been used to stabilise hill slopes, allowing agroforestry to be practiced on steep land, where previously cultivation would have caused excessive soil erosion. Whilst *Acacia* hybrid is beneficial for this application, they are unsuitable as windbreaks because of the tendency for trees to snap in high winds. The plantation of *Acacia* hybrid also has a role to play in reducing greenhouse gases, if the wood is not harvested for pulp or firewood. *Acacia* hybrid is gaining favour over eucalypts for commercial pulpwood production as it is faster growing, less susceptible to disease and more adaptable to poor soil types (ACIAR, 2004).

5.1.2 Propagation and Planting

Clonal selection techniques and propagation methods

The clonal selection techniques and propagation methods developed by the Commonwealth Scientific and Industrial Research Organisation (CSIRO) were adopted by the Vietnamese hybrid selection programme, which began in 1992. The steps involved in selecting, testing and commercialising hybrids are summarised in Figure 4. The hybrid specimens (or clones) must undergo extensive screening before being selected for commercial release. An initial round of selection is conducted based on the best performing hybrids observed growing in the field. There is, however, no guarantee that these superior traits will be retained in trees propagated by cutting. This is because both genetics and the environment exert a profound influence over performance. To ensure the selected clones are indeed superior to their parents, the clones are grown under a variety of environmental conditions or ‘zones’ and their performance is tested (ACIAR, 2004).

Clonal Propagation

Low cost mist chambers consist of pits dug in compact soil, generally 12 m long, 1.3 m wide and 27 cm deep. The pit is lined on all sides using a single layer of bricks arranged vertically. A 7 cm-thick layer of sand and pebbles is laid on the bottom. Then, 6 cm of water is poured into the pit, or alternatively the water is poured into channels (15 cm wide and 23 cm deep) on all four sides. The hydro pit is covered with polythene sheet, mounted on a semicircular bamboo or cast iron frame. The water vapour collected on the inner surface of the polythene sheet will reduce the temperature and the drops formed will fall on the leaf laminae and continue to keep their surfaces wet.

Under favourable conditions (i.e. 80% humidity and 25–30 °C) roots develop in 20–25 days. The species should be propagated by root-cuttings (macro-cutting) or by tissue culture, as both methods have proven very successful. Cuttings from pre-juvenile plants usually root well (more than 92%).

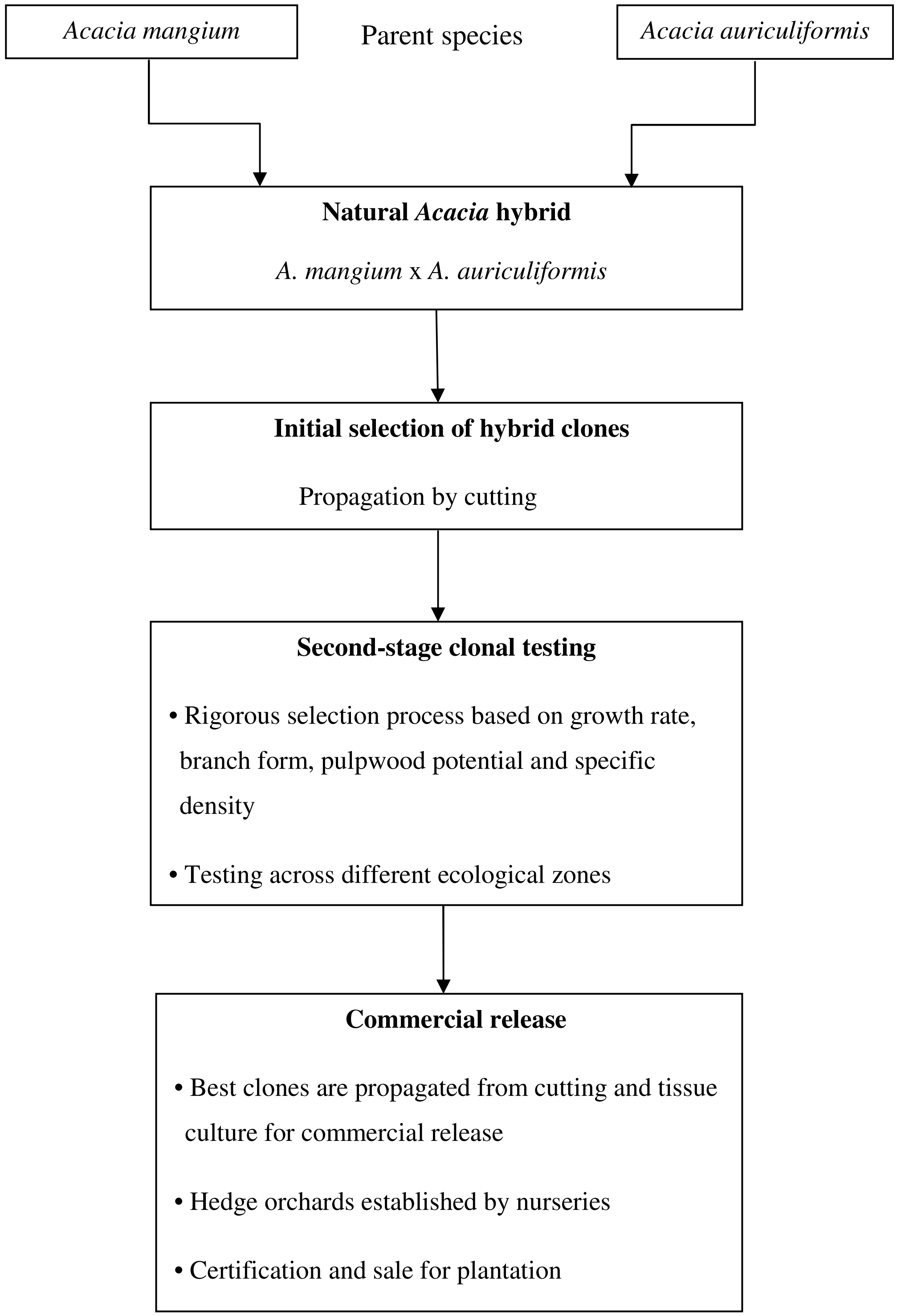


Figure 5: *Acacia* hybrid selection process

Source: Modified from ACIAR, 2004.

Coppicing shoots from tree stumps or from pre-juvenile shoots originating in hedge orchards should be treated with a rooting hormone and kept under controlled conditions. Relative humidity should remain above 80% and temperature below 30 °C. Tissue culture techniques have also been successfully developed using aseptic emerging seedlings as multiplication materials (WCPM, 2005).

The rooted ramets are transferred to a shade house for acclimatisation and hardening. Twelve days later they are transferred to an open nursery and are nursed until they attain planting height, which occurs after about 2–3 months. The clonal identity of each plant is preserved to assess the field performance of each specimen. Clonal technology for production of outstanding, high yielding, disease resistant planting stock of *Acacia* hybrid is in the process of being perfected and is being adopted on a large scale for mass propagation.

Preparation of planting site

Land covered in grasses or light brush is cleared by bulldozers in flat or slightly undulating terrain. Land is cleared manually in steeper terrain and where residual secondary vegetation needs to be removed. The slashed vegetation is usually cleared though burning, despite the fact that this has been illegal in Indonesia and Vietnam since 1995: whereas chemical treatments are involved in areas affected by *Imperata cylindrica.* Most site preparation is designed to disturb topsoil minimally, which is quite different from site preparation for estate crops.

Planting

Clonal plants or rooted cuttings are planted in contour lines on slopes, and in straight lines on flat terrain. A 30 x 20 x 30–40 cm deep planting hole is used for each plant. The most suitable stocking for pulpwood plantations in Vietnam is between 1,111 trees/ha (initial spacing of 3 x 3 m) and 1,666 trees/ha (3 x 2 m) (CARD, 2005). Spacing of the seedlings in the plantation is adjusted depending on the intended uses of the trees and the fertility of the site. Since the species displays poor natural pruning tendencies, the trees are planted close together to deter epicormic branches from occurring. In mono-specific stands, a spacing of 2 x 2 m or 2.5 x 2.5 m is common. However, if saw log production (large diameter stems) is the objective, wider spacing (3.0 x 3.5 m between rows and between plants) is employed. In agro-forestry situations, spacing within rows and between rows must take into account the effect of shade and root competition on the yield of associated crops.

In Vietnam, planting takes place twice a year, in February and August, during the rainy season, when the soil is wet, so that the seedlings can become established before the dry season starts. As soon as the land has been prepared it is marked with lines, and each planting point is marked with a stick.

5.1.3 Plantation Maintenance

Weeding

Weeding is an important element in industrial plantation and helps meet production requirements, as well as quality control standards. In order to prevent trees suffering any serious slowing in growth, weeding should be timed to coincide with when the trees are least susceptible to damage. Particular care should be taken to remove climbers, creepers and vines in the first year. *Acacia* hybrid has been found to be very sensitive to herbicides (PROSEA, 2011).

Generally, the greater the area weeded around a tree, the less the competition the tree is subjected to and therefore the better it grows. Typically, spot weeding is less effective than strip weeding, whereas clean weeding is optimum. Lowery *et al*. (1993) concluded from a review of weed control in tropical forest plantations that complete weeding in most cases results in the best growth and survival, but partial weeding in strips along the tree rows may be a good compromise between making soil resources available to the tree and nutrient conservation. Adherence to the general principle of ‘the more weed control the better’ can only be entertained when cost, the risk of soil erosion, and the possibility of reducing biodiversity are also taken into account. Weed control conducted by manual weeding or by herbicide application has been shown to improve stand productivity. A minimum of weeding twice a year during the first 2 years of plantation growth is encouraged. After that, on more productive sites, weed growth is suppressed by the development of the tree canopy, whereas on poorer sites weed control is necessary for a longer time.

Fertilising

Fertiliser is used during the growing season to improve the health and appearance of trees. In Vietnam, the most commonly used fertilisers are nitrogen/phosphorus/potassium (NPK) mixtures, urea, superphosphate, potassium, calcium, decomposed manure, and a micro-organism enriched fertiliser (consisting of a mixture of organic matter, micro-organisms and added nutrients). Generally, fertiliser is applied at the time of planting and 6 months after planting. The highest dose used in Vietnam has been 25.0 g nitrogen, 25.0 g phosphorus, 20.7 g potassium and 100 g micro-organism enriched fertiliser per seedling, applied to Acacia at planting (CARD, 2005). Fertiliser is most effective when applied just before a good rainfall. In Vietnam, Hai *et al*. (2005) reported that adding up to 20 g of phosphorus fertiliser at planting was adequate to give a noticeable response in early height growth and has already sustained a full rotation of *Acacia* hybrid growth. In an experiment with *Acacia* hybrid in three different ecological regions of Vietnam, Son *et al*. (2006) found that the best growth increments in Binh Duong Province occurred when a mixture of 200 g NPK (containing 28 g nitrogen, 8 g phosphorus and 10 g potassium) and 100 g of micro-organism enriched fertiliser was applied per tree. The annual volume increment was 36.7 m^3/ ha/ year at age 6 years, compared to 28.8 m^3/ ha/ year in the control (no fertiliser) treatment.

Refilling

The first refilling is usually done in the rainy season, 1 month after planting, to replace the dead rooted cuttings or clonal plants. The second is carried out at the end of the second year. If the survival rate is less than 70% further refilling is necessary for large scale plantations.

Pruning

The purpose of pruning is to encourage trees to develop a straight stem and more valuable, knot-free trunks. High density plantations will have lower pruning costs than lower density plantations. The greater the initial distance in the tree spacing, the more artificial pruning will be necessary to produce a clear bole. The closer the spacing of trees in a higher density plantation, the more they will be forced into an upright growth habit. The resultant lack of light will increase natural pruning of the lowest branches.

Pruning some branches increases the growth rate of the remaining branches (Ramos *et al*., 1998). In contrast, careless pruning can significantly reduce growth, introduce disease and reduce timber value. When the trees reach 2 years of age, pruning in late winter can begin to develop a single stem. Pruning should be done with great care in order to avoid damage to the branch collar and the branch bark bridge, which can lead to disease. Pruning tools should always be cleaned and sharpened to ensure a clean, smooth cut.

Two common management options are stocking and form pruning. Higher initial stocking densities reduce the incidence of large branches (Neilsen and Gerrand, 1999) but may lead to a reduction in the average growth of individual trees. Unlike lift pruning, form pruning selectively removes branches throughout the crown and can be used to reduce average branch size before subsequent lift pruning (Pinkard, 2002). It can also be used to correct potential deviation of stems from a pathway of vertical growth (Nicholas and Gifford, 1995, Medhurst *et al*., 2003).

In a review of pruning research on *Acacia* hybrid, Dung *et al*. (2005) concluded that only height growth was significantly different between pruning and no pruning treatments, as 3 years after treatment, the pruned trees were observed to be taller. It is possible that pruned branches in the lower, shaded part of the crown were unable to survive owing to their inability to photosynthesise sufficiently. In Vietnam, CARD (2005) recommended that a first pruning for *Acacia* plantations should be undertaken at the time of canopy closure and before crown lift has started. Trees selected for pruning are determined by their form, the characteristics of the branches and diameter at breast height. The number of trees pruned is determined by the distribution of log sizes required at harvest. No more than 30% of the green crown length should be removed when the selected trees are lift pruned. Form pruning may be required before canopy closure occurs to increase the numbers of trees that meet the requirements for lift pruning.

Thinning

Thinning is the selective process of removing or harvesting some trees to allow the remaining trees to maintain a steady growth rate. Thinning also provides the opportunity to selectively remove poorly formed trees and species of lower value, which are sometimes referred to as ‘wolf trees’. If growth and survival vary significantly, thinning may be necessary only in areas where the trees are very dense. Monitoring the growth rate of the tree is important because the goal of thinning is to maintain steady growth. Thinning is usually conducted when the plantation is 3, 5 and 7 years old.

Control of pests and diseases

The major pests associated with *Acacia* hybrid cause direct damage to seedlings, branches and stems, as well as wilting caused by root damage. Damage does not result in death, but may deform or suppress tree growth. Most disease agents of *Acacia* hybrid are associated with or caused by fungi. Common afflictions include damping-off, heart rot, and powdery mildew, stem galls, dieback, leaf spots and root rot. *Acacia* hybrid is particularly susceptible to heart rot. In Malaysia, the incidence of heart rot has been frequently observed in *Acacia mangium* but it has never been reported in *Acacia* hybrid (Lee, 2002). Insect attacks can be controlled using insecticidal spot treatment (Old *et al*., 2000). Major disturbances, pests and disease were not found in the *Acacia* hybrid plantations in the Binh Dinh Province, Vietnam, although a few plantations were attacked by termites. In these instances, farmers used pesticides to combat the problem. Heart rot is the only disease of tropical Acacia that has been the subject of sustained research during the last decade (Lee *et al*., 1988, 1996, Lee and Maziah, 1993).

Damping-off affects many host species including *Acacia* spp. and is caused by *Fusarium. solani, Phytophthora* spp., *Pythium* spp. and *Rhizoctonia solani* (Lee, 1985, Liang, 1987, Maziah, 1990). Damping-off probably occurs wherever tropical Acacia are nursery-grown on a large scale. Damping-off can be managed efficiently by following suitable nursery practices. Seedlings grown in either polypots or in root trainers are less vulnerable to disease, as several common damping-off pathogens do not readily spread from one container to another. Proper management of the nursery, including good hygiene and good quality water supply, are needed to decrease disease incidence. If disease occurs, it can be prohibited by reducing watering of beds to a bare minimum and by regulating shading. Chemical treatment can become essential to control outbreaks of damping-off. Depending upon the pathogen(s) involved, drenching with carbendazim, captan or mancozeb, applied in place of normal watering, has been found to be very effective. After treatment, control of watering to prevent excessive soil moisture helps to check further spread of the disease (Old *et al*., 2000).

Leaf spot may be serious when plants are of low vigour or when planted in high-humidity sites with poor air circulation. Overcrowding and poor soil conditions can also indirectly increase host susceptibility to the disease. The most effective means of control and management of the disease are proper cultural practices. Selective pruning and thinning can be carried out to improve air circulation and penetration of sunlight, thereby reducing disease incidence (Old *et al*., 2000).

On Acacia, powdery mildew is found on the phyllodes, mainly of plants in the nursery and also in the lower crown of young trees in the field. Chemical treatments are not usually necessary unless damage is severe. Sulphur dusting or application of fungicides such as benomyl, chlorothalonil, triadimefon, maneb and zineb gives efficient control (Old *et al*., 2000). Josiah and Allen-Reid (1991) indicated that the disease can be controlled by placing diseased seedlings in direct sunlight for an extended period.

5.2 Ecology and Silviculture of *Acacia mangium*

5.2.1 Description of the Species

Taxonomy

Botanical name: *Acacia mangium* Willd

Family: Fabaceae

Sub-family: Mimosoideae

Synonyms: *Mangium montanum, Racosperma mangium*

Vernacular/ common names: Arr (Papua New Guinea), Black wattle (Australia, UK and USA), Brown salwood (Australia, UK and USA), Kayu safoda (Peninsular Malaysia), Keo tai tuong (Vietnam), Kra Thin Tepa (Thailand), Mangge hutan (Indonesia), Tongke hutan (Indonesia) (Turnbull, 1986).

Morphological characteristics

Acacia mangium is a fast growing, nitrogen fixing, ever-green with phyllodes that serve as leaves (NFTA, 1987). It is a medium-sized to fairly large tree measuring up to 35 m tall. Its bole is branchless for up to 15 m, and can measure up to 90 cm in diameter. The bark's surface is fissured near the base and of a greyish brown to dark brown colour, whereas the inner bark is a paler shade of brown. Branchlets are observed to be acutely triangular, the phyllodes straight, or straight along one side and curved along the other. These branchlets measure up to 25.0 x 3.5–9.0 cm and are 2–5 times as long as wide, with 4 or 5 main longitudinal veins, the secondary veins finely anatomising. Flowers possess five merous and having a corolla 1.2–1.5 mm long. The pods of the tree are broad, linear and irregularly coiled, measuring up to 10 x 0.3–0.5 cm when ripe. These pods are membranous to slightly woody and inconspicuously veined (PROSEA, 1995).

Distribution

Acacia is a large genus with over 1,300 species widely distributed throughout the tropics and subtropics. Most species are found in the southern hemisphere and the main centre of diversity is located in Australia and the Pacific. Acacia is found, sometimes dominant, in primary and secondary forest, forest margins, savannah, grassland, and savannah woodland, on poorly drained floodplains and along fringes of mangrove forest, where it is sometimes associated with *Melaleuca* and *Rhizophora* spp. Its altitudinal range is up to 200 m in Malaysia, stretching to up 500–800 m in Australia. Within the Indonesian region alone, 29 native or naturalised species occur, and several more have been introduced, mainly in the mountain regions of Java. Most of the timbers producing species are found in New Guinea. *Acacia mangium* occurs on the Aru Islands, Irian Jaya, Sula Islands, Seram, Western Province of Papua New Guinea and north-eastern Queensland, Australia. It is also planted elsewhere in the Malaysian region, especially in Sabah and Peninsular Malaysia (PROSEA, 1995).

Acacia from the southwest of Western Province, Papua New Guinea, and from the adjacent Western Papua display the fastest growth, followed by those originating from the Claudie River in far north Queensland (16–18° S). Acacia from the Indonesian island of Ceram, and from Piru in western Papua grow the slowest (Hardwood and Williams, 1992, Turvey, 1996, Nirsatmanto *et al*., 2003).

Acacia mangium is found in areas of high rainfall in northern Australia, New Guinea and some adjacent islands. The prevailing climate in these areas is usually strongly seasonal, with rainfall of less than 50 mm/month in June–October, in contrast to the average annual rainfall of 1,450–1,900 mm in southern New Guinea, and 2,100 mm in northern Queensland (PROSEA, 1995).

Ecological range

Acacia mangium occurs naturally in the humid tropical lowlands of Queensland, which is the species' southern limit (18° 5' S): its northern limit is 0° 5' S in Irian Jaya (Das, 1984). It has been successfully used in reclamation of soils mined for bauxite, gold, copper, charcoal, iron and tin, especially in tropical Asia, Australia and Brazil (Ang and Ho, 2002, Ferrari *et al*., 2004, Maiti, 2006). It can be planted in hard compact soils, savannah areas, dry ridge tops and slopes of hills, moist foothills and infertile dry soils. On poor sites in Sabah, Malaysia, *Acacia mangium* notably outperformed the other species tested. On disturbed or burned sites, on degraded oxisols (laterite) underlain with volcanic rock, on soils so worn out that shifting cultivation had been abandoned, and on hill slopes infested with weeds *Acacia mangium* has grown vigorously (Anon, 1983). Ahmad and Ang (1993) noted that *Acacia mangium* is suitable for reclaiming compacted sites, including decking and primary logging roads in logged-over forests. Midgley and Vivekanandan (1986) reported that *Acacia mangium* has the ability to tolerate extended drought, as proven by agroforestry trials in Sri Lanka. According to Haishui and Zengjiang (1993), large scale plantations of the species are being established successfully in Southern China: below latitude 23.5° N, with an annual mean temperature of 20 °C (maximum 38° C, minimum 5° C) and annual rainfall of 1,500 mm mainly occurring in March–July, on the mainland (June–October on Hainan Island).

Acacia mangium plantations are being established in Sri Lanka in the lowland wet zone and highlands with remarkable success (Vivekanandan, 1993). The species is found to be promising for planting in acid sulphate soil in southern Vietnam, where the soil pH is low (3.2–3.5) and the ground remains waterlogged in the rainy season (Kha, 1993).

Pinyopusarerk *et al*. (1993) stated that *Acacia mangium* grows well under the latitudinal range of 0° 1'–1° 8' S, altitudinal range of 0–800 m and rainfall range of 1,000–3,000 mm in sandy loam soil exhibiting an acid-alkaline reaction.

In southern Sumatra, Indonesia, *Acacia mangium* plantations managed by Musi Hutan Persada are geographically located at 103° 10'–104° 25' E and 3° 5'–5° 28' S. The area has a lowland humid environment with an average daily temperature of 29 °C. The annual rainfall in the last 80 years has been 1,890–3,330 mm, mostly in January–May with a dry spell in October–December. However, during the dry spell there may be some light rain. The relative humidity varies from 56% in the dry season to 81% in the rainy season (Hardiyanto, 1998). The plantations are established on alang-alang (*Imperata cylindrica*) grassland, scrublands and logged-over secondary forest areas. Both the grassland and shrub lands were created by long-term shifting cultivation, using fire for site preparation. The terrain is mostly flat to undulating (0–8 %) although some areas are quite rolling (8–15 %).

In Colombia, the yearly rainfall in the planted areas is 2,000–2,500 mm. Rainfall is seasonal and unimodal, with 3–4 ecologically dry months (with less than 60 mm). Normally, water is scarce in December–March. Monthly temperatures are high and uniform all year round. The mean annual temperature is 26.6–27.7 °C (Diez, 1992).

Wood characteristics

Acacia mangium is a medium weight hardwood. The heartwood is pale olive-brown, grey brown to pink, darkening to a reddish brown or dark red, and often attractively streaked. The sapwood is yellowish white, cream or straw coloured and distinctly demarcated from the heartwood. Heartwood formation varies significantly with provenance. Like the wood of other fast growing tree species, the wood from wattle plantations has the potential disadvantage of small diameter, knottiness, low density, and little strength. Other species are usually preferred for production purposes because *Acacia mangium* has a large proportion of reaction wood, greater incidence of spiral growth, greater growth stress and a greater proportion of juvenile wood. *Acacia mangium* has a density of 560–1,000 kg/m^3 at

15% moisture content. The grain is straight to shallowly interlocking with an even, fine to medium texture. Wood of *Acacia mangium* tested in Australia at 11% moisture content showed a modulus of rupture of 106 N/mm^2, shear rate of 8.0–10.5 N/mm^2 and compression parallel to grain of 60 N/mm^2.

The rates of shrinkage are fairly low to moderate: 1.0–1.45% radial and 2.3–4.2% tangential, from green 12% moisture content. When seasoned with care, end splitting and surface checking are not significant during drying. Boards 25 mm thick take about 3 months to air dry. The timber kiln dries rapidly but marked collapse may occur in early stages of seasoning, though this can be combated through reconditioning.

Acacia mangium wood is easy to work with all tools. It planes easily to a smooth, lustrous surface using cutting angles of 15–25° and finishes well with sharp tools. It drills quite easily, provided the base is supported to prevent end-chipping and it turns well under low to moderate pressures. The nailing and screwing properties are satisfactory and the wood takes a good polish.

Acacia mangium wood is usually durable when exposed to the weather, but is not durable in contact with the ground. It is mostly resistant to termite attack via a root fungus but not entirely. The heartwood is moderately resistant to preservative treatment, but the sapwood is permeable. The pulping properties are excellent and comparable to those of commercial *Eucalyptus*. In tests in Australia using the sulphate process, wood chips of *Acacia mangium* from a nine-year-old plantation required only moderate amounts of alkali to yield in excess of 50% of screened pulp with paper making properties. Pulp yields were even higher (up to 75%) with the neutral sulphides semi-chemical process, and the pulp was readily bleached to brightness levels acceptable for use in fine papers. The energy value of *Acacia mangium* wood is 20,100–20,500 kJ/kg (PROSEA, 1995).

Uses

The timber of *Acacia mangium* species is incredibly multifunctional and can be used for furniture and cabinet making, light to heavy construction, mouldings, poles, posts, panelling, mining timbers, boat building, carts, joinery, turnery, tool handles, agricultural implements, matches, splints, particle boards, hard board and veneer, as well as for plywood, pulp and paper. The wood is tough and resilient and particularly suitable for axe handles and sports equipment. The pulp is suitable for the manufacture of linear boards, bags, wrapping papers and multiwall sacks. The wood makes a good fuel-wood and good charcoal as it has a high energy value. The sawdust provides a good medium for the production of shiitake mushrooms. Other non-timber uses include honey production, adhesives and as an ornamental and shade tree for roadsides or other urban forestry (PROSEA, 1995).

Since *Acacia mangium* can grow on marginal soils, many farmers choose to plant this species to improve the soil fertility of fallowed fields or pastures. Since trees with diameters of 7 cm are fire resistant, *Acacia mangium* plantations can be used as fire breaks. The trees are also planted as windbreaks, for shade, soil protection and as ornamentals. The leaves and pods of some species are used for animal fodder. The germinated seeds can be cooked and eaten in the same manner as a vegetable.

5.2.2 Seed Production

Seed collection

The small flowers are grouped in spikes up to 10 cm long and occur singly or in pairs in the leaf axils near the branch tips. The trees flower annually, usually at the end of the rainy season or the early part of the dry season, and the fruits ripen 5–7 months after flowering. *Acacia mangium* starts to flower and produces seeds 18–20 months after planting. Flowering occurs in Australia in May, with fruits maturing in late October–December.

Fruits ripen in Indonesia in July, in Papua New Guinea in September (Turnbull, 1986), and in Central America in February–April (Francis, 2003). The seeds are dispersed when small birds consume the oily funicle, or they eventually fall to the ground under the mother trees. Individual trees in an *Acacia mangium* plantation produced 1 kg of seed per year (Francis, 2003). The fruits may be harvested by clipping them with pruning poles when they become dark brown and begin to crack open. Although they are best harvested before the fruits are fully open, the pods with hanging seeds remain available on the trees for several weeks (Bowen *et al.*, 1981).

Seed preparation

The seed coat is very hard when ripe. Therefore pre-germination treatments should be carried out to promote prompt, uniform, and high levels of germination. Before planting, seeds should be placed in boiling water for 30 seconds and then cooled by soaking in cold water for 2 hours: alternatively they can be manually scarified. Germination, reported at 60–80% (after pre-germination treatments), may begin after 1 day and continue for 10–15 days (Francis, 2003).

Seed storage and viability

The viability of *Acacia mangium* seeds tends to increase over the course of the fruiting season, whilst the seed size decreases (Bowen and Eusebio, 1981). After air drying, small amounts of seed may be separated by hand. Mechanical separation involves hammer milling the pods followed by shaking, blowing, and screening. Seed cleaning is difficult because the stringy funicles tangle with debris and screens. Cleaned seeds average 80,000–110,000 per kg (Francis, 2003). Storage with moisture content of 4–12% at 3–5 °C in sealed containers is recommended, although seed stored at ambient temperatures will retain its viability for up to 2 years (Bowen and Eusebio, 1981).

5.2.3 Propagation and Planting

Sowing

Seeds are sowed in germination trays or beds, and when seedlings have about three leaves they are packed into plastic nursery bags where they grow to a plantable size (Turnbull, 1986). Seeds are sometimes sowed directly into 1–2 litre nursery bags, a method which requires pricking to one plant per bag after seedlings emerge. The appropriate height for transplanting is 25–40 cm, which is reached when the seedlings have been in the nursery for 9–16 weeks. Although *Acacia mangium* seedlings usually auto-inoculate with *Rhizobium* symbiotic nitrogen fixers, artificial inoculation in the nursery is recommended (Von Carlowitz *et al*., 1991). Bare-root planting and direct seeding into prepared seed spots has been used but owing to the relatively low survival rate, these methods are generally not favoured. Seedlings are ready to be planted out in about 16 weeks (Turnbull, 1986).

Plants can also be propagated vegetatively through single-node stem cuttings 4–5 cm long and 0.5–1.5 cm in diameter, leaving 0.5–1.0 cm phyllodes, a commonly used method in Vietnam. The application of indolebutyric acid or rooting powder enables 65–75% rooting and is reported to be slow. Air-layering gives promising results (PROSEA, 2011).

Preparation of planting site

In Vietnam, preparation of the planting site, through tilling the land and excavating planting holes, is carried out at different times in various regions. In some regions, smallholders plant twice per year. In the north, plantations are established in February–August: with February and August being the two main months for planting. On sites covered by grasses or light brush, the area can be cleared by bulldozer, if it is not too hilly. On steeper terrain, where residual secondary vegetation needs to be cleared, manual labour is necessary as the slopes are often incapable of supporting heavy machinery. Though illegal, the slashed vegetation is usually burned as part of site preparation. In contrast to site preparation for estate crops, most site preparation of this nature is designed to disturb topsoil minimally.

Planting

In Vietnam, planting holes are dug about 1 month before planting and two-thirds of the hole is filled with a mixture of top soil. The hole is normally 30 cm deep, 20 cm wide at the base and 30–40 cm square at the top. The most suitable stocking for pulpwood plantations is between 1,111 trees/ha (initial spacing of 3 x 3 m) and 1,666 trees/ha (3 x 2 m) (CARD, 2005). Spacing of the seedlings in the plantation is adjusted depending on the intended uses of the trees and the fertility of the site. Since the species displays poor natural pruning tendencies, the trees are planted close together to deter epicormic branches from occurring. In mono-specific stands, a spacing of 2 x 2 m or 2.5 x 2.5 m is common. However, if saw log production (large diameter stems) is the objective, wider spacing is used (3.0–3.5 m between rows and between plants). In agro-forestry situations, spacing within rows and between rows must take into account the effect of shade and root competition on the yield of associated crops.

In Vietnam, planting takes place in the rainy season, when the soil is wet, so that the seedlings can become established before the dry season starts. As soon as the land has been prepared it is marked with lines, and each planting point is marked with a stick.

5.2.4 Plantation Maintenance

Weeding

Weeding is important in industrial plantations as it helps meet production requirements and quality control standards. In order to prevent trees suffering any serious slowing in growth, weeding should be timed to coincide with when the trees are least susceptible to damage. Generally, the greater the area weeded around the tree, the less competition the tree is subjected to and therefore the better it grows. Typically, spot weeding is less effective than strip weeding, whereas clean weeding is optimum. Lowery *et al*. (1993) concluded from a review of weed control in tropical forest plantations that complete weeding in most cases results in the best growth and survival, but partial weeding in strips along the tree rows may be a good compromise between making soil resources available to the tree and nutrient conservation. Adherence to the general principle of ‘the more weed control the better’ can only be entertained when cost, the risk of exposing soil to erosion, and the possibility of reducing biodiversity are also taken into account. Weed control conducted by manual weeding or by herbicide application has been shown to improve stand productivity. However, *Acacia mangium* has been found very sensitive to herbicides (PROSEA, 2011). A minimum of weeding twice a year during the first 2 years of plantation growth is encouraged. After that, on the more productive sites, weed growth is suppressed by the development of the upper stories of the tree canopy, whereas on poorer sites weed control is necessary for a longer time.

Fertilising

Fertiliser application can replenish the nutrient supply to maintain or even increase productivity. The highest dose used in Vietnam has been 25.0 g nitrogen, 25.0 g phosphorus, 20.7 g potassium, and 100 g micro-organism enriched fertiliser per seedling, applied to Acacias at planting (CARD, 2005). Riaufiber research in Riau, Indonesia indicates that application of balanced nitrogen/phosphorus/potassium (NPK) fertilisers, and good harvest-residue management, lead to increased height and diameter at breast height of 3-year-old *Acacia mangium* in the second rotation, compared with the first rotation at the same age (Siregar *et al*., 2008). In Malaysia, Wan *et al*. (1989) concluded that the soils are low in nutrients, especially phosphorus. A number of fertiliser trials have been carried out to determine the best schedule for fertilisers. In Bengkoka (Sabah, Malaysia), 90–100 g of Christmas Island rock phosphate (CIRP) is applied at the time of planting, followed by 45 g of NPK mixture 2 months later, at the time of first weeding. Further application of fertiliser may be needed, according to Udarbe and Hepburn (1987). In Dingmen, China, a regime of 100 kg/ha nitrogen, 50 kg/ha phosphorus, and 50 kg/ha potassium was applied to an *Acacia mangium* plantation resulting in 179% increased production volume at age 2.6 years (Simpson, 1992).

Refilling

The first refilling is usually done in the rainy season, 1 month after planting, to replace the dead plants, rooted cuttings or clonal plants: the second is carried out at the end of the second year. If the survival rate is less than 70%, further refilling is necessary for large scale plantations.

Singling and pruning

The purpose of pruning is to encourage trees to develop a straight stem and more valuable, knot-free trunk. High density plantations will have lower pruning costs than lower density plantations. The greater the initial distance in the tree spacing, the more artificial pruning will be necessary to produce a clear bole. The closer the spacing of trees in a higher density plantation, the more they will be forced into an upright growth habit. The resultant lack of light will increase natural pruning of the lowest branches.

Pruning some branches increases the growth rate of the remaining branches (Ramos *et al.,* 1998). In contrast, careless pruning can significantly reduce growth, introduce disease and reduce timber value. Usually, pruning is done twice: the second time, branches are pruned off further up the trunk, often to a height of 6 m. Pruning off branches with a diameter of 2 cm or more makes the trees susceptible to infections, especially heart rot (Srivastava, 1993). Pruning should be done with great care in order to avoid damage to the branch collar and the branch bark bridge, which can lead to disease. Pruning tools should always be cleaned and sharpened to ensure a clean, smooth cut.

Acacia mangium has a strong tendency to produce multiple leaders from the base: as single stems are preferred for harvesting, ‘singling’ (conversion of multi-stemmed to single-stemmed trees) is undertaken routinely at about age 4–6 months. Pruning is unnecessary for pulpwood, however, persistent branches are pruned off in plantations where the objective is to produce high quality saw or veneer logs. This has led to the development of lift-pruning regimes, with the intention of converting the bottom log to clear or knot-free wood (Mead and Speechly, 1991, Weinland and Zuhaidi, 1991). The preferred practice is green pruning, which removes live rather than dead branches. Dead branches are associated with a high percentage of discoloration and decay in unpruned *Acacia mangium* (Ito and Nanis, 1994).

Two common management options are stocking and form pruning. Higher initial stocking densities reduce the incidence of large branches (Neilsen and Gerrand, 1999) but may lead to a reduction in the average growth of individual trees. Unlike lift pruning, form pruning selectively removes branches throughout the crown and can be used to reduce average branch size before subsequent lift pruning (Pinkard, 2002) or to correct potential deviation of stems from a pathway of vertical growth (Nicholas and Gifford, 1995, Medhurst *et al*., 2003).

In *Acacia mangium* plantations in Indonesia, Beadle *et al*. (2007) observed no significant differences in diameter increment between the two pruning treatments. The removal of either 25% of leaf area (form pruning) or 25% crown length from below (lift pruning) would not be considered severe pruning treatments. In Peninsular Malaysia, according to Majid and Paudyal (1992), significant reductions in diameter growth were only observed after crown length removal from below exceeded 40% in an experiment in an *Acacia mangium* plantation. Mead and Speechly (1991) reported that *Acacia mangium* has around 50 branches in the lower 6 m of the stem. Hence pruning from below removes a greater proportion of the leaf area than represented by the crown length (Pinkard and Beadle, 1998) because the branches in this section of the stem are, on average, larger and the internode length is smaller than higher in the crown. Form pruning, however, removes branches higher in the crown that are more photosynthetically active per unit leaf area than those lower in the crown. Significant differences in growth from these two treatments were therefore not anticipated.

In a review of pruning research on *Acacia* hybrid, Dung *et al*. (2005) concluded that only height growth was significantly different between pruning and no pruning treatments, as 3 years after treatment, the pruned trees were observed to be taller. It is possible that pruned branches in the lower, shaded part of the crown were unable to survive owing to their inability to photosynthesise sufficiently. In Vietnam, CARD (2005) recommended that a first pruning for Acacia plantations should be undertaken at the time of canopy closure and before crown lift started. Trees are selected for pruning according to their form, the characteristics of the branches and diameter at breast height. The number of trees pruned is determined by the distribution of log sizes required at harvest.

Thinning

Many reforestation projects in Southeast Asia traditionally prioritised the planting of forests with little regard for the tending of the stands after establishment, thereby leaving them unmanaged for long periods. *Acacia mangium*, which is planted widely in Southeast Asia, has the potential to produce both pulpwood and lumber (Groome, 1991). However, in order to produce large volume a tree, thinning is required (Kato, 1999).

In tropical tree plantations, thinning is usually conducted from a relatively early stage of stand development (Lamprecht, 1989, Evans and Turnbull, 2004). Plantations need to be conscientiously managed to enhance stand quality and promote wood production. Tending operations such as thinning are typically used to increase production of usable-sized trees (Zeide, 2001). Thinning could also provide an intermediate financial return from the removed trees (Evans and Turnbull, 2004). In plantations of fast growing, exotic species, thinning is unnecessary for biomass production: whereas, production of higher quality, large-diameter timber usually necessitates at least one thinning (Lamprecht, 1989). In this case, thinning would be conducted when the plantation is 3, 5 and 7 years old.

In plantations for pulpwood production, thinning can be carried out to achieve a final stock of 600–700 stems/ha from the 1,250 trees/ha planted. Trees are thinned after 18 months. These plantations are clear felled after 6–8 years. In plantations producing high quality logs, the initial number of trees is generally thinned, reducing them from 900/ha to 100–200/ha in 2–3 thinning operations. The first thinning is done when trees are 9 m tall, that is, before 2 years of age. The rotation is 15–20 years. In Papua New Guinea, plantations grown on a 7–8 year rotation for pulpwood and are not thinned (PROSEA, 1995).

In a 12-year-old *Acacia mangium* plantation in Kemasul Forest Reserve, Peninsular Malaysia, Zuhaidi and Mohd (1997) observed that anannual diameter increment for the whole stand ranged from 0.7 cm (unthinned) to 1.8 cm (heavy thinning) for the whole 12-year period. Likewise, the periodic annual diameter increment ranged from 1.1 cm (unthinned) to 2.4 cm (heavy thinning) for the potential final crop of 200 trees. The highest total volume increment (was observed in the moderately thinned plots (211.77 m^3) and the lowest in the unthinned plots (199.55 m^3). However, no significant effect was observed from the thinning interventions on live crown ratios, which ranged from 18% (unthinned) to 30% (heavy thinning). Generally, *Acacia mangium* responded favourably to thinning, with improvement in growth rates. But, in a rotation period of 15 years, the initial target of 3 cm/year annual increment is not certain to be achieved.

Control of diseases

Damping-off is one the most serious diseases which can afflict the nursery. Caused by a wide variety of fungi, this ailment can thankfully be overcome with the use of fungicide. The young plants of *Acacia mangium* are also susceptible to other common diseases in their nurseries, the most serious of which is heart rot. This disease invades through branch wounds (e.g. those caused by pruning) and is also known as white rot, as the affected wood becomes whitish, spongy or fibrous and is surrounded by a dark stain. Its presence is indicated by dead or broken branches, wounds and cankers.

The major pests associated with *Acacia mangium* cause direct damage to seedlings, branches and stems, as well as wilting caused by root damage. Damage does not result in death, but may deform or suppress tree growth (Hutacharern, 1993). Heart rot, root rot and phyllode rust are the main threats (Old *et al*., 2000), with heart rot by far the most widespread, having been observed in most countries in which *Acacia mangium* has been planted, including Malaysia (Mahmud *et al*., 1993, Zakaria *et al*., 1994, Ito and Nanis, 1994, Ito, 2002), Bangladesh, Papua New Guinea, Thailand, Vietnam (Basak, 1997), India (Mehotra *et al*., 1996) and Indonesia (Old *et al*., 2000). Heart rot is usually associated with older trees, but it occurs from the age of 2 years in *Acacia mangium* because of the early formation of heartwood. Heart rot can dramatically decrease timber volume and quality (Lee, 2002).

In Peninsular Malaysia, a volume loss of up to 17.5% of the merchantable timber of *Acacia mangium* has been reported as a result of heart rot (Lee *et al*., 1988, Zakaria *et al*., 1994). In Sabah, up to 18.1% of merchantable volume was affected by decay (Mahmud *et al*., 1993). Heart rot presents little problem for the pulpwood industry (Gales, 2002), because the fungi that cause heart rot preferentially remove lignin, which must be removed by chemical treatment for pulp production. In Peninsular Malaysia, heart rot incidence in *Acacia mangium* has been reported in 57% of 2-year-old trees and 98% of 8-year-old trees (Zakaria *et al*., 1994). In Sabah, the average incidence of heart rot was 35.5% amongst 6-year-old trees (Mahmud *et al*., 1993) and was a maximum of 50% in a different study of 9-year-old trees (Ito and Nanis, 1994). In Bangladesh, heart rot incidence ranged from 49% to 58% in different regions (Basak, 1997).

5.3 Ecology and Silviculture of *Eucalyptus urophylla*

5.3.1 Description of the Species

Taxonomy

Botanical name: *Eucalyptus urophylla* S.T. Blake

Family: Myrtaceae

Subfamily: Myrtoideae

Vernacular / Common names:

Bach dan Urophylla (Vietnam): Timor white gum, Timor mountain gum (United Kingdom): Popo, Ampupu (Indonesia): Palavao Preto (Portuguese), Eucalipto (Brazil) (Jøker, 2004).

Morphological characteristics

Eucalyptus urophylla can reach heights of 45–55 m and is evergreen. In unfavourable environments it grows as a gnarled shrub, though its bole is usually straight. The bark varies depending on available moisture and altitude but is usually persistent, smooth and subfibrous, reddish brown to brown in colour, with shallow, close longitudinal fissures. Sometimes, however, it may appear rough, especially at the base of the trunk. Juvenile leaves are subopposite, whilst the stalks are broadly lanceolate and discolourous, and measure 10–15 cm x 5–8 cm. Lateral veins are just visible from 5–70 ° to the midrib. Adult leaves are phyllodinous, subopposite to alternate, long stalked (12–30 mm), broadly lanceolate and abruptly narrowed into a short tip or lanceolate. They taper into a long drip tip, 12–20 cm x 2–5 cm, at 40–50° to the midrib, and are dark green above and paler green on the underside. The inflorescence is an axillary, simple umbelliform: a condensed and reduced dichasium, called a conflorescence. Umbles are solitary and possess 5–8 flowers. The peduncle appears somewhat flattened and is generally 8–22 mm long, whilst the pedicel is angled and 4–10 mm long. Flowers are regular and bisexual. Flower buds are either ellipsoid or obvoid, shortly pointed to rotund, and measure 10–14 mm x 6–10 mm. They can be divided into a calyx tube or bipanthium (lower part) and an operculum (upper part) which is shed at anthesis. The flower has numerous stamens. The fruit is a dry, thin-walled capsule enclosed in a woody hypanthium, with 3–5 included to partly exserted valves. The fruit is also obconical to cup shaped and measures 6–14 mm x 7–18 mm, in a disk-shape which appears almost folded or obliquely depressed. The seed is small, approximately semicircular and black. Germination is epigeal and the cotyledons are usually bilobed near to the centre. The first 5–7 pairs of leaves are opposite, though subsequent pairs are subopposite (PROSEA, 1993).

Distribution

Eucalyptus urophylla naturally occurs on volcanically derived soils on seven islands in eastern Indonesia (Adonara, Alor, Flores, Lembata (Lomblem), Pantar, Timor and Wetar) at altitudes of 180–3,000 m (Pepe *et al*., 2004). The range extends about 500 km between longitudes 122°–127° E and latitudes 7° 30'–10° S. It was introduced to Java in 1890 and to Brazil in 1919. In 1966, it was introduced to Australia and since then to many other countries, notably Cameroon, China, Congo, French Guiana, Gabon, Ivory Coast, Madagascar, Malaysia and Papua New Guinea (PROSEA, 1993).

Ecological range

Eucalyptus urophylla has the largest altitudinal range of any *Eucalyptus*, covering 1,000–2,960 m in Timor, 70–800 m in Wetar, and 300–1,100 m in Flores and the smaller islands to its east. It is frequently found as the dominant species in secondary montane forest. At lower altitudes and in drier, exposed locations, usually below 1,500 m, it is often replaced by *Eucalyptus alba*. The natural range of *Eucalyptus urophylla* is in the humid and subhumid climatic zones. At an altitude of about 400 m the mean maximum temperature of the hottest month is 27–30 °C, which may drop to 15–21 °C at 1,900 m. The mean maximum temperature of the coldest month is 8–12 °C. In Timor, many of the *Eucalyptus* *urophylla* forests occur at about 1,000 m, where mist and frost are common. Annual rainfall in this area is 1,300–2,200 mm: the dry season lasts for 3–4 months. On other islands, drier conditions prevail, with rainfall of 600–1,500 mm, and a dry season of 5–8 months (PROSEA, 1993).

It may also be found on ridges and on loamy, lateritic and sometimes clayed soils. *Eucalyptus urophylla* occurs in open, often secondary, mountain forest and performs best on deep, moist, well-drained soils. It grows in the vegetal formations of dry deciduous forest and moist evergreen forest (Endo, 1992). Because the species has no major edaphic requirements, it is appropriate for reforestation, both in flooded soils and in dry soils of low tropical lands.

Wood characteristics

The wood of *Eucalyptus urophylla* is light, medium weight or heavy. The heartwood is light- to reddish-brown, sometimes dark reddish brown on exposure. The sapwood is white, cream or light pinkish, is 20–60 mm thick, and is distinctly demarcated from the heartwood. The grain is straight to interlock and the texture moderately coarse to coarse. A ribbon figure is often present on quarter-sawn surfaces. The rate of shrinkage is moderate to high, 1.8–3.0% (-4.4%) radial and 3.4–7.0% (-8.9%) tangential from green to 12% moisture content. Care is needed during seasoning, especially with heavier timber, as backsaw boards tend to check, close spacing of stacking strips is important. The wood glues well, but pre-boring is advisable for screwing and nailing to prevent end splitting. It stains and paints well. It slices well if the wood has high moisture content, and the veneer often dries satisfactorily and has an attractive figure. The heartwood is usually resistant to preservative treatment and the sapwood is permeable. The chief constituent of Eucalyptus oil is eucalyptol. The oil has a camphor-like odour and a spicy, cooling taste. It is practically insoluble in water, but mixable with alcohol, chloroform, ether, glacial acetic acid and oils (PROSEA, 1993).

Fibres are relatively short (about 1.0 mm in length). The wood is very suitable for producing bleached chemical pulp, with an average pulp yield of 49.5%. The wood of *Eucalyptus urophylla* is less dense than most *Eucalyptus*, the basic density is 540–570 g/m^3 (RISE, 2009).

The most important traits for increased pulpwood production are volume and basic density (Borralho *et al*., 1993). In research in Vietnam, Pinyopusarerk *et al*. (2006) observed that for most growers, high density wood is the most valuable, as it is sold on a weight basis. Wood is often sold on a stacked-volume basis in the field, but by green-weight at the pulp or chip mill. Thus the target for growers is big, healthy, straight trees with higher density wood. An average wood basic density of 500–550 kg/m^3 is considered desirable for pulpwood plantations.

Uses

Eucalyptus urophylla wood is primarily used for pulp production, fuel-wood and for charcoal. The wood's other primary use is for boards, though it is also used for electrical transmission poles, long-lasting posts and pilings, light and heavy construction, cabinet-making, carpentry and for plywood and agglomerate boards. It is useful in protecting river banks and providing shade and is a honey-producing species with good properties (PROSEA, 1993). The bark has a tannin content of over 10%, but it is not used commercially. The leaves yield pale-yellow oil, the major components of which are paecymene (76%), alpha-pinene (7%) and gamma terpenene (4%). The essential oil is a good source of paracymene, which possesses disinfectant properties and is used in soap making and in the perfume industry (Orwa *et al*., 2009).

5.3.2 Seed Production

Seed collection

Eucalyptus urophylla first begin flower when they are 2–3 years old, with seeds being produced abundantly by the age of 4. Flowering occurs during the dry season and within 6 months the seeds reach maturity. The major pollinators of the flowers are insects, birds and mammals, and to a lesser extent, wind. The fruits occur in rosettes of 5–7. The seeds can be judged mature when the fruits become hard and brown and begin to open. Prior to opening, the fruits should be cut from the branches by hand and placed in paper or cloth sacks. To avoid the formation of fungi, the seeds must be kept well ventilated and should not be exposed to high temperatures.

Seed preparation and storage

The fruit is a typical *Eucalyptus* capsule: cup-shaped and made up of 3–5 valves. It has a double operculum (lid) and the outer operculum is shed early. On average there are 400,000–700,000 seeds/kg: with 1,000 viable seeds weighing 1.4–2.5 g. The ripe seeds can be kept viable for 5–20 years if they are stored in a sealed container and kept at low humidity (8–10%) and a temperature of 3–5 ˚C in order to protect against insects and fungi.

Seed viability

Most *Eucalyptus* seeds germinate well without pre-germination treatment, but some species require cold and humid stratification to break latency. This treatment consists of moistening the seed and placing it in a cold room (3–5 ˚C) for 2–10 weeks. The appropriate temperature for germination is 20 ˚C. Complete germination occurs in 10–21 days, depending on the species (Vozzo, 2002). The seed is usually relatively easy to germinate.

5.3.3 Propagation and Planting

Sowing

Seeds can be scattered or planted in furrows prepared with friable, porous or light textured organic matter, which allows for adequate drainage. Usually, 25–50 g of seed is mixed with an equal quantity of fine sand and is broadcast sown over each levelled nursery bed before being covered with a thin layer of fine sand. Beds are watered with a watering can fitted with a fine rose and are normally covered with bamboo slats during the day time until the seedlings have attained a height of 5–6 cm and are suitable for pricking out.

The potting mixture consists of 7 parts of soil, 2 parts of fine sand and 1 part of compost or organic manure. Although tolerant of chemically poor soils, the species must be planted in loose textured soils. It does not tolerate very clayey soils with a shallow phreatic layer and shows much improved growth in soils that remain wet during the dry season.

Seeds germinate in approximately 20 days and the seedlings can be transferred to planting tubes when they have 2–3 leaf pairs. Seedlings are container raised and pricked out into 22 x 10 cm perforated, clear, polythene bags. Seedlings 5–6 cm high are pricked out and, in the initial stages, shaded. Regular watering is carried out and, when they are 25–30 cm in height, usually after 3–4 months, the seedlings are ready for planting in the field. Hardening off should be done about 2 weeks before planting into the field by reducing watering and removing shade.

Provenance selection is very important, with low-altitude provenances usually giving the highest yields (NAS, 1983). According to Whitesell *et al*. (1992), previous work in Hawaii suggested that desirable criteria for selection of the species should include:

- fast growth and good stem form for the provision of high biomass production over a range of site conditions,
- the ability to be asexually reproduced using vegetative propagation methods,
- a superior ability for coppicing,

- resistance to serious disease or insect attacks,
- suitability for other uses besides biomass, for example pulp, lumber or chemicals.

Clonal technology

Clonal technology can be used to improve the productivity and quality of produce of new plantations. Candidate trees with phenotypical characteristics (straight bole, fast growth, weak branches, disease-free, small crown, self-pruning capacity) should be selected for propagation. Propagules should be prepared from stem cuttings of 30–35-day-old coppice shoots or pollards.

Early in the morning, the juvenile shoots of *Eucalyptus urophylla* are brought to the processing unit to avoid desiccation. The cuttings are washed with mild detergent and pure water. Then the cuttings are cut into 10 cm lengths, with two internodes, and half of each leaf is cut off to reduce the transpiration of water. These cuttings are kept in 2% fungicide solution for 10 minutes and later a fresh cut is made at the lower end. The lower end of the cutting is given a quick dip in the root hormone IBA 4,500 ppm and transplanted in coco-peat for rooting. Transplanted cuttings are placed in low cost mist chambers without delay.

Low cost mist chambers are constructed from pits covered in polythene. Pits measuring 12 m long, 1.3 m wide and 27 cm deep, are dug in compact soil. The pits are lined on all sides with a single layer of bricks arranged vertically. A 7 cm layer of sand and pebbles is put at the bottom. Then, 6 cm of water is poured into the pit, or alternatively the water is poured into channels (15 cm wide and 23 cm deep) on all four sides. The hydro pit is covered with polythene sheet, fitted over semi-circular bamboo or cast iron frames to form a tunnel. The fog collected on the inner surface of the polythene sheet will reduce the temperature and the drops will fall on the leaf laminae and keep the surface wet.

Under favourable conditions (i.e. 80% humidity and 25–30 ˚C) roots should develop in 20–25 days. The rooted ramets are transferred to a shade house for adaptation and hardening. After 12 days the ramets should be transferred to an open nursery and nursed for 2–3 months until they reach planting height. The clonal identity of each clone should be maintained to assess field performance. Clonal technology for production of outstanding, high yielding, disease resistant planting stock of *Eucalyptus urophylla* is in the process of being perfected and is being adopted on a large scale for mass propagation (WCPM, 2005).

Preparation of planting site

Amongst countries that have highly productive *Eucalyptus* plantations, the benefits of optimal soil preparation practices are well recognised. Intensive cultivation practices, including the burning of plant residues, ploughing and harrowing, have given way to minimum cultivation techniques that involve disturbing the soil only to the extent necessary. This enables the retention of organic residues and makes the use of herbicides to control invasive weeds more effective (Evans and Turnbull, 2004).

Intensive mechanical site preparation is often avoided in Vietnam, since it is expensive and damaging to the environment. If existing ground vegetation and litter is too depleted, this can result in accelerated erosion of the soil and loss of nutrients.

This area is marked with a line: the planting lines in hilly terrain run parallel to the contour. A small patch, about 1 m in diameter, is marked out about a month before planting and the space around the planting hole is clean weeded. Planting holes are dug 25 cm in diameter and 45 cm deep.

The most effective method to control the weeds (especially *Imperata cylindrica*) is to use a glyphosate herbicide. Blanket spraying should be conducted at 4 L/ha, and strip spraying at 2 L/ha, with mixture of 250 ml of herbicide in 60 L of water.

Planting

Planting should be done early in the rainy season, or at the latest, 1 or 2 months before the end of the rainy season. It is important that seedlings have sufficient time before the beginning of the dry season to create a good wood system that will help them endure any extended dry period (RISE, 2009).

An initial growing space per tree should be set at 2.5 x 2.5 m. If larger tree sizes, longer rotation ages, or higher yields per hectare at harvest are desired, then a policy of wider spacing could be adopted. When mixed with other species such as teak (*Tectona grandis*), the usual spacing practice for *Eucalyptus* is 2.5 x 2.5 m. When *Eucalyptus* is mixed with *Acacia auriculiformis* in the dry and intermediate zones, a spacing of 2 x 2 m is maintained, as both species are grown as short rotation fuel-wood crops and additional spacing is not necessary. In the dry zone, when *Eucalyptus* is planted under the 'Taungya' system, the spacing adopted is 2.5 x 2.5 m to accommodate inter-row cultivation of food crops (Bandaratillake, 1996).

5.3.4 Plantation Maintenance

Weeding

Eucalyptus urophylla is extremely susceptible to competition in the early stages and must be kept weed free for 6–12 months (RISE, 2009). Post-planting weed control is required twice in the first 6 months and must be done carefully with manual backpack sprayers (Whitesell *et al*., 1992). Alternatively, weeds can be controlled by hand-pulling, hoeing or disc-cultivating. Clean tending near the young trees themselves by hand-pulling is not a difficult operation when the soil is in good condition. The weeds can be controlled by disc-harrowing between the rows. It is important to remove weeds before they seed and thereby multiply the problem (FAO, 1979). Frequent weeding, up to three times per year, is necessary until the canopy closes 3–5 years after planting. If weeding is not conducted efficiently a complete failure of the plantation may occur (Orwa *et al*., 2009). In Vietnam, the traditional way of controlling weeds in *Eucalyptus urophylla* plantation is by mix planting with cassava when the plantation is young.

Fertilising

The fertiliser requirements of *Eucalyptus urophylla* depends on the soil type in the area of tree planting. In the Philippines, the first application is with BFI fertiliser (200 g of nitrogen/phosphorus/potassium (NPK), 200 g Phoscal plus, 20 g Boron and 5 g Zinc sulphate for each tree). The second application (200 g Phoscal plus, 100 g Urea and 60 g Potassium chloride) is then conducted 2 months leter (RISE, 2009). In *Eucalyptus urophylla* plantations in southern China, Patrik (2007) recommended that at least 150 kg nitrogen: 115 kg phosphorus and 115 kg potassium per hectare, per year should be broadcast to achieve highest stem volume production. There was a significant difference between fertilisation once and twice per year with this mixture. The highest stem volume growth was observed when fertiliser was applied twice a year (34.4 m^3).

Refilling

Refilling is essential in areas where trees cultivated for timber or large poles have been harvested. This is because the stools will have been cut at various stages and regrowth will have been suppressed by the shade from remaining trees. The first refilling should be conducted in the rainy season, 1 month after planting (to replace dead seedlings), with the second being carried out at the end of the second year. If the survival rate on large scale plantations is less than 70%, further refilling will be necessary.

Coppice system

When the trees are felled, new stems often sprout from the stumps to produce another crop of trees. This new crop is called the ‘coppice crop’ to distinguish it from the ‘seedling crop’. Coppice crops play an important role in ensuring the profitably of *Eucalyptus* plantations, as replanting costs are reduced and coppice stems grow faster than seedlings, providing a shorter rotation and quicker returns. Several successive coppice crops are possible, however achieving a stable coppice crop depends on planting the suitable species in the right environment and harvesting in the correct manner (Orwa *et al*., 2009).

The first (seedling) crop is felled at age 7–10 years in most *Eucalyptus* coppice plantations. Felling is the most important operation in relation to the survival of the plantation through successive coppicing of the stumps, which can be repeated for 3 or 4 more rotations. The period of felling, type of equipment and techniques used are all important. Felling should not be done in dry periods and heavy frosts, which can loosen the bark from the stumps. The early growing period, after the heavy frosts, is probably the best time in cold areas, as the shoots will be established before the next winter. Felling tools are also important. With experience in Australia and South Africa, better results have been shown in coppicing from the use of chainsaws rather than axes. Using an axe increases the risk of loosening the bark on the stump. Alternatively, bow-saws and two-man crosscut saws have sometimes been reported to give better results than chainsaws.

Attention must also be paid to the felling level. If the stump is too high the chances of survival are lower. If the cut is at ground level the bark may loosen. A stump height of 10–12 cm is recommended, and should provide an adequate number of coppice shoots. The cut should be as smooth as possible and slanted so as to facilitate water run-off. The accumulation of water on the stump increases the risk of fungus attack. Lop and top should be removed from the stumps after felling so that the young coppice can develop without interference (FAO, 1979).

Pruning

Pruning is undertaken to maximise the amount of clear wood produced by a tree. Pruning achieves this by removing branches early, containing branch related defects to a central knotty core and allowing subsequent growth to be defect free (Shepherd, 1986). Pruning should be done carefully to avoiding damage to the branch collar and the branch bark bridge, which can lead to disease. Pruning tools should always be cleaned and sharpened to ensure a clean, smooth cut.

Pruning encourages a more uniform crop of logs, which can help to reduce the processing costs and result in a higher price. Before pruning it is imperative that growers draw-up a management regime that aims to produce logs of a certain specification for a particular market. If this planning is not implemented then increased returns from pruning may not be realised.

Only a percentage of trees should be pruned. Selection of the crop trees is required, as not all trees in a stand will be of sufficient form and vigour to produce logs to specification. The targeted specifications for logs should be based on a maximum allowable knotty core diameter (Stackpole *et al*., 1999, Koehler, 1984). For instance, to produce 90% clear wood volume from a 6 m log would need a centre diameter at harvest of 50 cm and a knotty core diameter of 15 cm (Gerrand *et al*., 1997).

Forest managers should time pruning to coincide with canopy closure, to reduce the impact of pruning on tree growth. After canopy closure the lower branches become shaded and will develop minimally and contribute little carbon to the tree. Pruning before canopy closure will remove branches that are still contributing carbon to the tree and will be more likely to reduce tree growth rates (Kelvin, 2003). The branch size of individual trees is also an important factor in determining the timing of pruning. In low stocked plantings, failure to prune before branches become too large can be detrimental to wood quality. Large branches will not only take a longer time to block but also increase the risk of decay (FAO, 1979).

Pruning is a value adding activity, but it is labour intensive. Scheduling of pruning activities will thus vary depending on the scale of operation and the labour management regimes in place. Large scale industrial plantations will require more sophisticated scheduling, which will typically involve predictions of stand development, to optimise both time of pruning and labour use (Pinkard and Beadle, 2000).

Thinning

Thinning artificially reduces the number of trees growing in a stand. It is generally carried out several times and starts a few years after canopy closure. Thinning can be made at different intensities and in different ways. The two main approaches to thinning are (i) systematic, mechanical, or line thinning, and (ii) selective thinning. In systematic thinning, trees are thinned following an objective and systematic procedure in which individual tree quality is not considered. Removal of every third row of trees is an example, and only intensity is varied. In selective thinning, trees are thinned or left depending on the subjective judgment of the person making the thinning: both intensity and the kind of tree favoured can be varied. Selective thinning is particularly important in species with generally poor form, so that the best stems can be favoured. The two main methods of selective thinning are low thinning and crown thinning, and they determine which kinds of trees are removed (Evans and Turnbull, 2004).

Thinning practices can seriously affect the level of green pruning, also called ‘Summer pruning’, that is needed in a stand. Thinning of the stand will increase the amount of light reaching the lower canopy and hence the supply of carbon to the tree to support growth. Thus, if a stand is thinned and pruned, green pruning may have a greater effect on subsequent tree growth rates (Medhurst and Beadle, 2000). Regular thinning should be conducted when the plantation is 3, 5 and 7 years old.

The secret to maximising the yield of big trees is to implement thinning at exactly the right point in time. Large, straight trees are cultivated by regularly thinning out the crop, leaving the best trees to grow to a bigger size. However, if close to markets, the production of firewood and poles could be an important source of early income for the grower. Depending on the initial spacing, a selective thinning removing every second or third line can be carried out. Thinning conducted at a later stage would be more selective and leave behind the best, evenly spaced trees.

Control of pests and diseases

Though termite attacks are relatively common in *Eucalyptus* plantations in the dry zone, they are significantly scarcer in the wet zone. Depending on the intensity of the termite attack, insecticides are applied either at the time of planting or the moment an attack is discovered. Generally, when the incidence of attack is high, soil in the polythene tubes is dipped in a 0.5% Aldrin solution before planting. This is an effective method of controlling termite attack until the seedlings are established in the field (Bandaratillake, 1996).

Seedlings of *Eucalyptus urophylla* are susceptible to attack by stem borers such as *Zeuzera coffeae*. In the Solomon Islands, die-back attributed to the coreid insect *Amblypelta cocophaga* has been observed in 3–4-month-old plantings. Damping-off of seedlings occurs in cases of high humidity. Root fungi such as *Botryodiplodia spp*., *Fusarium spp*. and *Helminthosporium spp*. are also a severe problem (Orwa *et al*., 2009).

In the tropics and subtropics, *Cryphonectria cubensis* is a widespread and significant pathogen of plantation *Eucalyptus*. The main damage to trees caused by *Cryphonectria cubensis* is the development of large basal cankers which can kill trees during the first 2–3 years of growth. On older trees, extensive perennial cankers develop several metres in length up the bole of the tree. Under favourable climatic conditions, with susceptible species or clones, up to 50% of stems in plantations have been killed (Alfenas *et al*., 1983). Cankers are characterised by death of phloem, cambium and sapwood with partial girdling of trees. The economic effects of *Cryphonectria cubensis* canker are reduced growth rate (Camargo *et al*., 1991), reduced coppicing (Hodges and Reis, 1976) and increased mortality (Boerboom and Maas, 1970). Wood yield is significantly reduced when cankers extended to more than 25% of the commercially useful stem length (Ferrari *et al*., 1984).

5.4 Ecology and Silviculture of *Cinnamomum parthenoxylon*

5.4.1 Description of the Species

Taxonomy

Botanical name: *Cinnamomum parthenoxylon* (Jack) Meisn

Family: Lauraceae

Subfamily: Lauroideae

Vernacular/common names:

Re huong (Vietnam), Huang zhang (China), Saffrol Laurel, Martaban camphor (English), Dalchini, Ohez, Gondhori (India), Karawe, Hmanthein (Burma), Kayu (Sabah, Malaysia).

Source: woodworkerssource.com (18.9.2011)

Morphological characteristics

Cinnamomum parthenoxylon is a large, evergreen tree species, capable of reaching a height of 30 m and a diameter at breast height of 60–70 cm. The bark is silvery grey, smooth and slightly fragrant. The leaves occur singly, possess three basal veins and are alternatively situated. The leaves' upper layer is glabrous, whereas the lower layer is brilliantly green and slightly fragrant. The leaf measures 8–10 cm long and 4–6 cm wide. The inflorescence is apical, whereas the perianth is six lobed, oblong and tomentose on both sides. The fruit is ovoid and green when young, turning blackish green when ripe. The fruit possesses only one seed, which has a pale brown coat (Kha, 2004).

Distribution

Cinnamomum parthenoxylon is widely distributed in Vietnam but is from an elevation of 200 m upwards. It grows amongst other tree species such as *Michelia spp., Phoebe spp., Gironniera subaequalis, Vatica tonkinensis* etc. Sometimes, *Cinnamomum parthenoxylon* can be found growing in groups of 5–7 trees in secondary forest. It usually occupies the upper story of the forest canopy and forms a high percentage of the species present.

Cinnamomum parthenoxylon can grow in many soil types, though its appearance may be affected. On basalt it develops a reddish or yellowish brown hue whereas on shale, degenerated rock and acid magma rock it develops a yellowish red colour.

Original climate conditions are:

Average annual rainfall: 1,500–2,300 mm

Rainy season (≥ 100 mm/month): 6–7 months

Average annual temperature: 21.5–23.0 °C

Average highest temperature in the hottest month: 32–33 °C

Average lowest temperature in the coldest month: 10–14 °C (Kha, 2004).

The genus comprises several hundred species which occur naturally in Asia and Australia. *Cinnamomum parthenoxylon* is naturally distributed in China, India, Indonesia, Thailand and Vietnam. In Vietnam the species is found in tropical evergreen rainforests up to 700 m, on sheltered slopes, growing on deep, well-drained, fertile soils (JICA, 1996).

Ecological range

In Vietnam, *Cinnamomum parthenoxylon* is frequently found in secondary forest in Cao Bang, Dac Lak, Gia Lai, Ha Tinh, Hoa Binh, Kon Tum, Lang Son, Nghe An, Phu Tho, Thai Nguyen, Tuyen Quang and Yen Bai provinces. It is suitable to tropical-humid, monsoon climates and is widely distributed in ecological zones with a mean annual rainfall of 800–2,500 mm, a mean annual temperature of 20–22°C and an elevation of 50–1,500 m.

Cinnamomum parthenoxylon grows on many soil types. It exhibits fast growth on deep, sandy and well-drained soil, under medium forest cover. The tree regenerates strongly from seeds and can also regenerate from coppice. Natural and coppice regeneration are good in secondary forests. The tree grows particularly fast during 15–25 years of age. Whilst young, the trees prefer slight shading, when mature they are light demanding (JICA, 1996).

Wood characteristics

The wood of *Cinnamomum parthenoxylon* is rather soft with distinctive yellowish sapwood and orange heartwood. Heartwood occupies about 80% of diameter, the year rings being 4–6 mm in thickness. The specific density of wood is 500 kg/m^3 when it is dried. It is also resistant to termites and insects (JICA, 1996).

Uses

The wood is used for construction, to make household utensils, flooring strips, wood carvings and implements, and is a good timber for boat building. The trunk bark and leaves contain an essential oil which is traditionally used to treat liver ache, dyspepsia, backache, impotence, anemorrhoea and to enhance blood circulation. As *Cinnamomum parthenoxylon* possesses a deep taproot and an evergreen crown, it can be used for watershed management plantation (JICA, 1996).

5.4.2 Seed Production

Seed collection

Good seeds are selected from seed orchards, seed production areas and mother (plus) trees in order to attain a superior quality tree, with a straight stem devoid of disease. The optimum time for seed collection is as soon as the seed has reached maturity. If not collected then, the seed may over-ripen and not germinate well, or be susceptible to insect attack if fruit or pods stay on the tree too long. Seed collection should be conducted when pods or fruit are still on the tree.

Cinnamomum parthenoxylon flowers during the period March–May, with the fruits ripening in February–March the following year. When ripe, the fruits take on a black colour. Collected fruits should be kept for 2–3 days more, before the pulp is removed and the seeds acquired. Seeds can be stored together in layers 5–10 cm thick and left to dry in a cool place. Owing to the difficulties encountered in storing *Cinnamomum parthenoxylon* seeds they are usually sowed immediately. The number of seeds in 1 kg is about 3,200–3,500. The primary germination rate is over 70%.

Seed preparation

Before sowing, seeds are treated with Benlat C (concentration 0.3%) for 20 minutes to prevent fungi, and then submerged in water which has been heated to 40–45°C for 10–12 hours. Seeds are then incubated in wet sand beds.

Seed storage and viability

Seeds contain oil and easily loose germination capacity if temperature, moisture and sunshine are unfavourable. As seeds of *Cinnamomum parthenoxylon* are difficult to conserve, they should be sown immediately after collecting. If not immediately sowed, collected seeds should be stored in moist sand in a proportion of 2 parts of sand: 1 part of seeds within 1 month. Each kilogram of seeds should be capable of producing 1,500–2,000 seedlings.

5.4.3 Propagation and Planting

Sowing

Within 5–7 days of incubation, the seeds split and should be sown into tube pots or beds. Seeds sown in beds should be spaced at 1 phalange between every 2 seeds, and then covered with a layer of soil 1 cm thick, before the beds are overlain with straw. Seeds sown in pots should be planted one seed to each pot, with a mixture of 85–90% nursery soil combined with 10–15% well-decomposed manure.

It is necessary to keep the sown pots moist and shaded with plants or nets to ensure no more than 40–50% sunlight. The seeds should germinate after 15–20 days and when the seedlings are 3–4 months old the sunlight should be reduced to 30–40%.

Weeding and the application of additional fertiliser (nitrogen/phosphorus/potassium [NPK] 1%) should be carried out once a month. The containers should be changed 20 days before out planting and sprayed with Daconil 75 WP (0.15%) mixed at 8 litre/100 m^2 to prevent root boring. After that, the plants should be sprayed once every 15 days. Seedlings can be planted out in the field at 6–7 months old, 30–35 cm high and with a root neck of 0.4–0.5 cm diameter. The plants should be checked for pests, disease or other damage (FSIV and JICA, 2003).

Preparation of planting site

Cinnamomum parthenoxylon is best suited to deteriorated forest or shrub land which still maintains a semblance of its former forest condition. Generally, preparing the level of site cultivation will result in better tree growth and survival. The degree of slope and intensity of soil compaction are the main factors influencing the potential for site cultivation. Before cultivating, it is important to reduce the existing vegetation by slashing or burning in order to improve the ease of machinery access and effective soil cultivation.

Cultivation provides a better soil tilth for planting and can be achieved with a wide range of implements. Cultivation should be planned for a period when the soil is not too wet, thereby avoiding soil compaction and damage to the structure of the soil. Cultivating well in advance of planting will allow the soil to settle.

Planting

Cinnamomum parthenoxylon are planted at varying distances and in various densities – ranging from 250 trees/ha to 1,100 trees/ha. In Vietnam, it is common to plant *Cinnamomum parthenoxylon* in rows, 2.0 x 2.5 m wide, with rows spaced 6 m apart and trees spaced 3 m apart. Mixed planting with other broad-leaved species is possible and results in high productivity. Planting is usually done in pits of 40 cm depth and 40 cm diameter. About 15 days before planting, two-thirds of the pit is filled with soil and the area around the planting hole is clean weeded. In Vietnam, *Cinnamomum parthenoxylon* is planted in spring (February–April) and autumn (July–September) in the Northern provinces and in the rainy season (September – November) (in the central provinces and high plateau (Kha, 2004).

5.4.4 Plantation Maintenance

Weeding

Weed control is necessary to reduce the competition for water and nutrients between trees and weeds. Competition from weeds severely decreases early tree performance, and weed growth can be prolific in subtropical and tropical regions. Weed control before planting and for at least 12 months after should be considered essential for successful plantation establishment. A 2 m wide weed-free strip along each planting row should be established during the first 2 years. Weed control conducted by manual weeding or by herbicide has been shown to improve stand productivity. A minimum of weeding twice a year during the first 2 years of plantation growth is encouraged. After that, on the more productive sites, weed growth is suppressed by the development of the upper stories of the tree canopy, whereas on poorer sites weed control is necessary for a longer period of time.

Fertilising

Trees require nutrients to live and thrive: when a soil is nutrient poor, trees will not reach their full potential, will be more susceptible to disease and insect problems, and will have a shorter lifespan than similar, well-fertilised trees. Fertiliser products aimed at providing trees with the appropriate nutrients abound. Generally, fertiliser is applied at the time of planting and 6 months after planting. The most commonly used fertilisers are NKP and those based on micro-organisms. An indicator of the need for fertilisation is the history of the nursery. Trees in nurseries that are fertilised on a regular basis rarely need supplemental fertiliser applied on transplantation. Fertiliser is most effective when applied just prior to a good rainfall. The best fertiliser for common soil environments is not yet established, nor is there an acceptable financial cost–benefit analysis for fertiliser application.

Refilling

In the first year, dead trees are refilled, with the initial refilling taking place 2 months after planting and the secondary refilling being done after 11–12 months. If the survival rate is less than 70% further refilling is necessary for large scale plantations. In the second and third years, tending is done twice a year: once at the beginning of the rainy season and once at the end. This mostly involves the complete removal of vegetation and the piling up of soil around the roots to a width of 0.8–1.0 m.

Pruning

The purpose of pruning is to encourage trees to develop a straight stem and more valuable, knot-free trunks. High density plantations will have lower pruning costs than lower density plantations. The greater the initial distance in the tree spacing, the more artificial pruning will be necessary to produce a clear bole. The closer the spacing of trees in a higher density plantation, the more they will be forced into an upright growth habit. The resultant lack of light will increase natural pruning of the lowest branches.

Pruning some branches increases the growth rate of the remaining branches (Ramos *et al*., 1998). In contrast, careless pruning can significantly reduce growth, introduce disease and reduce timber value. When the trees reach 2 years of age, pruning in late winter can begin to develop a single stem. Pruning should be done with great care in order to avoid damage to the branch collar and the branch bark bridge, which can lead to disease. Pruning tools should always be cleaned and sharpened to ensure a clean, smooth cut.

Thinning

Thinning is the selective process of removing some trees in order to afford the remaining trees the opportunity to maintain a steady growth rate. Poorly formed trees and species of lower value may also be selectively removed through thinning. If there is a lot of variation in growth and survival, thinning may be necessary only in areas where the trees are very thick. As one of the primary goals of thinning is to maintain a steady growth rate, it is imperative that the growth rates of the trees are monitored.

In tropical tree plantations, thinning is usually conducted from a relatively early stage of stand development (Lamprecht, 1989, Evans and Turnbull, 2004). Plantations need to be conscientiously managed to enhance stand quality and promote wood production. Tending operations such as thinning are typically used to increase production of usable-sized trees (Zeide, 2001). Thinning can also provide an intermediate financial return from the removed trees (Evans and Turnbull, 2004). Producing higher quality, large-diameter timber usually requires at least one thinning (Lamprecht, 1989). Regular thinning should be conducted when the plantation is 3, 5 and 7 years old.

5.5 Ecology and Silviculture of *Erythropholeum fordii*

5.5.1 Description of the species

Taxonomy

Botanical name: *Erythropholeum fordii* Oliver

Family: Caesalpiniaceae

Sub-family: Caesalpinioideae

Vernacular/ common name in Vietnam: Lim Xanh

Morphological characteristics

Erythropholeum fordii is a large, evergreen tree species which is capable of reaching a height of 37–45 m and a diameter of 200–250 cm. The stem is rounded with dark brown bark, which is square cracking, has many conspicuous lenticels and can be peeled off in scales. The base of the stem has a small buttress. The foliage is thick and green all year round. The leaves are bipinnate and ovoid, with a rounded base and pointed tip. Their upper layer is dark green, whereas the lower layer is pale green with conspicuous veins. The inflorescence is apical racemose and 20–30 cm long with small, white flowers which open in March–April. The fruit is an oblong-elliptic pod, 15–30 cm long, which contains 6–12 seeds. Fruits ripen in December–January and are brown or greyish black. The seeds are large, flat and square-shaped with a pointed tip, and grow at an obtuse angle. The seed coat is hard and black (JICA, 1996).

Distribution

Erythropholeum fordii is distributed across the south of China (including eastern Taiwan) and the north of Vietnam. It occupies elevations of 300–900 m. *Erythropholeum fordii* is indigenous to Vietnam and is distributed across Bac Giang, Da Nang, Ha Tay, Hoa Binh, Lang Son, Nghe An, Ninh Binh, Phu Tho, Quang Binh, Quang Nam, Quang Ninh, Quang

Tri, Thai Nguyen, Thanh Hoa, Tuyen Quang, Vinh Phuc and Yen Bai provinces, and is also found in Ham Tan (Binh Thuan Province). It grows between 10° 47' N and 23° N, and 102°–108° E, but distribution is concentrated at 17°–23° N (FSIV and JICA, 2003).

Original climate conditions are:

Average annual rainfall: 1,500–2,800 mm

Rainy season (≥100 mm/month): 6–7 months

Average annual temperature: 22.0–24.8 °C

Average highest temperature in the hottest month: 31.7–33.8 °C

Average lowest temperature in the coldest month: under 14 °C (Kha, 2004).

Ecological range

Erythropholeum fordii grows in many kinds of soil, and can develop in various types of mother soil such as sandstone, shale, mica schist, and even soil with a mechanical composition ranging from light to heavy. It can tolerate high humidity, an average to high acidic content, and site conditions which have a humid and deep soil layer. It usually grows with many other broad leaved tree species in a multi-storeyed forest environment, where vegetation is rich (FSIV and JICA, 2003).

Wood characteristics

Research conducted in Southern Fujian assessed the physical and mechanical properties of *Erythropholeum fordii* wood, which is of high density and has good capacity for deformation. The air-dried density was 0.857 g/cm^3, the basic density was 0.746 g/cm^3 and the shrinkage coefficient of volume was 0.615. The compression strength parallel to grain was 67.59 MPa, the bending strength parallel to grain was 141.82 MPa and the composite strength was 209.41 MPa (Fang, 2006).

Uses

Erythropholeum fordii wood is a precious timber: it has fine veins, is hard, strong, durable, and weather resistant and seldom curves or cracks. The specific density of dry wood is 930 kg/m^3. The wood has high structural strength and is much sought after for use as flooring planks and in construction, as well as in certain infrastructure and transport capacities where long durability is required (FSIV and JICA, 2003).

5.5.2 Seed Production

Seed collection

Seeds should be collected from mother plants that exhibit good growth patterns, have thickly proportioned foliage, a round, straight trunk of 40 cm diameter or more, and have no pests or other natural flaws. The optimum time for seed collection is as soon as the seeds reach maturation. This happens in October–December, when the skin of the fruit is a grey brown and the seeds have turned shiny black and have hardened. If not collected then, the seed may over-ripen and not germinate well, or be susceptible to insect attack if fruits or pods stay on the tree too long. Seed collection should be conducted when pods or fruits are still on the tree.

Seed preparation

Processing *Erythropholeum fordii* seeds is a difficult task as they have hard skin and are covered by a firm film, thus making it difficult for them to absorb water. To solve this problem, one of the following methods can be employed.

Mechanical processing combined with heating. The seeds should be rubbed on hard rough surfaces to create deep scratches, or a sharp knife should be used to cut a corner of the seeds. Once this has been done, the seeds should be soaked in warm water (60 ˚C) for

6–8 hours. All the film should be washed from around the seeds and they should be stored in a cloth bag. The seeds should be washed every day for 10–12 days, after which they should germinate. Those seeds which exhibit cracks should be chosen for sowing.

High temperature combined with chemical processing. The seeds should be soaked in potassium permanganate 0.1% for 30 minutes, then transferred to warm, weak vinegar dissolved in water, for 1–2 hours. Next the seeds should be poured out into big, open baskets and rubbed hard to remove the film. Once this has been done, the seeds should be soaked in boiling water (100 ˚C) then left to cool down and stand for 10–15 hours. At this point, those seeds which are enlarged should be selected and put into a cloth bag to keep warm until they begin to crack. Seeds still haven't enlarged after soaking could be soaked for another 3–4 hours.

Seed storage and viability

Erythropholeum fordii seeds can be stored using one of the following methods:

(i) **Dry storage in a suitable room**. Put all the seeds in cloth bags and place them in jars or wooden tanks with a small amount of lime powder to encourage desiccation. Seeds can be stored this way for 1–2 years.

(ii) **Dry storage in a cold store**. Put the seeds in **polyethylene** bags with silica gel for desiccation and store at 5–10 ˚C. Seeds can be stored this way for over 3 years.

Number of seeds per kilogram: 9,500–1, 1000

Primary germination rate: over 80%

Germination rate after storage: 60–70%

5.5.3 Propagation and planting

Sowing and transplanting

Following appropriate preparation the seeds can be sown either in pots or in beds.

Sowing into pots. Use a pointed stick to drill a hole 1–2 cm deep in the soil in the middle of the pot, then put in a seed and cover it with soil. The number of seeds per pot determines the security of successful germination: e.g. 3 seeds 40–60%, 2 seeds 60–90%, 1 seed > 90%. Use sterilised straw to cover the pots and maintain humidity. It is necessary to water once a day with 3–4 litres/m^2 to keep seeds moist after sowing.

Sowing into beds. The soil in the beds should be carefully prepared for sowing. Create a bed surface 0.8–1.0 m wide and cover it with 3–5 cm of fine sand. About 5–7 days before sowing, spray the seeds with Viben C 0.3% to prevent collar rot. A day before sowing, water the beds to keep them damp. Seeds should be sprinkled evenly onto beds, at 1 kg of seeds for every 8–10 m^2, and then covered with a 1–2 cm layer of fine soil. Afterwards, the bed surface is covered with sterilised straw. The seeds should be watered every day using about 4 litres/m^2 each time. The beds need to be shaded so that the plants only receive 20–30 % sunlight. When the seeds have germinated, they should be transplanted into pots.

Transplanting seedlings into pots. Shoots of 1.0–1.5 cm long should be transplanted during cool weather or in light rain, whereas days of strong sunlight or heavy rain should be avoided. Each pot should consist of 85–89% upper layer soil, 10–15% manure and 1% phosphate. Pots should measure 9 x13 cm and should have root-training ridges. The pots should be dampened with water one day before transplanting. Use a pointed stick to drill holes in the middle of the soil of each pot, deep enough for the shoots. The shoots should be inserted so that their collars are at the pot's surface. Sticks should be used to press the soil down around the shoots.

Care for the seedlings. After transplanting, it is important to shade the plants, as they can only tolerate 10–20% sunlight during their first stages of growth. After one month, the shading could be reduced to allow 30% sunlight to filter through, and after 45 days it can be removed completely. The plants should be watered once a day for the first 15 days: if it is hot and dry, this should be increased to twice a day. Afterwards, they should be watered every 2–3 days. The amount of water depends on the weather, but it is vital to keep the pots damp (3–4 litres/m^2): excessive watering, however, could cause disease and should be avoided.

About every 15–20 days, the pots in which the seedlings are being stimulated should be combined and the 2-month-old seedlings should be classified: the seeds in the pots should be stimulated for growth for the last time 3–4 weeks before being planted out.

When the seedlings growth is slow, top dressing should be applied. The first 3 months apply this dressing once a month: nitrogen/phosphorus/potassium (NPK) (5:10:3) at a concentration of 1% (0.1 kg/10 litres of water). Water the area with 3litres/m^2. It is recommended to water the plants in the early morning or evening and then thoroughly wash the leaves with clean water (2.5litres/m^2) to prevent diseases (Duc, 2004).

Preparation of planting site

Generally, increased tree growth and survival can be achieved through increased site cultivation. The degree of slope and level of soil compaction are the primary factors which influence the ability to conduct extensive site cultivation. Before cultivating, slashing or burning should be carried to reduce the existing vegetation as far as possible, in order to improve the ease of site access for heavy machinery and thereby effective soil cultivation.

Cultivation provides a better soil tilth for planting and can be achieved with a wide range of implements. Cultivation should be planned for a period when the soil is not too wet, avoiding soil compaction and damage to soil structure. Cultivation should be carried out well ahead of planting to allow the soil to settle. One month before planting, holes measuring 40 x 40 x 40 cm should be dug, arranged in a quincunx pattern, in two corridors.

The holes should be filled with soil and clean weeded at least 10–15 days before planting (Kha, 2004).

Planting

The criteria for selecting seedlings to be planted out should be as follows: (1) seedlings should be 16–18 months old, green, well proportioned, pest-free, with best quality: (2) seedlings should be 40–50 cm in height and the diameter of root collar should be above 0.8 cm: (3) pots should be intact and seedlings should have many small, well developed roots (Duc, 2004).

The planting operation itself should ideally be done in drizzle or on an overcast day. The planted holes should be banked up, without stones and weeds. If the plantation is to be established by direct sowing, 3–4 seeds should be placed in each hole, which should then be covered with a soil layer 1.0–1.5 cm thick. When using seedlings, shade giving trees should be maintained in the vegetative belts to assure 50% sunlight. *Erythropholeum fordii* should be planted with varying spacing and with a maximum density of 1,100 trees/ha, or 1,600 trees/ha at most (Kha, 2004).

5.5.4 Plantation maintenance

Early and sustained weed management and fertiliser treatment, and occasional watering in are all key elements in the successful establishment of an *Erythropholeum fordii* plantation. The appropriate stocking rate (planting density) must be established in order to promote optimum growth rates and efficient plantation management.

Weeding

Weed control is necessary to reduce the competition for water and nutrients between trees and weeds. Competition from weeds severely decreases early tree performance, and weed growth can be prolific in subtropical and tropical regions. Weed control before planting and for at least 12 months after should be considered essential for successful plantation establishment. A 2 m-wide weed free strip should be established along each planting row during the first 2 years (Kha, 2004).

Fertilising

Trees require nutrients to live and thrive: when a soil is nutrient poor, trees will not reach their full potential, will be more susceptible to disease and insect problems and will have a shorter lifespan than similar, well fertilised trees. Fertiliser products aimed at providing trees with the appropriate nutrients abound. Organic and inorganic fertilisers may be administered in a combination which allows nutrients to be delivered to a plant rapidly and for an extended period of time. Generally, fertiliser is applied at the time of planting and 6 months after planting. The most commonly use fertilisers are NPK and those based on micro-organisms. An indicator of the need for fertilisation is the history of the nursery. Trees in nurseries that are fertilised on a regular basis rarely need supplemental fertiliser on transplantation. Fertiliser is most effective when applied just prior to a good rainfall. The best fertiliser type for common soil environments is not yet established, nor is there an acceptable financial cost–benefit analysis for fertiliser application.

Refilling

The first refilling is usually done in the rainy season, 1 month after planting, to replace dead rooted cuttings or clonal plants, and the second is carried out at the end of the second year. If the survival rate is less than 70% further replanting is necessary for large scale plantations.

Pruning

The purpose of pruning is to encourage trees to develop a straight stem and more valuable, knot-free trunks. High density plantations will have lower pruning costs than lower density plantations. The greater the initial distance in tree spacing, the more artificial pruning will be necessary to produce a clear bole. The closer the spacing of trees in a higher density plantation, the more they will be forced into an upright growth habit. The resultant lack of light will increase natural pruning of the lowest branches.

Pruning some branches increases the growth rate of the remaining branches (Ramos *et al*., 1998). In contrast, careless pruning can significantly reduce growth, introduce disease and reduce timber value. When the trees reach 2 years of age, pruning in late winter can begin to develop a single stem. Pruning should be done with great care in order to avoid damage to the branch collar and the branch bark bridge, which can lead to disease. Pruning tools should always be cleaned and sharpened to ensure a clean, smooth cut.

Thinning

Thinning is a meaningful interference in the life of a stand to reform its growth and development to obtain certain objectives (Turnbull, 2004). Thinning is the process that artificially reduces the number of trees growing in a stand. Generally, it can be conducted several times and begun a few years after canopy closure. Thinning is done for many purposes of which the paramount ones are: (i) to decrease the number of trees in a stand so that the remaining ones have more space for crown and root development to encourage stem diameter increment (ii) to eliminate the dead, dying and diseased trees which may be a source of or which may encourage pest and disease attack (iii) to remove trees of poor form (iv) to prefer the most vigorous trees with good form for final crop, (v) to furnish intermediate financial return from sales of thinning. Regular thinning would be conducted when the plantation is 3, 5 and 7 years old.

6 Results and discussion

6.1 Stand parameters

6.1.1 Stand structure

6.1.1.1 Diameter distributions

The diameter distribution of a stand is required to construct stand tables, estimate the total or merchantable stand volume and estimate the volume of a wide range of products, which are recovered from a stand of a given mean diameter and mean height (Van Laar and Akça, 1997). In a forest stand, the tree diameter is easy to measure. In both natural and plantation forests, the diameter distribution of trees is a useful expedient for describing forest structure and applying different forestry calculations (Loetsch *et al.*, 1973). There are numerous functions accessible to exemplify diameter distributions. According to Zutter *et al.* (1986), the WEIBULL distribution has been applied most widely to fit the diameter distributions of forest stands. In this study, the WEIBULL probability density function (pdf) for three parameters was used and the function is as follows:

$$f(x) = \frac{\beta}{\gamma}\left(\frac{X-\alpha}{\gamma}\right)^{\beta-1} * \exp\left[-\left(\frac{X-\alpha}{\gamma}\right)^{\beta}\right] \qquad \textbf{(6.1)}$$

Where,

X = Diameter at breast height (dbh)
α = Location parameter
β = Shape parameter
γ = Scale parameter

The location parameter α gives the minimum value of the distribution (the minimum diameter). The shape parameter β determines the skewness of the distribution. The scale parameter γ is related to the range of distribution. There are two means that can be used to indicate the parameters of the function, a) the parameter forecast mean and b) the parameter improvement mean. In this study, the three-parameter WEIBULL function was applied to obtain the most suitable fitting. XL STAT, 2011 software (developed by the Kovach Computing Services, Anglesey and Wales) was used for this purpose. Here, the parameter forecasting mean was used and the estimation method was the maximum likelihood method. The scale in the y-axes of the graphs shows the probability density function (pdf) and the x-axes show the diameter classes to assist in the comparison of graphs with the same scale framework.

To determine WEIBULL distribution for all age classes of the selected species, the Kolmogorov-Smirnov test was applied by comparing calculated p value with the significant alpha value 0.05. It was observed that all the distributions are following the three-parameter WEIBULL distribution. Figures 6.1 and 6.2 indicate the dynamics of the diameter distribution for each corresponding species over different ages. It is obvious that the development of diameter classes increases with increase in age and the trivial for distribution of broader width classes.

All selected species were planted under different management regimes and the number of trees/ha varied among species. The model parameters and the clarified variance of the eq 6.1 for selected species are shown in tables 6.1 and 6.2. The diameter distributions for the 1- and 5-year-old stands of *Acacia* hybrid and *Eucalyptus urophylla* stands are given in figure 6.1.

In the Binh Dinh Province, *Eucalyptus urophylla* stands with 1-year-old trees had a higher percentage of smaller diameter trees with lower probability density than the *Acacia* hybrid stands. However, stands with trees of age 5 years had a medium percentage of larger diameter trees with low probability density for both species.

Table 6.1: Age classes, parameter values and variances of three- parameter WEIBULL distributions for *Acacia* hybrid and *Eucalyptus urophylla* stands in the Binh Dinh Province.

Species	Age (years)	Parameter values			mean	variance
		α	β	γ		
Acacia hybrid	1	0.354	2.808	1.730	1.894	0.359
	2	-1.956	4.204	8.295	5.626	3.721
	3	-2.660	4.769	11.420	7.858	5.606
	4	-4.744	5.357	15.388	9.435	9.436
	5	0.583	3.048	10.363	9.863	10.600
	6	2.548	2.760	8.702	10.293	10.368
Eucalyptus urophylla	1	-0.274	3.393	2.984	2.406	0.769
	2	-1.798	3.331	7.243	4.793	4.090
	3	-4.012	4.906	12.028	7.112	5.504
	4	-0.455	2.777	9.037	7.611	7.359
	5	6.526	18.445	-4.676	12.539	8.869

Moreover, based on the variance results, 1- and 5-year-old stands of *Eucalyptus urophylla* had larger mean diameter than same age stands of *Acacia* hybrid in the Binh Dinh Province. But others ages of *Acacia* hybrid stands had larger mean diameter than *Eucalyptus urophylla* because of site difference among the species. Smallholders cannot decide only knowing the mean diameter but they should also take into consideration site differences among the species.

Under different management practice, the number of trees/ha varied among the species. *Acacia* hybrid had the lower number of trees/ha at 909, while *Eucalyptus urophylla* had 884 trees/ha. Due to low crowding, many diameter classes were observed in *Acacia* hybrid.

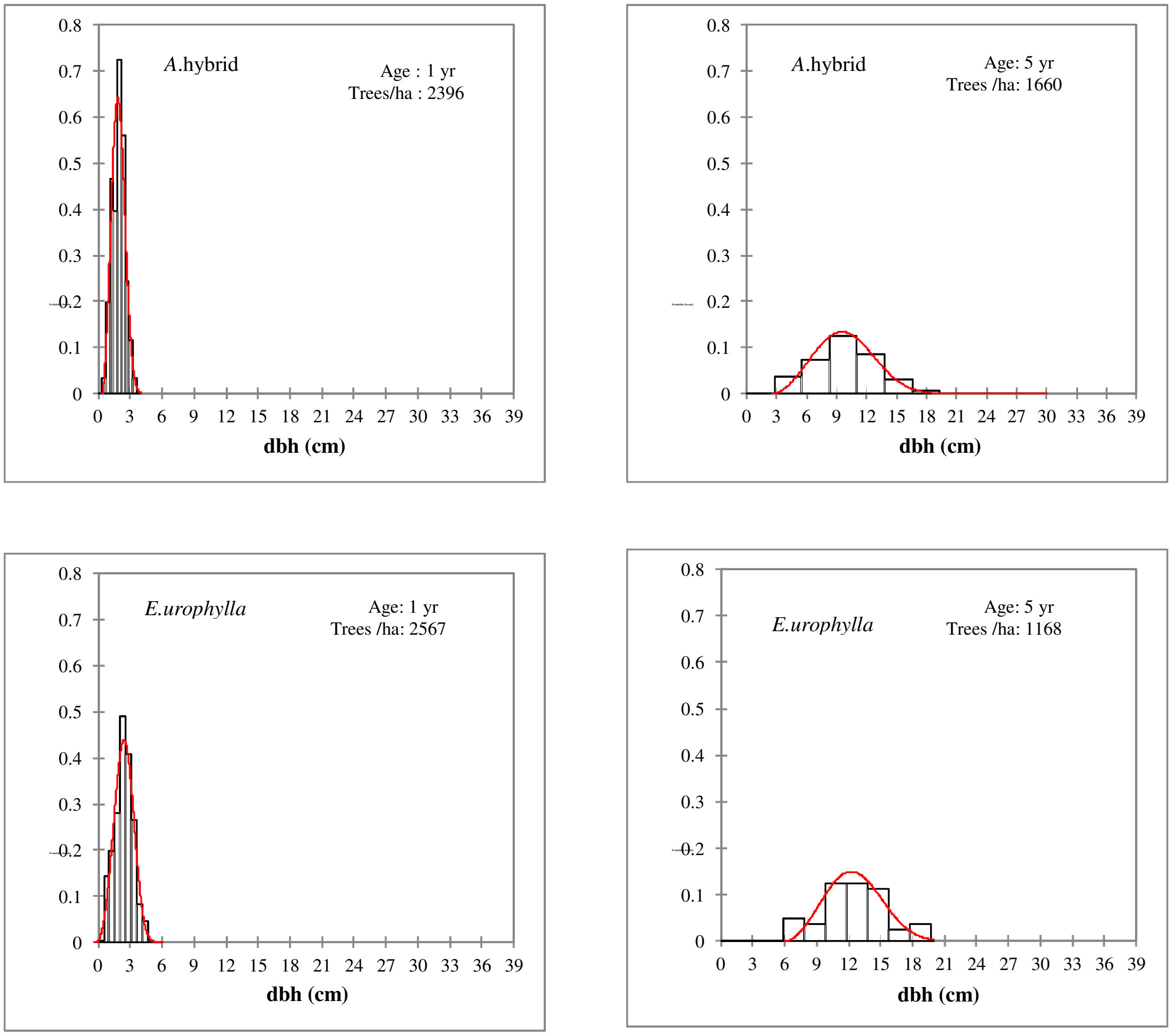


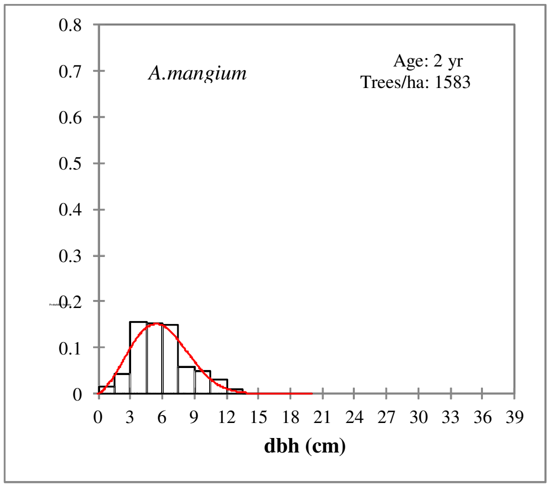
Figure 6.1: Diameter distributions (the three- parameter WEIBULL function) of 1 and 5 year old stands of *Acacia* hybrid and *Eucalyptus urophylla* in the Binh Dinh Province.

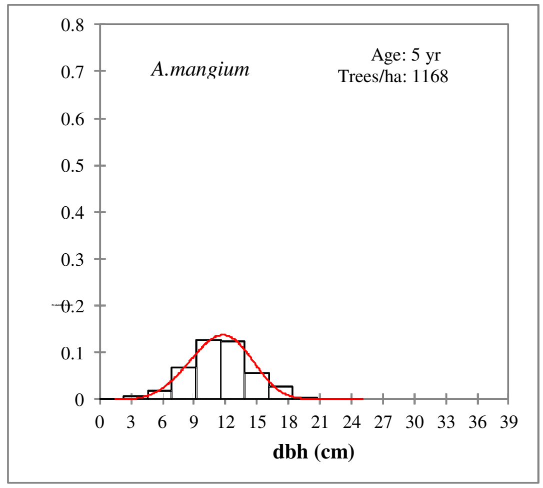
Table 6.2: Age classes, parameter values and variances of three-parameter WEIBULL distributions for *Acacia mangium* and *Eucalyptus urophylla* stands in the Phu Tho Province.

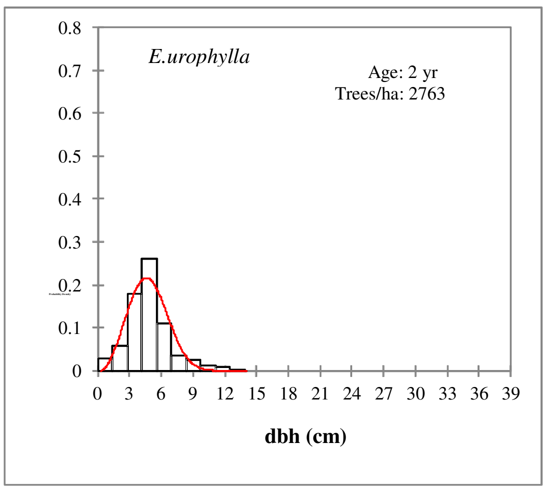
Species	Age (years)	Parameter values			mean	variance
		α	β	γ		
Acacia mangium	1	0.647	1.777	4.488	4.682	5.168
	2	-0.099	2.530	6.719	5.876	6.348
	3	-1.608	4.062	10.883	8.273	7.293
	4	-0.784	3.419	10.355	8.613	8.301
	5	-5.391	5.920	18.103	11.480	9.447
	6	0.372	3.007	14.186	13.401	18.463
	7	4.837	3.293	10.180	13.973	9.205
Eucalyptus urophylla	1	-0.038	2.515	3.715	3.253	2.013
	2	0.409	2.126	4.741	4.627	4.246
	3	0.083	2.713	7.169	6.460	6.417
	4	0.913	1.665	3.198	3.792	3.800
	5	1.142	2.306	6.542	6.990	7.250

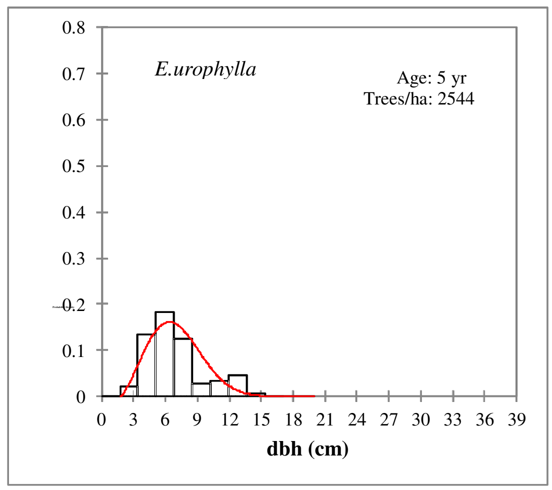
Table 6.3: Age classes, parameter values and variances of three- parameter WEIBULL distributions for *Cinnamomum parthenoxylon and Erythropholeum fordii* stands in the Phu Tho Province.

Species	Age (years)	Parameter values			mean	variance
		α	β	γ		
Cinnamomum parthenoxylon	2	0.852	2.205	2.512	3.074	1.310
	3	1.707	2.075	2.261	3.711	1.047
	5	1.370	2.463	2.734	3.795	1.156
	11	-2.152	4.937	16.951	13.372	14.232
	17	1.340	2.373	11.898	11.988	22.614
Erythropholeum fordii	2	0.693	2.964	2.185	2.644	0.510
	3	0.715	3.224	3.599	3.943	1.179
	5	0.586	3.268	4.036	4.199	1.549
	6	1.325	2.525	3.013	3.996	1.317
	13	2.679	2.002	13.540	14.712	39.454
	16	9.573	3.282	7.695	16.468	5.602
	17	2.467	3.618	13.801	15.036	13.082
	23	5.402	2.756	14.636	18.408	27.110


A.mangium
Age: 2 yr
Trees/ha: 1583
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8
0 3 6 9 12 15 18 21 24 27 30 33 36 39
dbh (cm)


A.mangium
Age: 5 yr
Trees/ha: 1168
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8
0 3 6 9 12 15 18 21 24 27 30 33 36 39
dbh (cm)


E.urophylla
Age: 2 yr
Trees/ha: 2763
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8
0 3 6 9 12 15 18 21 24 27 30 33 36 39
dbh (cm)


E.urophylla
Age: 5 yr
Trees/ha: 2544
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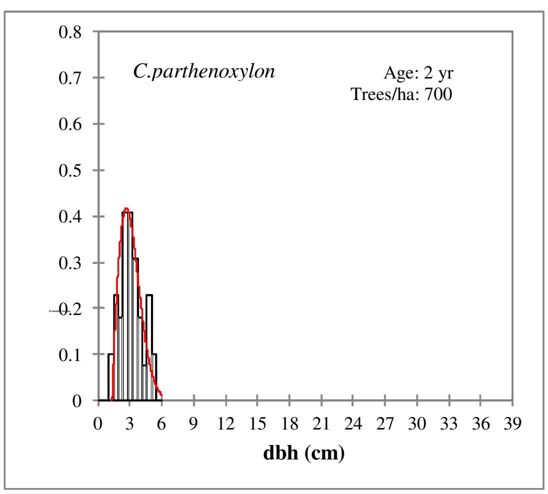
0 3 6 9 12 15 18 21 24 27 30 33 36 39
dbh (cm)


C.parthenoxylon
Age: 2 yr
Trees/ha: 700
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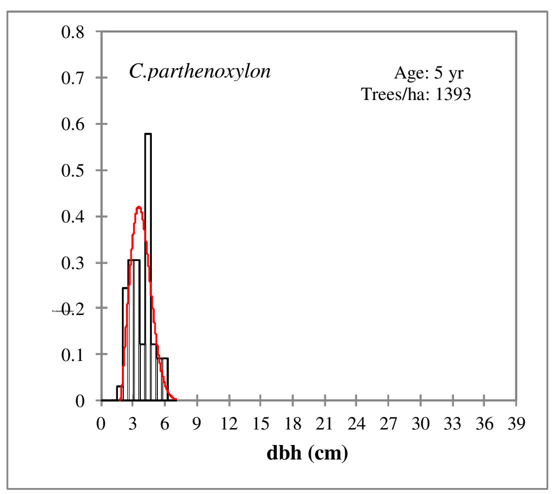
0 3 6 9 12 15 18 21 24 27 30 33 36 39
dbh (cm)


C.parthenoxylon
Age: 5 yr
Trees/ha: 1393
0 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8
0 3 6 9 12 15 18 21 24 27 30 33 36 39
dbh (cm)

(Continued)

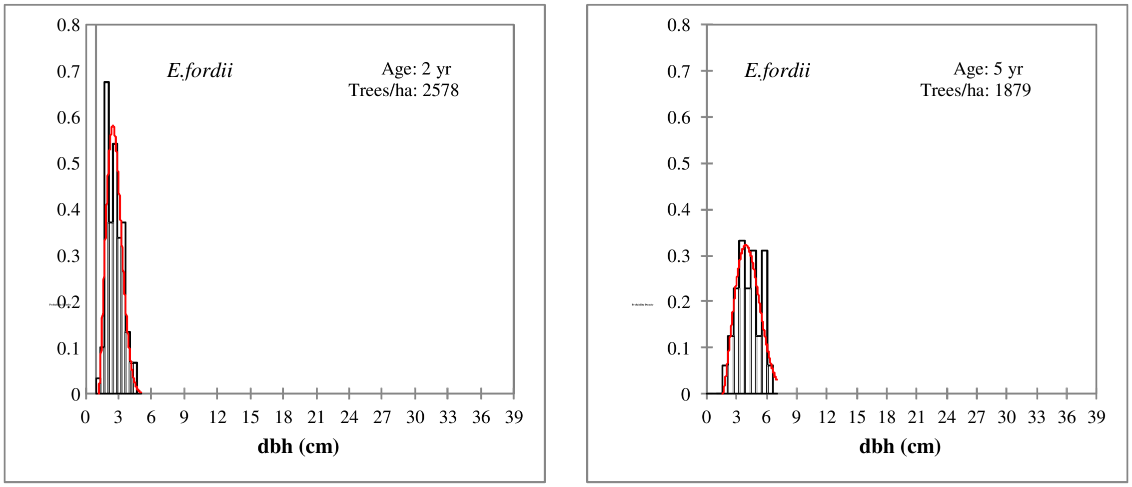


Figure 6.2: Diameter distribution (three-parameter WEIBULL functions) of 2 and 5 year old stands of *Acacia mangium*, *Eucalyptus urophylla*, *Cinnamomum parthenoxylon* and *Erythropholeum fordii* for different ages in the Phu Tho Province, Vietnam.

In the Phu Tho Province, the diameter distributions for 2- and 5-year-old *Acacia mangium, Eucalyptus urophylla*, *Cinnamomum parthenoxylon* and *Erythropholeum fordii* stands are given in figure 6.2. 2-year-old trees of *Acacia mangium* and *Eucalyptus urophylla* stands had same percentage of smaller diameter and *Acacia mangium* had lower probability density than *Eucalyptus urophylla*. 5-year-old stands of *Acacia mangium* had a higher percentage of larger diameter trees with relatively low probability density than the *Eucalyptus urophylla* stands.

On the other side, due to the results of variance, 2- and 5-year-old stands of *Acacia mangium* had larger mean diameter than same aged stands of *Eucalyptus urophylla*. For two 2-year-old stands of native species, *Cinnamomum parthenoxylon* had same percentage of smaller trees but lower probability density than *Erythropholeum fordii.* For 5-year- old stands, *Erythropholeum fordii* had same percentage of smaller diameter trees but lower probability density than *Cinnamomum parthenoxylon.* According to the results of variance, 2-year-old stands of *Cinnamomum parthenoxylon* had larger mean diameter than same age stands of *Erythropholeum fordii*. However, for 5-year- old stands of *Erythropholeum fordii*: it had larger mean diameter than same age of *Cinnamomum parthenoxylon.* Both of them are slow growing, native species so that it is difficult to distinguish the diameter of younger plantations. For older plantation, 17 year- old stands of *Cinnamomum parthenoxylon* had smaller mean diameter than same age of *Erythropholeum fordii.*

The two native species showed a lower number of trees/ha due to the wider spacing in plantation establishment. *Acacia mangium* had the lowest number of trees/ha, which amounted to 508, while *Eucalyptus urophylla* amounted to 904, *Cinnamomum parthenoxylon* and *Erythropholeum fordii* amounted to 541 and 573 trees/ha.

Knowing the mean of the diameter of the selected stands will aid in making proper management decisions by allowing smallholders to accurately depict stand structure and to decide for the most profitable species in both provinces in accordant with suitable site condition.

6.1.1.2 Relationship between diameter and height

The measurement of tree height can be complicated due to the visibility of the accurate tip of the tree. Also, it is somewhat hard to observe the base of a tree in a stand with very dense undergrowth, so it becomes necessary to clear out the sampling area before measurements are made. In any case, the relationship between the diameter and height of trees is vital to estimate the respective height by measuring the dbh. Stout and Shumway (1982) developed a method to estimate site quality by means of the height and diameter of dominant and co-dominant trees, while neglecting tree age. Many additional models have been applied to clarify the relationship between diameter and height. For example, Wenk *et al.* (1990) have utilized 30 different functions in attempt to accurately determine the relationship between diameter and height. Here, 11 different models (see table 6.4) were tested using the accessible diameter and height data in this study to obtain the best fit.

The Prodan model was selected as the best fits for the selected species based on the results of the coefficient of determination (r^2). The diameter-height relationship was implemented for each age class in an individual species, i.e transition curves of height, since r^2 was not suitable to construct a diameter-height relationship for all ages of an individual species. However, age should be the same for different species in order to make comparisons of diameter-height relationships. For this reason, 5-year-old stands were selected to compare the different species in the Binh Dinh and Phu Tho Provinces. The height growth with dbh in different species of 5-year-old stands can be seen in figure 6.3 and the parameter values for the fitted Prodan model are shown in table 6.5. The smallest number of observation of *Eucalyptus urophylla* was found in the Binh Dinh province. *Acacia* hybrid and *Eucalyptus urophylla* had smallest r^2 in both provinces. It was not due to the number of observations, but could be due to site differences among the stands.

Table 6.4: Models tested for diameter-height relationship.

$h = e\^{}(a_1 + a_2 * \ln(dbh) + a_3 * (\ln dbh\^{}2)\^{}2)$	Korsun (1948)
$h = a_1 + a_2 * \ln(dbh)$	Log linear
$h = a_1 + \frac{a_2}{dbh}$	Inverse
$h = a_1 + a_2 * dbh + a_3 * dbh^{\wedge 2}$	Parabola
$h = 1.3 + \left(\frac{dbh^2}{a_1 + a_2 * dbh + a_3 * dbh^{\wedge 2}} \right)$	Prodan (1944)
$h = \left(\frac{dbh}{a_1 + a_2 * dbh} \right)^3$	Petterson (1955)
$h = 1.3 + \left(a_1 * dbh + a_2 * dbh^{\wedge 2}\right)$	Van Laar and Akca (1997)
$h = e^{\wedge}\left(a_1 + a_2 * \ln(dbh)\right)$	Van Laar and Akca (1997)
$h = e^{\wedge}\left(a_1 + a_2 * \frac{1}{dbh} \right)$	Van Laar and Akca (1997)
$h = e^{\wedge}\left(a_1 + a_2 * \ln(dbh) + a_3 * dbh\right)$	Freese (1964)
$h_i = 1.3\left(\frac{d_i}{a + b * d_i} \right)^2$	Petterson (1955)

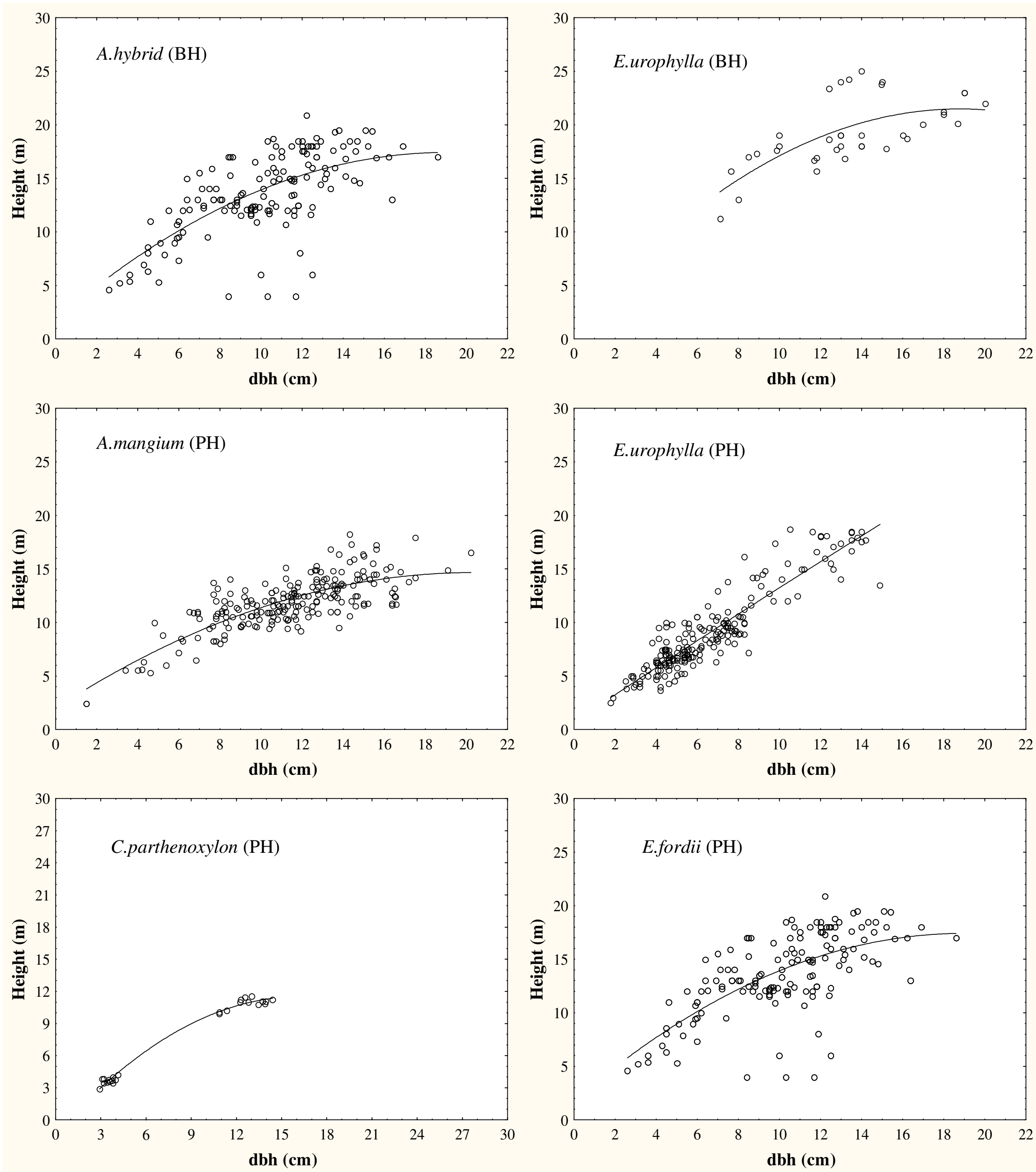
Only *Eucalyptus urophylla* occurs in both provinces. *Acacia* hybrid, *Acacia mangium* and *Eucalyptus urophylla* exhibited obvious site variation in height growth over dbh. The appropriate species for the two provinces could be distinguished by using these diameter-height curves as guides. *Eucalyptus urophylla* showed stronger height growth compared to the others in the Phu Tho Province. The performance of the fitted line for *Cinnamomum parthenoxylon* was equal to that of *Erythropholeum fordii* (see figure 6.3).

Table 6.5: Prodan model parameters of different species (age=5years).

Province	Species	a_1	a_2	a_3	N	r^2
Binh Dinh	*Acacia* hybrid	0.07716	1.74568	-12.9315	335	0.45
	Eucalyptus urophylla	0.10117	2.15331	-9.94165	41	0.45
Phu Tho	*Acacia mangium*	0.09928	1.37520	-10.1093	470	0.59
	Eucalyptus urophylla	0.06213	1.12859	-16.0905	618	0.85
	Cinnaomum parthenoxylon	0.07952	0.53346	-12.5386	63	0.74
	Erythropholeum Fordii	0.07902	0.47990	-12.6113	87	0.85

Moreover, model fitting was also applied for each species in both provinces irrespective of age factor. All models provided comparatively similar results (r^2). However, the Prodan model provided the best fit for the diameter-height relationship.

The model parameters and r^2 values for the Prodan functions for different species are shown in table 6.6 and the fitted curves (within the diameter range for each species) are displayed in figures 6.4 and 6.5.



BH: Binh Dinh Province, PH: Phu Tho Province

Figure 6.3: Diameter-height curves of *Acacia* hybrid, *Acacia mangium*, *Eucalyptus urophylla*, *Cinnamomum parthenoxylon* and *Erythropholeum fordii* (Prodan, 5-year-old stands) in the Binh Dinh and Phu Tho Provinces.

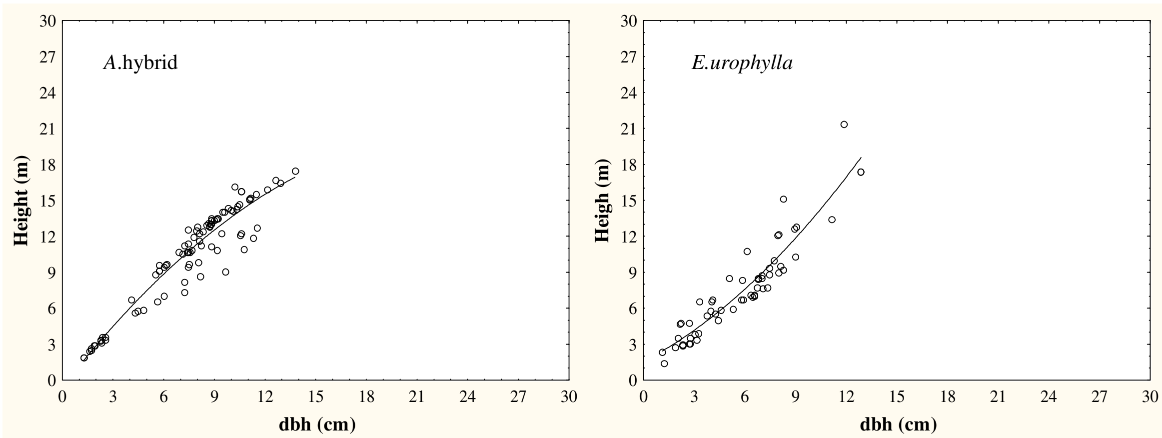


Figure 6.4: Diameter-height curves fitted by the Prodan model for *Acacia* hybrid and *Eucalyptus urophylla* in the Binh Dinh Province (age = all ages).

In accordance with figure 6.4, *Acacia* hybrid exhibits more remarkable height growth in contrast with *Eucalyptus urophylla* in the Binh Dinh Province, when different age classes are neglected. In the Phu Tho Province, *Eucalyptus urophylla* exhibits good height growth followed by *Acacia mangium*, as seen in figure 6.5. With neglect to different age classes, one could conclude that *Eucalyptus urophylla* is the best species for planting in the Phu Tho Province. *Cinnamomum parthenoxylon* exhibits poor performance in contrast to *Erythropholeum fordii*. The less good height performance of its respective dbh was likely due to undergrowth because these areas receive sufficient precipitation both by rainfall and fog interception. And also, the poor performance is due to the slow growth of the trees.

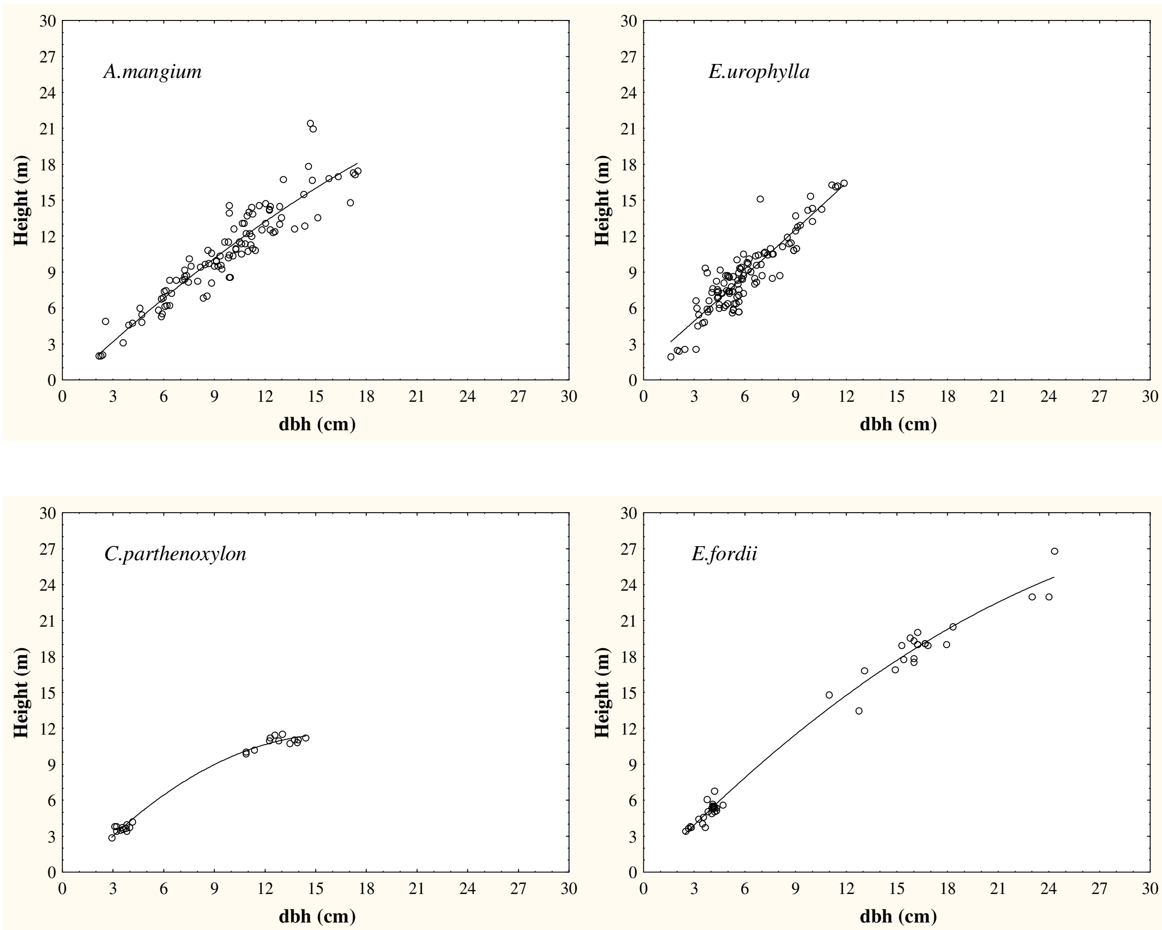


Figure 6.5: Diameter-height curves fitted by the Prodan model *for Acacia mangium*, *Eucalyptus urophylla*, *Cinnamomum parthenoxylon* and *Erythropholeum fordii* in the Phu Tho Province (age = all ages).

Table 6.6: Parameters and r^2 of diameter–height relation (Prodan fitted model, age = all ages)

Province	Model	Species	a_1	a_2	a_3	N	r^2
Binh Dinh	Prodan	*Acacia* hybrid	0.07049	1.28409	-14.1927	89	0.88
	Prodan	*Eucalyptus urophylla*	0.09956	0.80854	-10.0036	57	0.86
Phu Tho	Prodan	*Acacia mangium*	0.05449	0.94205	-18.3477	104	0.85
	Prodan	*Eucalyptus urophylla*	0.06974	1.19599	-14.3325	110	0.82
	Prodan	*Cinnamomum parthenoxylon*	0.10023	0.72875	-9.97609	25	0.94
	Prodan	*Erythropholeum Fordii*	0.06675	1.06675	-14.9355	45	0.81

The smallest r^2 value of *Eucalyptus urophylla* was found in the Phu Tho Province. It was not because of the number of observations but because of the site difference (see table 6.6). The r^2 values of the fitted curves for all species were good for both provinces. *Eucalyptus urophylla* was observed to be a poor performer in the Binh Dinh Province due to unsuitable soil. Furthermore, *Eucalyptus urophylla* shows less crown density compared to the other species. Therefore, intercropping with cassava or other soil improving agricultural crops to enhance the soil fertility should be an essential silvicultural management activity to improve the growth in these areas under management planning.

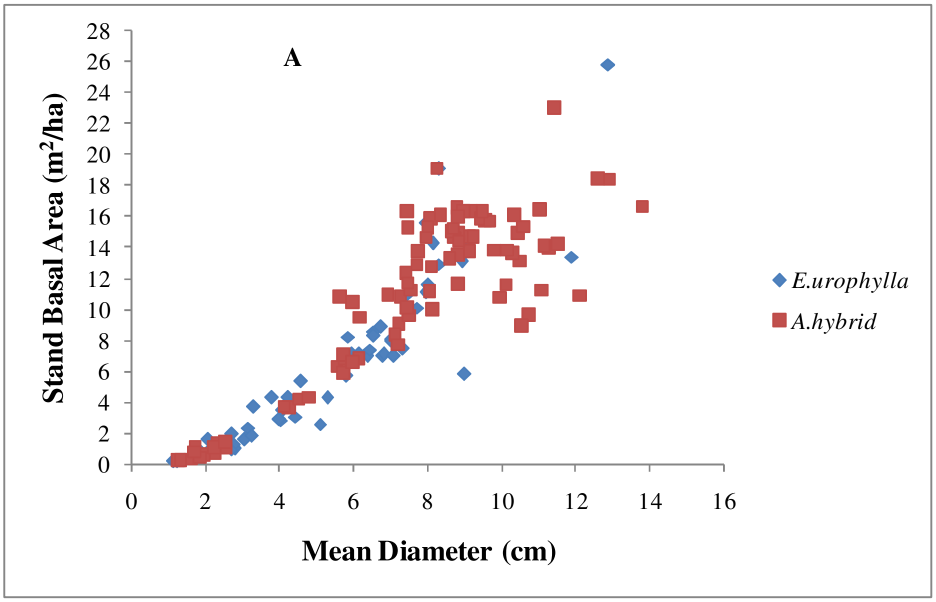
6.1.2 Stand density

6.1.2.1 Estimated basal area of stand

There are many definitions for stand density. Stand density is an important parameter to schedule the thinning regions, especially in even-aged stands. Stand density is a measure of how many trees are growing per unit area, either absolutely in terms of number of trees, basal area or volume per unit area or relative to some stand condition. Stand density can describe how much a site is being used and the intensity of competition between trees for the site's resources (i.e., water, light, nutrients, and space). At greater stand densities, the growth rates of individual trees slow down because there are more trees competing for the site's limited resources. Stand density measures are the quantative descriptions of stocking (Helm, 1998). In this study, three parameters of basal area, stand density index and relative spacing were chosen to determine stand density.

Stand basal area (SBA) is simply the cross-sectional area of all trees at breast height per hectare of forest or plantation (m^2/ha). Stand basal area can be used to estimate stand volume and is a useful measure of stand density, as it is simple to measure. Stand basal area values not only depend on the number of trees, but also on the size of trees. The relationship between stand density and average tree size is important to compare different thinning regimes for industrial plantation. Von Gadow and Bredenkamp (1992) concluded that sawn timber necessitates larger diameter trees, whereas a large stand basal area is needed for pulpwood.

The approximate average stand basal area in a moist evergreen forest is about 30 m^2 per hectare (Weidelt, 1998). The un-thinned 67-year-old stand of *Flindersia brayleyana* on basaltic soil carried a stem basal area of 78 m^2 /ha (Brown *et al*., 2004). This is similar to the basal area recorded in the Monteverde forests of Costa Rica (Nadkarni *et al.,* 2000), of which 70% was contributed by *Flindersia brayleyana*. Stand basal area may be up to 80-85 m^2/ha in a Eucalypts plantation at a productive site. The stand basal area is a suitable parameter to compare un-thinned even-aged stands of a given age and site. In this study, the maximum stand basal areas were 24.3 m^2/ha (3165 stems/ ha) and 26.6 m^2/ha (4456 stems/ha, higher number of stems because of the coppice rotation).



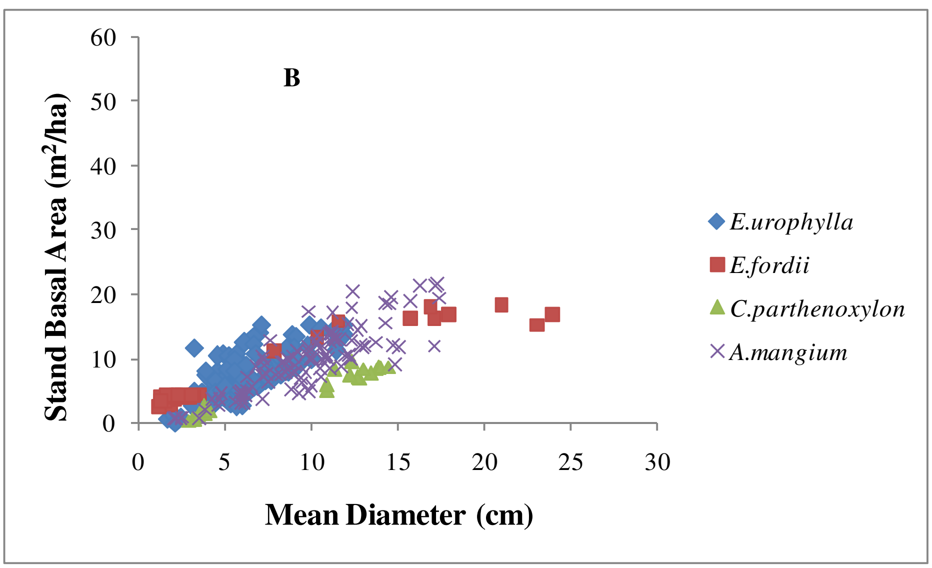


Figure 6.6: Mean diameter and stand basal area of selected species in the Binh Dinh Province (A) and Phu Tho Province (B).

The minimum were 0.9 m^2/ha (909 stems/ha) and 0.4 m^2/ha (884 stems/ha) for *Acacia* hybrid and *Eucalyptus urophylla* in the Binh Dinh Province. The maximum stand basal areas in the Phu Tho Province were 23.7 m^2/ha (2663 stems/ha), 14.7 m^2/ha (5857 stems/ha, higher number of stems because of the coppice rotation), 9.1 m^2/ha (1393 stems/ha), 19.5 m^2/ha (2578 stems/ha). The minimum were 0.54 m^2/ha (508 stems/ha), 0.20 m^2/ha (904 stems/ha), 0.46 m^2/ha (541 stems/ha) and 1.2 m^2/ha (573 stems/ha) for *Acacia mangium*, *Eucalyptus urophylla*, *Cinnamomum parthenoxylon* and *Erythropholeum fordii,* respectively. Figures 6.6- A and B shows the basal area calculated for various plots relative to their mean diameter ("mean basal area tree", definition see below) in the Binh Dinh and Phu Tho Provinces.

In most stand volume estimation models, the stand basal area plays the key role. Consequently, it is essential for the projection of potential volume to identify how one can forecast the future basal area. Hui and von Gadow (1993) developed a model that includes the stem number and top height to calculate the basal area in *Cunninghamai lanceolata* stands. A modified version of this model was applied to determine basal area in this study. This model includes the varying age and is as follows:

$$G = a * N^{\alpha} * H_d^{\beta} * t^{\delta} \qquad \textbf{(6.2)}$$

Where G = Stand basal area (m^2)

N = Number of stems (per ha)

H_d = Top height (m)

t = Age (years)

a, α, β and δ = Model parameters

The parameter values for equation 6.2 for selected species are given in table 6.7.

Table 6.7: Parameters for the estimation of the basal area of selected species in the Binh Dinh and Phu Tho Provinces.

Province	Species	Model parameter				r^2
		a	α	β	δ	
Binh Dinh	*Acacia* hybrid	0.101513	0.498291	1.113972	0.239711	0.86
	Eucalyptus urophylla	0.002095	0.669137	1.252431	0.285338	0.79
Phu Tho	*Acacia mangium*	0.005495	0.586705	1.075295	0.476531	0.78
	Eucalyptus urophylla	0.007118	0.439335	1.925507	0.130323	0.64
	Cinnamomum parthenoxylon	0.000054	0.988888	2.734492	-0.384621	0.90
	Erythropholeum fordii	0.000238	0.894656	1.765334	0.095384	0.92

The same model was used for different species, irrespective of site differences. Depending on the specific site or species, this model provides an estimation of the basal area of the stand.

In the Binh Dinh Province, *Acacia* hybrid had a high r^2 of 0.86, followed by *Eucalyptus urophylla* with an r^2 of 0.79. In the Phu Tho Province, *Acacia mangium* and *Eucalyptus urophylla* had r^2 of 0.78 and 0.64, respectively. In both provinces, a lower r^2 value of *Eucalyptus urophylla* was occurred. The two native species, *Cinnamomum parthenoxylon* and *Erythropholeum fordii* had r^2 of 0.90 and 0.92, respectively. The higher r^2 value was occurred in native species as they were older aged plantations. The smallholders can easily estimate the basal area of the stands of the five selected species by substituting the parameter values of table 6.7 in the above equation if they know top height, number of stems and age of the stand.

6.1.2.2 Stand density index (SDI)

Stand density index (SDI) has been used in past strategic-scale fire hazard assessments for determining relative stand density (Vissage and Miles, 2003, USDA Forest Service, 2005). SDI was first proposed by Reineke (1933) as a stand density assessment tool based on size-density relationships observed in fully stocked pure or nearly pure stands. It is a measure of the stocking of a stand of trees based on the number of trees per unit area and diameter at breast height of the tree of average basal area. SDI may also be defined as the degree of crowding within stocked areas by using various growing space ratios based on crown length or diameter, tree height or diameter and spacing. The number of trees per unit area is inversely related to the mean diameter of the trees. High-density stands will undergo density-dependent mortality or self-thinning. According to von Gadow and Hui (1998), this relation can be defined by a limiting line. The following model was developed by Reineke (1933):

$$N = \alpha * D_g^{\beta} \qquad \textbf{(6.3)}$$

Where, N = Number of stems per unit area

D_g = Mean diameter (mean basal area tree in cm)

α, β = Parameters

It is necessary to comprise data from un-thinned stands of different ages to determine the relationship between number of trees and mean diameter. However, as all smallholders' industrial plantations are short rotation, it is actually impossible to include an old stand. In this study, the data were collected from un-thinned stands. Parameter values for the Reineke model applied to stands in the Binh Dinh and Phu Tho Provinces are given in table 6.9.

In this study, the parameter β values ranged from -0.4345 to -1.1888 and from -0.8999 to -1.5227 for selected species in the Binh Dinh and Phu Tho Provinces. According to

Reineke's findings (1933), the parameter β value of the limiting line in several even-aged stands of different species, including Pinus and Eucalyptus, was -1.605. In South Africa, von Gadow (1986) also found that *Eucalyptus grandis* and some other pines had a limiting line value of -1.98.

Table 6.9: Parameter values of Reneike model (1933) for selected species in the Binh Dinh and Phu Tho Provinces.

Province	Species	Parameter values for Reneike model		N	r^2
		α	β		
Binh Dinh	*Acacia hybrid*	31999	-1.1888	89	0.12
	Eucalyptus urophylla	6147	-0.4345	57	0.09
Phu Tho	*Acacia mangium*	17493	-0.9199	104	0.18
	Eucalyptus urophylla	75129	-1.5227	110	0.17
	Cinnamomum parthenoxylon	7600	-0.8999	25	0.39
	*Erythropholeum fordii**				

*) To fit the curves of *Erythropholeum fordii* according to Reneike model is not possible in this study as there are many variations of mean diameter and maximum number of stems per hectares because of the gaps in some plots.

Figures 6.7 and 6.8 show the fitted curves to the Reineke model for selected species in the Binh Dinh and Phu Tho Provinces. The curves were not extended over the maximum calculated mean diameter. The highest number of trees present is 3616 trees/ha and 4456 trees/ha, given for the original spacing as 1.5 x 1.5 m and 1 x 2 m or 1.5 x 1.5 m for *Acacia* hybrid and *Eucalyptus urophylla* in the Binh Dinh Province. 2663 trees/ha, 5856 trees/ha (because of the coppice rotation of *Eucalyptus urophylla*) and 2291 trees/ha, given for the original spacing as 1 x 3 m, 1 x 2 m and 1.5 x 2 m for *Acacia mangium*, *Eucalyptus urophylla* and *Cinnamomum parthenoxylon* in the Phu Tho Province respectively.

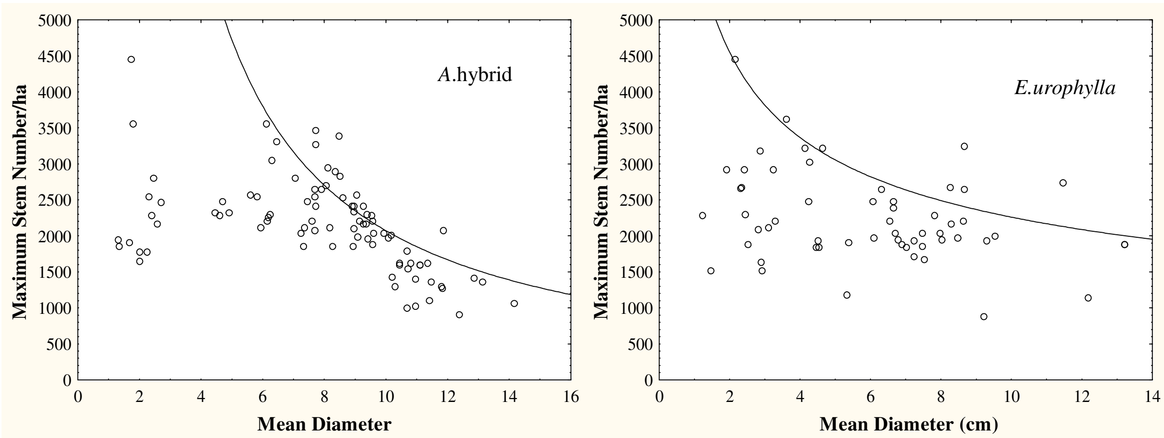


Figure 6.7: Fitted curves by the Reneike model for selected stands in the Binh Dinh Province.

Generally, 25-35 percent of the basal area is harvested depending on the growth behavior of the species. In Vietnam, thinning is not conducted for smallholder's industrial plantations. The thinning regimes for the selected species are described by the curves as shown in figure 6.7 and 6.8, indicating a slight difference among the species. Height variation of mean diameter is due to a number of reasons. The first reason is site differences. As a consequence, the limiting line could be applied to determine such site differences (von Gadow and Bredenkamp, 1992). The second reason is the difference in original spacing for plantation establishments. The third is pests and diseases, which have affected young stands. The fitted curves of all selected species represent impressive forms of 'limiting lines', which are acceptable for growing in both provinces. For instance, if the mean diameter is 8 cm, 4.8 cm, 8.5 cm, 7.8 cm and 4.8 cm, the number of stems per hectare should be 2745, 3232, 2663, 3958, 2190 per hectare for *Acacia* hybrid and *Eucalptus urophylla* in the Binh Dinh Province, and for *Acacia mangium*, *Eucalyptus urophylla* and *Cinnamomum parthenoxylon* in the Phu Tho Province, respectively (see table 6.10).

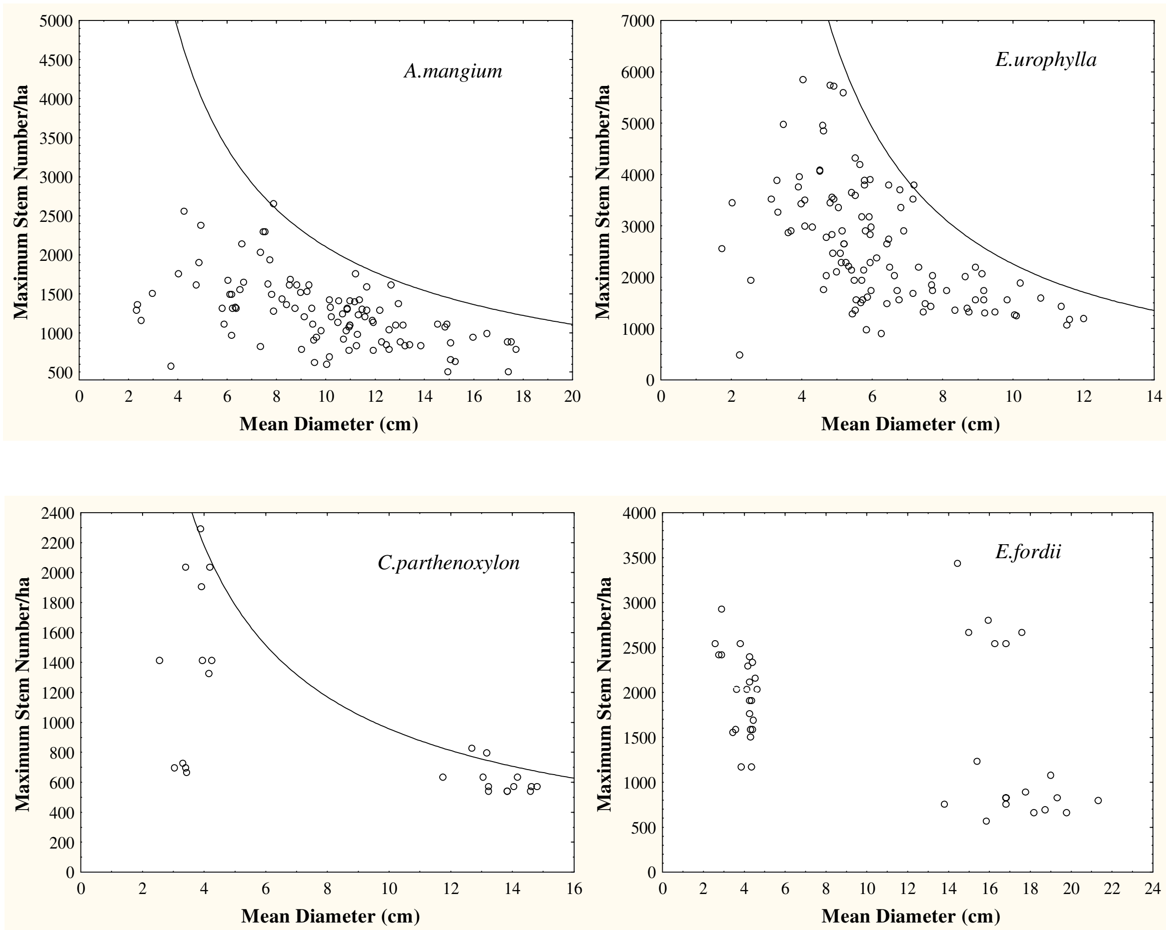


Figure 6.8: Fitted curves by the Reineke model for selected stands in the Phu Tho Province.

In South Africa, Bredenkamp (1984) observed an 80 cm mean diameter value in 22-year-old *Eucalyptus grandis*, which is very good for a fast growing species plantation. The limiting lines for all selected species can also be applied to other plantations in order to plan thinning operations. However, depending on the quality of site, the limiting line could be shifted to the origin. The general degree of crowding for a stand could be stated numerically as the projected number of trees per hectare at a specific mean diameter. When the mean diameter is 8 cm, the Reineke equation could be written as equation 6.4, which shows the maximum number of stems per hectare for the respective mean diameter.

$$N = \alpha(8)^{\beta} \qquad \textbf{(6.4)}$$

Then the SDI for any stand of given N and D_g of 8 cm is defined by the following formula:

$$SDI = N\left(\frac{8}{D_g}\right)^{\beta} \qquad \textbf{(6.5)}$$

In accordance with the above consideration, if α and β (equation 6.4) for Acacia *hybrid* is known, Reineke's N will be 2745 stems/ha when D_g is 8 cm. This means that the stand is under-stocked when the SDI value is less than 2745. For the estimation of this value with other stands, N and D_g can be substituted in equation 6.5.

Table 6.10: Example calculations for the estimation of mean diameter and number of stems per hectare in the Binh Dinh and Phu Tho Provinces.

Province	Species	D_g	No. stems/ha according to equation 6.3
Binh Dinh	*Acacia hybrid*	8	2745
	Eucalyptus urophylla	4.8	3232
Phu Tho	*Acacia mangium*	8.5	2663
	*Eucalyptus urophylla***	7.8	3958
	Cinnamomum parthenoxylon	4.8	2190
	*Erythropholeum fordii**		

*) To fit the curves of *Erythropholeum fordii* according to Reneike model is not possible in this study as there are many variations of mean diameter and maximum number of stems per hectares because of the gaps in some plots.

**) Many trees because of coppice rotation.

Thinnings can increase stand yield by utilizing merchantable trees and by maintaining rapid growth of individual trees by minimizing competition. Thinnings should be timed correctly, however, if benefits are to be maximized. Growing stock is liquidated and the stand yield is reduced when stands are thinned too early. On the other hand, the trees respond slowly, when stands are thinned too late. Thinning schedule can also be differing where site quality and management objectives differ. A more theoretical approach, the smallholders are allowed to develop thinning schedules quickly for a wide range of site qualities and management objectives by using the fitted curves according to the Reineke model in figures 6.7 and 6.8 with considering the limiting line. To fit the curves of *Erythropholeum fordii* to the Reineke model is not possible in this study as there are many variations of mean diameter and maximum number of stems per hectares because of gaps in some plots.

6.1.2.3 Relative spacing

Relative spacing (RS) is defined as the ratio of the average distance between trees to the dominant height of the stand. RS includes the number of trees and incorporates both site quality and age through dominant height. Thus, Wilson (1946) proposed that it is a useful measure of stand density for developing thinning specifications for even-aged plantations. The trend of relative spacing over time is also depending on height increment and mortality (Parker, 1978). Prior to mortality, changes in relative spacing are due primarily to height growth. With crown closure, the increasing mortality plays a more important role as changes in relative spacing are slowing down. Stands reach a minimum relative spacing value when the percentage height increment rate equals one-half of the percentage mortality rate (Parker, 1978), and then maintain it. With the neglect of site quality and initial age, all stands of a given species approach a common minimum relative spacing asymptote with time (Clutter *et al*., 1983). This statement has rarely been tested with experimental studies, except for the study of Bredenkamp and Burkhart (1990) in which they found the minimum value of relative spacing varied with the planting density for *Eucalyptus grandis* plantations. According to Clutter *et al.* (1983), the relative spacing can occasionally be mentioned as spacing index and written as follows:

$$RS = \frac{Average\ \ distance\ between\ trees}{Dominant\ Stand\ Height} \qquad \textbf{(6.6)}$$

In natural forest, it is always a large problem to measure relative spacing due to the mass variation within the same stand and complicated to determine the distance between trees of the same species. The relative spacing differs with tree species but is not affected by the site index (Bredenkamp and Burkhart, 1990). As a result, the relative spacing is more relevant in a stand where trees have relatively similar distance. In plantations, the trees which have square spacing, relative spacing can be resolute as:

$$RS = \frac{\sqrt{10000/N}}{H_d} \qquad \textbf{(6.7)}$$

Where N = Number of trees per hectare

H_d = Dominant stand height / Top height (m)

Bredenkamp and Burkhart (1990) found that relative spacing is closely related to age: hence displaying an inverse-J shaped curve. The curve's slope will be increasing with increasing stems per unit area i.e variance of RS increasing with the increasing number of stems/ ha i.e with decreasing age. Despite the consequences of site quality and initial age, all stands of a specified species move towards a general minimum relative spacing value with ongoing age. When the dominant height increases with time and the number of stems per unit area is comparatively stable, this inverse curve could be gained and the relationship can be articulated as follow:

$$RS = \beta_0 + \beta_1 * t^{\beta_2} \qquad \textbf{(6.8)}$$

Where t = Age (yrs)

β_0, β_1 and β_2 = Parameters

According to Wilson's rules of thumb (1946, 1979), with square spacing, the proper minimum and maximum relative spacing are 0.14 and 0.16, for spruce, 0.16 and 0.20 for white pine, 0.16 and 0.24 for red pine and 0.20 and 0.25 for Jack pine. For loblolly pine plantations, the minimum and maximum relative spacing are 0.20 and 0.30 respectively.

Relative spacing was calculated for each species using the equation 6.7. The minimum observed relative spacing of *Acacia* hybrid and *Eucalyptus urophylla* in the Binh Dinh Province was 0.17 and 0.15 and the maximum observed RS was 0.90 and 0.73 respectively. The maximum number of observed trees per hectare was found to be 3165 at the age of 2 years for *Acacia* hybrid and 4456 at the age of 3 year for *Eucalyptus urophylla* from the time of being planted (see table 6.11).

Table 6.11: Relative spacing value for selected species with different age and stem number using equation 6.7 in the Binh Dinh Province.

Species	Age	Trees/ha	RS
Acacia hybrid	1	2396	0.71
	2	3165	0.90
	3	2279	0.49
	4	1917	0.27
	5	1660	0.19
	6	909	0.17
Eucalyptus urophylla	1	2567	0.65
	2	2330	0.38
	3	4456	0.73
	4	884	0.15
	5	1168	0.22

The minimum observed relative spacing of *Acacia mangium, Eucalyptus urophylla, Cinnamomum parthenoxylon and Erythropholeum fordii* in the Phu Tho Province was 0.21, 0.22, 0.25, 0.23 and maximum observed RS was 0.53, 0.80, 0.65 and 0.74 respectively. The maximum number of observed trees per hectare for the different species was found to be 2663 for *Acacia mangium* at the age of 1 year, 5857 for *Eucalyptus urophylla* at the age of

Table 6.12: Relative spacing values for selected species with different age and stem number using equation 6.7 in the Phu Tho Province.

Species	Age	Trees/ha	RS
Acacia mangium	1	2663	0.53
	2	1583	0.44
	3	1343	0.32
	4	1339	0.28
	5	1168	0.25
	6	1093	0.22
	7	508	0.21
Eucalyptus urophylla	1	3698	0.61
	2	5857	0.80
	3	2763	0.56
	4	2527	0.31
	5	2544	0.38
	6	904	0.22
Cinnamomum parthenoxylon	2	700	0.32
	3	1451	0.65
	5	1393	0.56
	11	541	0.25
	17	707	0.36
Erythropholeum Fordii	2	2578	0.74
	3	1958	0.60
	5	1879	0.55
	6	1721	0.31
	13	1780	0.39
	16	828	0.24
	17	836	0.26
	23	573	0.23

2 year, 1451 for *Cinnamomum parthenoxylon* at the age of 3 years, 2578 for *Erythropholeum fordii* at the age of 2 years from the time of being planted (see table 6.12). The stem number for the fitted curves based on r^2 values ranged from 884 to 4456 stems

per hectare in the Binh Dinh Province and from 508 to 5857 stems per hectare in the Phu Tho Province (see table 6.11 and 6.12).

The fitted curves between RS and age for different ages at various stem numbers of selected species using equation 6.8 are given in figures 6.9 and 6.10 respectively. In this study, low r^2 values of *Eucalyptus urophylla* for both provinces were observed (see table 6.13). This may be because of less age groups were included in a particular stem number. Bredenkamp and Burkhart (1990) found that the RS for limiting stand density of *Eucalyptus grandis* was to be 0.05, which was derived from the stand having 6726 stems per hectare.

Table 6.13: Parameters and r^2 values of the fitted curves between RS and age of selected species using equation 6.8.

Province	Species	Model parameter			r^2
		β_0	β_1	β_2	
Binh Dinh	*Acacia* hybrid	0.16339	0.61304	-2.75457	0.78
	Eucalyptus urophylla	0.07431	0.60015	-1.15514	0.52
Phu Tho	*Acacia mangium*	0.20509	1.58064	-2.46941	0.60
	Eucalyptus urophylla	0.21597	2.12256	-4.44616	0.42
	Cinnamomum parthenoxylon	0.25800	0.91288	-1.16193	0.86
	Erythropholeum fordii	0.15007	1.32291	-1.03096	0.85

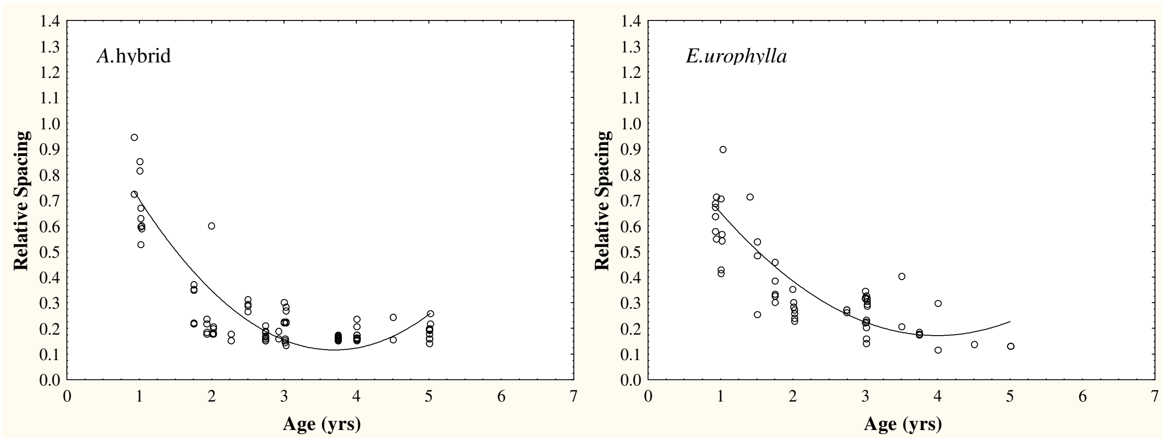


Figure 6.9: Age-relative spacing relationship of selected species in the Binh Dinh Province.

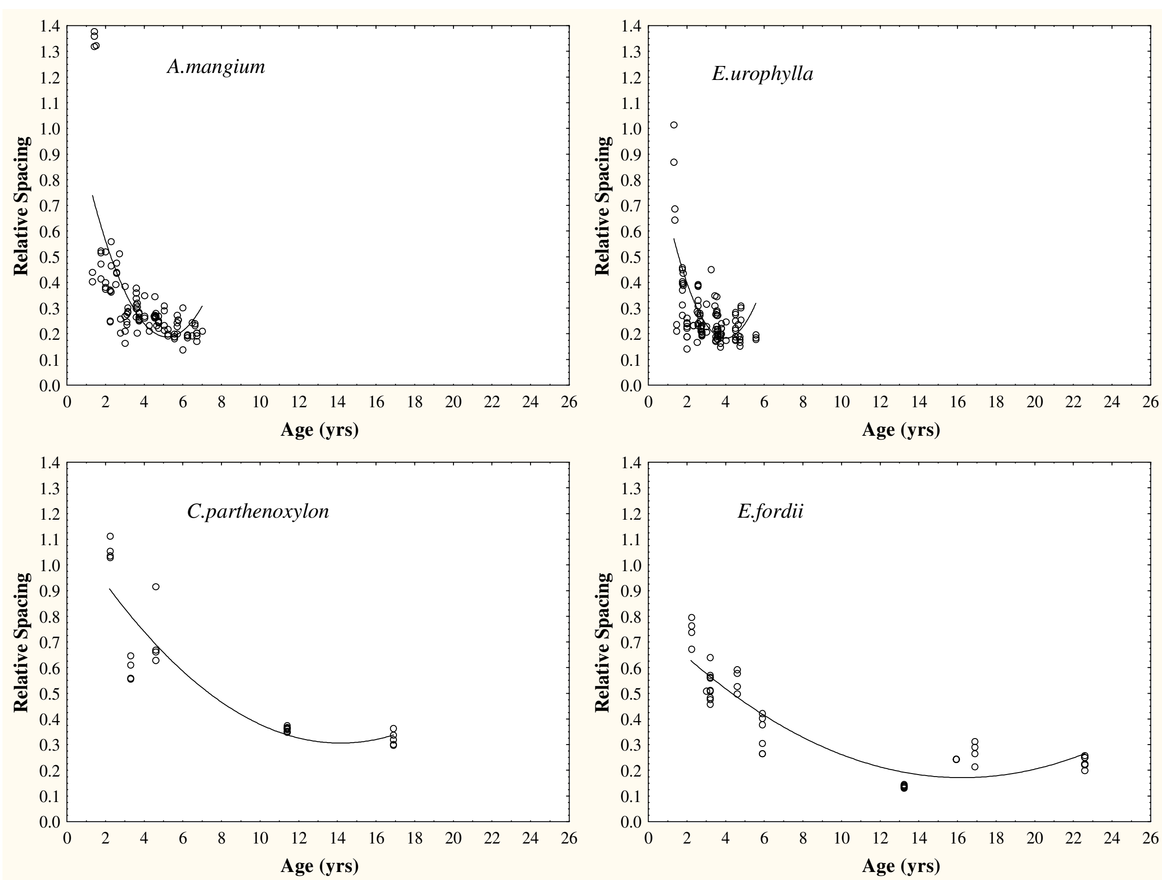


Figure 6.10: Age-relative spacing relationship of selected species in the Phu Tho Province.

The relative spacing index is used to define the thinning weight. Moreover, a thinning schedule could be defined by combining the thinning interval, in terms of dominant height growth, with the thinning weight defined as the increment of the relative spacing index value that guarantees stand stability after thinning. Abetz (1975) had built up such a guide curve for the European spruce plantations. The relationship between age and relative spacing of the selected species are developed as shown in figures 6.9 and 6.10 to define the thinning weight in the Binh Dinh and Phu Tho Provinces. However, according to (von Gadow and Bredenkamp, 1992), present thinning programmes are not scheduled based only on relative spacing.

In addition, smallholders can use the relative spacing index to define the thinning weight. As in consequence, a thinning schedule could be defined in terms of dominant height growth with the thinning weight.

6.1.3 Volume Production

In forestry, it is indispensable to estimate the volume of a stand based on variables measured in the field. Since volume production is usually the growth parameter of greatest interest to the forest manager, an evaluation of site productivity in terms of volume is desirable (Sammi, 1965). There are a number of practical approaches to determine stand volume. It can be calculated by means of other correlated variables such as basal area, tree height, form factor and sometimes stand age. The measurement of volume production as a guide to site productivity in plantations is used in Germany (Shrivasta and Ulrich, 1976), Sweden (Johnston *et al*., 1967) and Britain (Johnston and Bradley 1963, Bradley *et al*., 1966) as well as in a number of other countries (e. g. France, Finland, Norway). Estimates of volume production are helpful in planning when to harvest or how much to remove in a thinning operation. These estimates can also assist with financial analysis and the tax implications of a timber harvest. There are two main approaches to estimate volume production. The first one is by stem analysis, wherein calculations are derived from the segmented stems and the second one is by estimation via obtainable volume equations or volume tables.

The dbh, height and form factor are the parameters required for the basic volume estimation of a single tree. The stem mass can be stated either in volume or in weight, depending on the final product. Likewise, there are two options for measurement of tree height: total height and merchantable height. The normally used measures of stem form (form factor) are fractions of volume of a tree related to a pillar with diameter equal to tree dbh. The volume equation may be commonly written as follows:

$$V = f(D, H, F) \qquad \textbf{(6.9)}$$

Where V= Stem Volume

D= Stem diameter at breast height

H= Stem Height

F= Stem Form factor

6.1.3.1 Relationship between single tree volume and basal area

The relationship between volume and basal area enables the estimation of individual tree volume by measuring only the dbh (basal area). It is impossible to assess all variables for every tree in each sample plot due to the limitation of time and money. In both natural forests and plantations, dbh measurements can be attained at low cost. It is difficult to measure the heights of large dense stands. In forest management, dbh measurement is a regular practice, particularly in plantations. The allometric regression was applied to fit the following equation for selected species.

$$V = \alpha * g^{\beta} \quad \textbf{(6.10)}$$

Where

V= Individual tree volume, up to top diameter 5 cm (m^3)

g= Individual tree basal area (m^2)

α and β= Intercept and regression coefficient

The relationship between volume and basal area of individual trees using equation 6.10 are shown in figures 6.11 and 6.12 and the parameters are given in table 6.14. The relationship between individual tree basal area and respective volume for all the species proved to be observed strong. *Acacia* hybrid appears to be the best volume manufacturer compared to *Eucalyptus urophylla* in the Binh Dinh Province.

Table 6.14: Parameter values for the relationship between volume and basal area of individual trees using equation 6.10 for selected species in the Binh Dinh and Phu Tho Provinces.

Province	Species	Parameter values		r^2
		α	β	
Binh Dinh	*Acacia* hybrid	15.450	1.171	0.92
	Eucalyptus urophylla	57.967	1.498	0.92
Phu Tho	*Acacia mangium*	22.930	1.281	0.94
	Eucalyptus urophylla	22.840	1.289	0.92
	Cinnamomum parthenoxylon	21.611	1.319	0.95
	Erythropholeum fordii	15.809	1.215	0.95

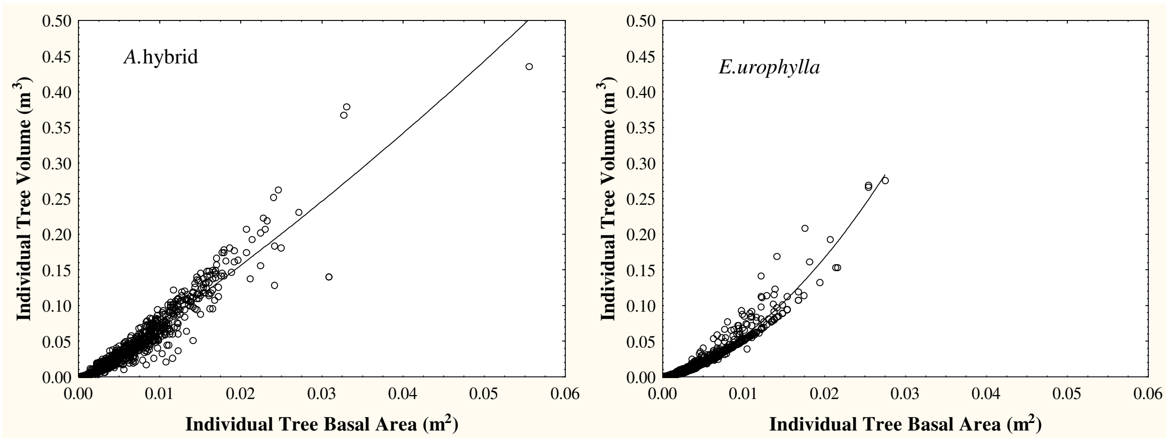
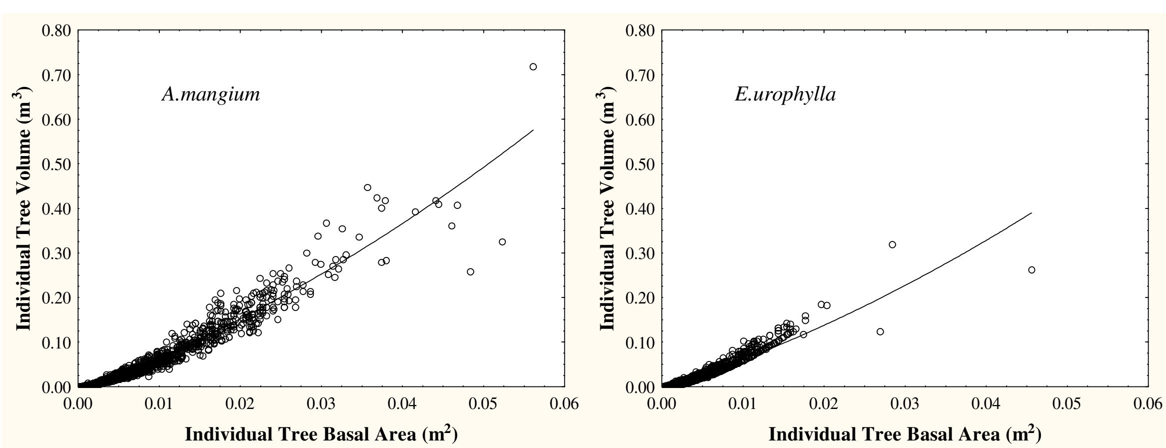


Figure 6.11: The relationship between volume and basal area of selected species in the Binh Dinh Province.

Acacia mangium appears to be the greater volume producer in contrast to other species, and then followed by *Erythropholeum fordii* and *Cinnamomum parthenoxylon* in the Phu Tho Province. *Eucalyptus urophylla* shows poor volume production in both provinces. The two native species had 95% of volume variations. This can be because of the older harvesting age of these plantations. The fitted lines for each species were extrapolated only within the observed individual tree basal area (dbh). That is, there was no extrapolation in figures 6.11 and 6.12.



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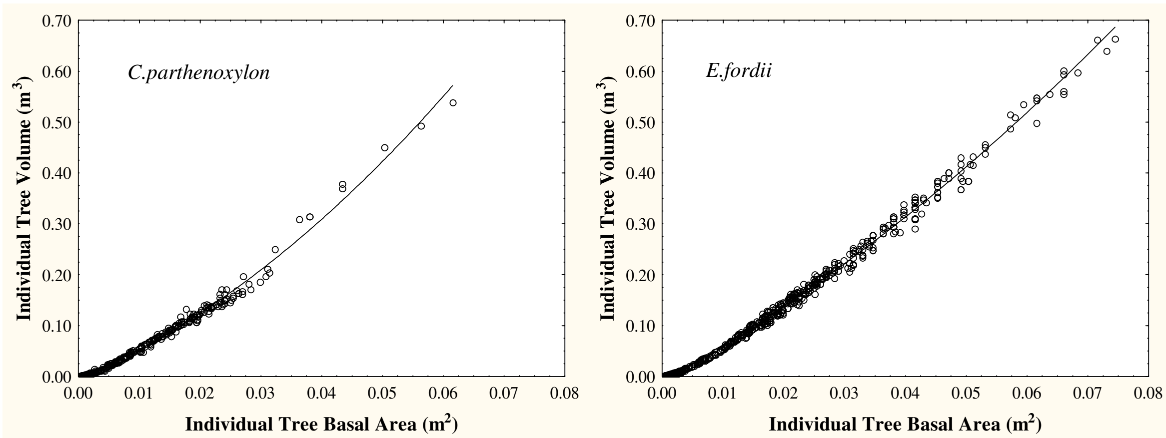


Figure 6.12: The relationship between volume and basal area of selected species in the Phu Tho Province.

The smallholders can also estimate the yield of their plantation by using the above fitting curves in figures 6.11 and 6.12.

6.1.3.2 Unambiguous estimation of existing volume

There are two systems involved in existing volume estimation. The first one is called the unambiguous prediction system and uses different equations to obtain volume per unit area. The second system is called the unconditional calculation system and utilizes an equation that provides basic information on stand structure. Clutter *et al*. (1983) observed that volume estimates indicated by the predicted structures are computed from additional calculations relying on stand structure information.

In the unambiguous prediction system, there are four different models that produce excellent results (based on r^2) for the estimation of existing volume. These models are as follows:

$$V = a * G * H_d \quad \textbf{(6.11)}$$

$$V = a * G\left[1 - e^{-b*t}\right]^c \quad \textbf{(6.12)}$$

$$V = a * G * H_d\left[1 - e^{-b*t}\right]^c \quad \textbf{(6.13)}$$

$$V = a * S * G\left[1 - e^{-b*t}\right]^c \quad \textbf{(6.14)}$$

Where V = Stand volume (m^3)

G = Stand basal area (m^2)

H_d = Top height (m)

S = Site index (base age 4 years for exotic species and 12 and 15 years for native species)

T = Age (years)

a, b, c = Model parameters

Based on the obtainable variables, the above described models can be applied in forest inventory work or in other volume estimations. The fitted models for selected species based on model equations 6.11, 6.12, 6.13 and 6.14 for selected species in the Binh Dinh and Phu Tho Provinces are given in tables 6.15 and 6.16 respectively.

The models in table 6.15 accounted for approximately 52-59% of the volume variation within the stand parameters (basal area, top height or site index and age). The stated model of volume variation, which included basal area and age explained only 51% of volume variation for *Eucalyptus urophylla* in the Phu Tho Province, while others had volume variation between 60 and 94 %. The site indexes in tables 6.15 and 6.16 were obtained from the average of top heights at their respective reference age for selected species (see figures 6.17-6.22).

Table 6.15: The fitted models for selected species based on equations 6.11, 6.12, 6.13 and 6.14 in the Binh Dinh Province.

Species	Model	No. of plots	r^2
Acacia hybrid	$V = 0.879945 * G * H_d$	89	0.54
	$V = 8.619953 * G\left[1 - e^{-0.000585 * t}\right]^{-0.068364}$	89	0.52
	$V = 0.081818 * G * H_d\left[1 - e^{-0.003404 * t}\right]^{-0.542964}$	89	0.57
	$V = 3.592045 * S * G\left[1 - e^{-8.862920 * t}\right]^{0.498678}$	89	0.56
Eucalyptus urophylla	$V = 0.460408 * G * H_d$	57	0.57
	$V = 4.949547 * G\left[1 - e^{-0.00000701 * t}\right]^{-0.047377}$	57	0.58
	$V = 0.163531 * G * H_d\left[1 - e^{-0.004230 * t}\right]^{-0.252052}$	57	0.58
	$V = 1.472156 * S * G\left[1 - e^{-0.000025 * t}\right]^{-0.020460}$	57	0.59

Table 6.16: The fitted models for selected species based on equations 6.11, 6.12, 6.13 and 6.14 in the Phu Tho Province.

Species	Model	No. of plots	r^2
Acacia mangium	$V = 0.587054 * G * H_d$	104	0.64
	$V = 6.200117 * G\left[1 - e^{-0.000096 * t}\right]^{-0.042963}$	104	0.60
	$V = 0.167464 * G * H_d\left[1 - e^{0.005748 * t}\right]^{-0.355693}$	104	0.64
	$V = 1.793204 * S * G\left[1 - e^{0.000074 * t}\right]^{-0.025846}$	104	0.60
Eucalyptus urophylla	$V = 0.656859 * G * H_d$	110	0.63
	$V = 6.653800 * G\left[1 - e^{0.000025 * t}\right]^{-0.013205}$	110	0.51
	$V = 4.449219 * G * H_d\left[1 - e^{-0.004989 * t}\right]^{0.478220}$	110	0.64
	$V = 1.676542 * G * H_d\left[1 - e^{-0.000037 * t}\right]^{-0.013736}$	110	0.51
Cinnamomum parthenoxylon	$V = 0.613704 * G * H_d$	25	0.93
	$V = 9.094955 * G\left[1 - e^{-0.257357 * t}\right]^{6.095293}$	25	0.92
	$V = 0.613704 * G * H_d\left[1 - e^{-1.622660 * t}\right]^{4.621990}$	25	0.94
	$V = 0.584663 * S * G\left[1 - e^{-2.003008 * t}\right]^{8.648821}$	25	0.94
Erythropholeum fordii	$V = 0.700680 * G * H_d$	45	0.94
	$V = 12.26923 * G\left[1 - e^{-1.212808 * t}\right]^{1.479799}$	45	0.92
	$V = 0.823383 * G * H_d\left[1 - e^{-1.383990 * t}\right]^{1.357294}$	45	0.94
	$V = 0.701330 * S * G\left[1 - e^{-0.003400 * t}\right]^{1.93889}$	45	0.93

These volume models could be used for the above selected species grown in Vietnam. All models showed good r^2 values. Smallholders can apply these models to estimate the existing stand volume under different situations: when the age is unknown in the absence of tree height, when top height and stand age are known and when site index is known. The site index used for all selected species was maintained by the average top heights at the reference age of 4 years for exotic species, and 12 and 15 years for *Cinnamomum parthenoxylon and Erythropholeum fordii.*

6.1.3.3 Mean annual increment (MAI)

Helms (1998) defined mean annual increment (MAI) as the entire increment of a tree or stand up to a known age divided by that age. Since the rotation length and target of the yield differs between species, there is no defined standard age. In this study, the mean annual increment was considered for each stand independently based on their age at measurement because data were not maintained on an annual basis. For the different species, the ‘Arc shape’ fitted curves were fit with different maximum mean annual increment values at different ages. The equation for the MAI parabolic model is as follows:

$$V = a * t + b * t^2 + c * t^3 \qquad \textbf{(6.15)}$$

Where V = Mean annual increment (m^3/ha)
t = Age (years)
a, b, c = parameters

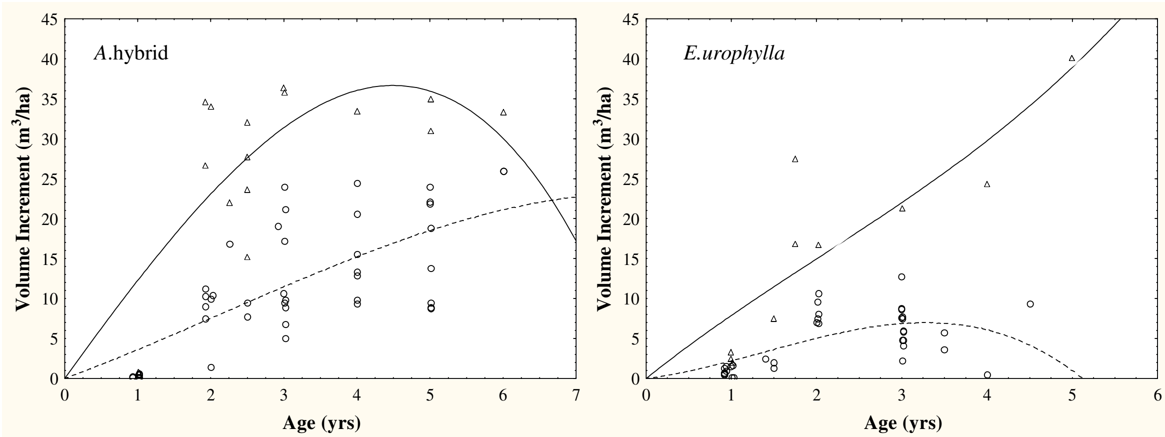
The parameter values for the selected species are given in table 6.17.

The fitted curves produce some remarkable results for species in the Binh Dinh Province. The maximum MAI for *Acacia* hybrid occurred at 3 years of age and for *Eucalyptus urophylla* at 5 years of age, as shown in figure 6.13. This phenomenon may be associated with the site. One could hypothesize that the better site carries the stand to its maximum MAI at the premature stage compared to the poor site. In keeping with this hypothesis, one could state that required conditions for large increment were fulfitted to a higher degree for *Acacia* hybrid than for *Eucalyptus urophylla*. On the other hand, the value for maximum MAI varied between these species. *Eucalyptus urophylla* had the highest maximum MAI of 40 m^3/ha, while the maximum MAI for *Acacia* hybrid was 38 m^3/ha.

Table 6.17: Parameters values for fitted MAI curves for selected species in the Binh Dinh and Phu Tho Provinces.

Province	Species	Parameter values			r^2
		a	b	c	
Binh Dinh	*Acacia* hybrid (tissue culture)	12.591	-0.160	-0.184	0.56
	Acacia hybrid (seed)	3.371	0.276	-0.042	0.56
	Eucalyptus urophylla (tissue culture)	8.510	-0.763	0.124	0.81
	Eucalyptus urophylla (seed)	1.315	1.148	-0.274	0.41
Phu Tho	*Acacia mangium* (tissue culture)	1.257	3.477	-0.478	0.76
	Acacia mangium (seed)	3.793	-0.939	0.109	0.48
	Eucalyptus urophylla (tissue culture)	21.033	-5.233	0.426	0.26
	Eucalyptus urophylla (seed)	5.706	-1.304	0.110	0.18
	Cinnamomum parthenoxylon	-0.219	0.106	-0.005	0.87
	Erythropholeum fordii	-0.299	0.122	-0.004	0.77

For tree species in the Phu Tho Province, the fitted curves also showed some remarkable features. The first one is the maximum MAI. The maximum MAI values for *Acacia mangium*, *Eucalyptus urophylla*, *Cinnamomum parthenoxylon* and *Erythropholeum fordii* occurred at the ages of 5, 4, 17 and 17, respectively (see in figure 6.14). Again, these results may be associated with the site. Theoretically, the better site carries the stand to its maximum MAI at the premature stage compared to poorer sites, where maximum MAI occurs at older ages.



Δ -tissue culture —— curve for tissue culture

O- seed - - - - - - curve for seed

Figure 6.13: MAI curves for two species in the Binh Dinh Province.

In keeping with this, one could state that required conditions for large increment were fulfitted to a higher degree for *Acacia mangium* and *Erythropholeum fordii* than for *Cinnamomum parthenoxylon* and *Eucalyptus urophylla*. Maximum MAI values varied among the species. *Acacia mangium* had the highest maximum MAI of 38 m^3/ha, followed by *Eucalyptus urophylla* at 33 m^3/ha, *Erythropholeum fordii* at 23 m^3/ha, and *Cinnamomum parthenoxylon* had the lowest maximum MAI value of 6 m^3/ha.

The fact that the exotic species in figures 6.13 and 6.14 show so high variation of MAI in the same age of the stands is due to the original source of seedlings. High MAI values occur in the plantations of smallholders who used the original source of seedlings as tissue culture. Low MAI values at same age are due to the use of seeds as the origin. Eventhough the investment of tissue culture is much more expensive than seeds: smallholders should consider the end yield.

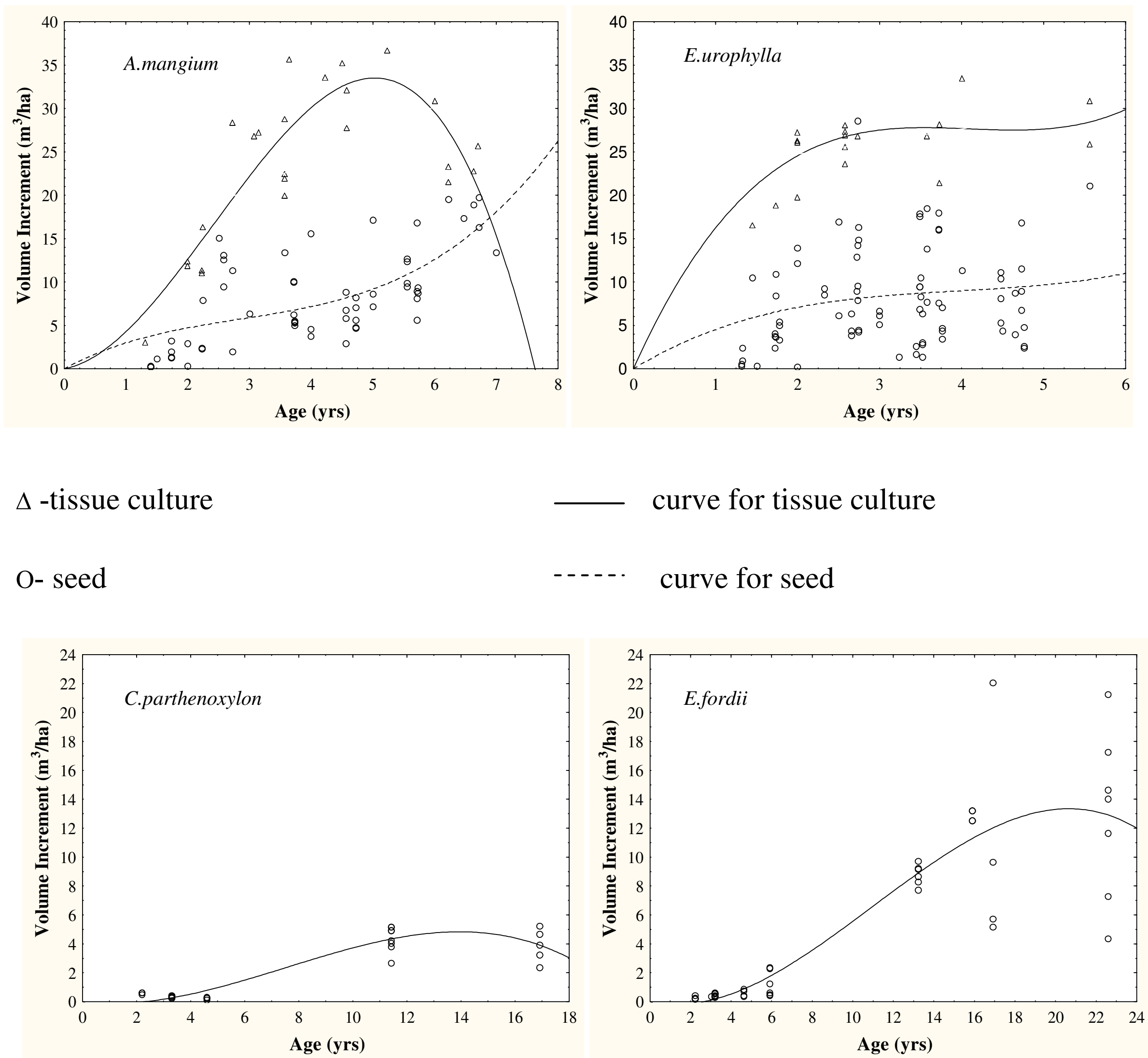


Figure 6.14: MAI curves for four selected species in the Phu Tho Province.

In a trial near Edea, Cameroon, Africa, an 8-year *Eucalyptus urophylla* rotation on a suitable and well-prepared site one obtained a MAI of 30 m^3/ha/yr following provenance screening (FAO, 2001). In Loudima in the Republic of Congo, growth of the Mt Lewotobi provenance from Flores was approximately 40 m^3/ha/yr at 5 years (Eldridge *et al*., 1993). The popularity of *Eucalyptus urophylla* species has increased markedly for plantations in humid and subhumid tropical climates that endure several months of drought annually (wet/dry tropics), such as parts of Indonesia, Brazil and Southern China. MAI values of 20-

30 m^3/ha/yr have been studied under favourable growing conditions (Eldridge *et al*., 1993). On degraded Imperata grasslands, Otsamo *et al.* (1995) observed that *Acacia mangium* had a MAI of 10 m^3/ ha/ yr, while the highest MAI estimate at the age of 3 years was 36.7 m^3/ ha/ yr in South Kalimantan, Indonesia. Nevertheless, these figures are generally based on the rotation age and the variation of site.

6.1.4 Assessment of site quality using site index

Site index is a common and convenient measure of a forest's potential productivity (Zeide and Zakrzewski, 1993, Garcia, 1998). Site index is usually defined as the height of the dominant or co-dominant trees at a specified reference age in a stand. It is calculated in an equation that uses tree height and age. Site index equations differ by tree species and region. The growth and improvement of a forest reflects to the site quality and exists as significant occurrence in both natural and plantation forests. Both edaphic and climatic factors affect attributes of a site in a plantation. Site quality has been determined previously using the aid of different indices in forest studies. In forest management and modeling, there is no particular guide based directly on environmental parameters that show adequate accuracy. Despite the superiority of volume production as an indicator of site productivity, site index based on height-age relationships has been widely adopted, principally because volume production is difficult to measure (Mader, 1965).

The main site quality assessment in even-aged stands uses site index and involves age and tree height of a species. Site quality indicates the productivity of a specific tree species for different sites. Vanclay (1994) found that stand height can be applied as a calculator for site productivity of a stand as well as provide a good estimate of the maximum potential height of that site. Von Gadow and Hui (1998) pointed out that height growth is somewhat independent of stand density and thus not really affected by thinning. Von Gadow (1983a) claimed that the mean height can also be used for depicting the quality of a growing site however this method is not common. Villiers and Van Laar (1986) also observed that the relationship between mean height and top height is favorably important and reliant on stand density.

To achieve the most excellent fit, different models were used with all height–age data points. Top height was defined as the regression height of the quadratic mean diameter of the trees per plot. Tables 6.18, 6.19 and 6.20 show the summaries of different fitted models for age and top height (refers to dominant height) of the selected species. Fitted models for the top height and age relationship of *Acacia* hybrid*, Eucalyptus urophylla, Acacia mangium, Cinnamomum parthenoxylon* and *Erythropholeum fordii* in the Binh Dinh and Phu Tho Provinces in Vietnam are shown in figures 6.13 and 6.14. Chapman-Richards generalization of Bertalanffy's growth model is used in even-aged conifers monocultures (Piennar and Turnbull, 1973). This model is quite accepted for even-aged plantations and has proved to be the best model compared to others.

A height growth study of *Eucalyptus grandis* on a particular site by von Gadow and Bredenkamp (1992) obtained the following results:

$$H = 45.1\left[1 - e^{-0.0726 * t}\right]^{1.0128} \qquad \textbf{(6.16)}$$

Also in a 20- year old plantation of conifers studied by von Gadow and Hui (1998), the guide curve was established by means of a variant of the Chapman-Richards model and site index is the dominant stand height (m) of plantation. The result is shown as follows:

$$H = \alpha * SI^{\beta}\left[1 - e^{r * t}\right]^{\sigma} \qquad \textbf{(6.17)}$$

Von Gadow and Bredenkamp (1992) accepted that the reference age used in site index is often confused and selected randomly with a number of reference ages for a specific species. The reference age is based on the rotations related to the end products of the specific species. The rotation for exotic species *Acacia* hybrid*, Acacia mangium* and *Eucalyptus urophylla* is less than 7 years to attain wood for pulp and paper industry. For native species *Cinnamomum parthenoxylon* and *Erythropholeum fordii*, the rotations are 17 years and 23 years, respectively, for construction material to make household utensils, flooring strips, wood carvings and implements. The Chapman-Richards model in tables 6.18, 6.19 and 6.20 can be rewritten as in table 6.21 and applied as a height growth interpreter for respective species. Then using the rewritten equations, the top height (H_2) at a projected age (t_2) can be predicted for a given top height (H_1) at the age t_1 for selected species.

Table 6.18: Top height and age relationship fitted models for *Acacia* hybrid and *Eucalyptus urophylla* stands in the Binh Dinh Province.

Species	Models	Model parameter values			r^2
		α	β	γ	
Acacia hybrid	Chapman-Richards: $H = \alpha\left[1 - e^{-\beta * t}\right]^{\gamma}$	18.454	0.375	1.791	0.86
	Cilliers-Van Wyk: $H = \alpha\left[1 - e^{-\beta(t-\gamma)}\right]$	19.138	0.296	0.780	0.86
	Lundqvist: $H = \alpha\left[e^{-\beta * t^{-\gamma}}\right]$	26.216	2.811	0.906	0.86
	$H = \alpha\left[1 - e^{\beta - \gamma * t}\right]$	19.138	0.232	0.279	0.86
	$H = \alpha + \beta * t^{\gamma}$	-63.363	64.084	0.112	0.86
	$H = \dfrac{\alpha}{1 + e^{\beta - \gamma * t}}$	-31.881	3.544	-0.053	0.82
Eucalyptus urophylla	Chapman-Richards: $H = \alpha\left[1 - e^{-\beta * t}\right]^{\gamma}$	13.802	0.627	2.594	0.81
	Cilliers-Van Wyk: $H = \alpha\left[1 - e^{-\beta(t-\gamma)}\right]$	14.523	0.447	0.830	0.81
	Lundqvist: $H = \alpha\left[e^{-\beta * t^{-\gamma}}\right]$	0.689	-1.619	-0.390	0.75
	$H = \alpha\left[1 - e^{\beta - \gamma * t}\right]$	14.523	0.371	0.447	0.81
	$H = \alpha + \beta * t^{\gamma}$	-45.992	47.099	0.138	0.81
	$H = \dfrac{\alpha}{1 + e^{\beta - \gamma * t}}$	-30.990	3.451	-0.074	0.77

Table 6.19: Top height and age relationship fitted models for *Acacia mangium* and *Eucalyptus urophylla* stands in the Phu Tho Province.

Species	*Models*	*Model parameter values*			r^2
		α	β	γ	
Acacia mangium	Chapman-Richards: $H = \alpha\left[1 - e^{-\beta * t}\right]^{\gamma}$	18.454	0.375	1.791	0.86
	Cilliers-Van Wyk: $H = \alpha\left[1 - e^{-\beta(t-\gamma)}\right]$	19.138	0.296	0.780	0.86
	Lundqvist: $H = \alpha\left[e^{-\beta * t^{-\gamma}}\right]$	26.216	2.811	0.906	0.86
	$H = \alpha\left[1 - e^{\beta - \gamma * t}\right]$	19.138	0.232	0.296	0.86
	$H = \alpha + \beta * t^{\gamma}$	-28.153	29.377	0.217	0.86
	$H = \frac{\alpha}{1 + e^{\beta - \gamma * t}}$	-31.882	3.544	-0.053	0.81
Eucalyptus urophylla	Chapman-Richards: $H = \alpha\left[1 - e^{-\beta * t}\right]^{\gamma}$	10.946	0.927	2.772	0.36
	Cilliers-Van Wyk: $H = \alpha\left[1 - e^{-\beta(t-\gamma)}\right]$	10.943	0.844	0.821	0.36
	Lundqvist: $H = \alpha\left[e^{-\beta * t^{-\gamma}}\right]$	1.249	-1.392	-0.293	0.36
	$H = \alpha\left[1 - e^{\beta - \gamma * t}\right]$	10.943	0.693	0.844	0.34
	$H = \alpha + \beta * t^{\gamma}$	-15.152	18.963	0.210	0.31
	$H = \frac{\alpha}{1 + e^{\beta - \gamma * t}}$	-17.057	3.051	-0.062	0.32

Table 6.20: Top height and age relationship fitted models for *Cinnamomum parthenoxylon* and *Erythropholeum fordii* stands in the Phu Tho Province.

Species	Models	Model parameter values			r^2
		α	β	ɣ	
Cinnamomum parthenoxylon	Chapman-Richards: $H = \alpha\left[1 - e^{-\beta * t}\right]^{\gamma}$	13.139	0.205	1.781	0.92
	Cilliers-Van Wyk: $H = \alpha\left[1 - e^{-\beta(t-\gamma)}\right]$	14.407	0.127	0.733	0.92
	Lundqvist: $H = \alpha\left[e^{-\beta * t^{-\gamma}}\right]$	22.910	3.903	0.668	0.90
	$H = \alpha\left[1 - e^{\beta - \gamma * t}\right]$	14.407	0.093	0.127	0.90
	$H = \alpha + \beta * t^{\gamma}$	-12.056	11.878	0.268	0.90
	$H = \frac{\alpha}{1 + e^{\beta - \gamma * t}}$	-37.520	3.686	-0.015	0.84
Erythropholeum fordii	Chapman-Richards: $H = \alpha\left[1 - e^{-\beta * t}\right]^{\gamma}$	15.943	0.158	1.526	0.96
	Cilliers-Van Wyk: $H = \alpha\left[1 - e^{-\beta(t-\gamma)}\right]$	16.710	0.118	0.883	0.96
	Lundqvist: $H = \alpha\left[e^{-\beta * t^{-\gamma}}\right]$	24.085	4.227	0.729	0.96
	$H = \alpha\left[1 - e^{\beta - \gamma * t}\right]$	16.710	0.104	0.118	0.96
	$H = \alpha + \beta * t^{\gamma}$	-42.780	41.117	0.114	0.96
	$H = \frac{\alpha}{1 + e^{\beta - \gamma * t}}$	-55.915	4.078	-0.009	0.88

The site index (SI) can be determined by substituting the variable t in the Chapman-Richards model equation of tables 6.18-6.20 with the site index reference age. It is frequently supposed that only the asymptote or scale parameter α varies with site index, whereas the slope of the growth curve determined by parameters β and γ is identical for all site indices.

Table 6.21: Height growth interpreter equation re-written by the Chapman-Richards model in tables 6.18, 6.19 and 6.20.

Province	Species	Model
Binh Dinh	*Acacia* hybrid	$H_2 = H_1 \left[\frac{1 - e^{-0.37 * t_2}}{1 - e^{-0.37 * t_1}} \right]^{1.79}$
	Eucalyptus urophylla	$H_2 = H_1 \left[\frac{1 - e^{-0.05 * t_2}}{1 - e^{-0.05 * t_1}} \right]^{1.07}$
Phu Tho	*Acacia mangium*	$H_2 = H_1 \left[\frac{1 - e^{-0.06 * t_2}}{1 - e^{-23.04 * t_1}} \right]^{0.90}$
	Eucalyptus urophylla	$H_2 = H_1 \left[\frac{1 - e^{-0.02 * t_2}}{1 - e^{-0.02 * t_1}} \right]^{0.60}$
	Cinnamomum parthenoxylon	$H_2 = H_1 \left[\frac{1 - e^{-0.21 * t_2}}{1 - e^{-0.21 * t_1}} \right]^{1.78}$
	Erythropholeum fordii	$H_2 = H_1 \left[\frac{1 - e^{-0.16 * t_2}}{1 - e^{-0.16 * t_1}} \right]^{1.53}$

In accordance with von Gadow and Bredenkamp (1992), the curves for all site indices showing the same shape under this hypothesis are called anamorphic curves. As a result, the general equations for site index for five species can be written as in table 6.22.

Considering 4 years as the respective reference age for exotic species and 12 and 15 years for native species, then the rewritten equations in table 6.23 can be given. For a given site index, these equations can be used to depict the height development over age.

Table 6.22: The general equations for site index of selected species in the Binh Dinh and Phu Tho Provinces.

Province	Species	Equation
Binh Dinh	*Acacia* hybrid	$SI = \alpha\left[1 - e^{-0.37 * t}\right]^{1.79}$
	Eucalyptus urophylla	$SI = \alpha\left[1 - e^{-0.63 * t}\right]^{2.60}$
Phu Tho	*Acacia mangium*	$SI = \alpha\left[1 - e^{0.38 * t}\right]^{1.80}$
	Eucalyptus urophylla	$SI = \alpha\left[1 - e^{-0.93 * t}\right]^{2.77}$
	Cinnamomum parthenoxylon	$SI = \alpha\left[1 - e^{-0.21 * t}\right]^{1.78}$
	Erythropholeum fordii	$SI = \alpha\left[1 - e^{-0.16 * t}\right]^{1.53}$

Table 6.23: The equations for site index of selected species in the Binh Dinh and Phu Tho Provinces (reference age= 4 years for exotic species and 12 and 15 years for *Cinnamomum parthenoxylon* and *Erythropholeum fordii*).

Province	Species	Equation
Binh Dinh	*Acacia* hybrid	$SI_4 = H \frac{\left[1 - e^{-0.37 * 4}\right]^{1.79}}{\left[1 - e^{-0.37 * t}\right]^{1.79}}$
	Eucalyptus urophylla	$SI_4 = H \frac{\left[1 - e^{-0.63 * 4}\right]^{2.60}}{\left[1 - e^{-0.63 * t}\right]^{2.60}}$
Phu Tho	*Acacia mangium*	$SI_4 = H \frac{\left[1 - e^{-0.38 * 4}\right]^{1.79}}{\left[1 - e^{-0.38 * t}\right]^{1.79}}$
	Eucalyptus urophylla	$SI_4 = H \frac{\left[1 - e^{-0.93 * 4}\right]^{2.77}}{\left[1 - e^{-0.93 * t}\right]^{2.77}}$
	Cinnamomum parthenoxylon	$SI_{12} = H \frac{\left[1 - e^{-0.21 * 4}\right]^{1.78}}{\left[1 - e^{-0.21 * t}\right]^{1.78}}$
	Erythropholeum fordii	$SI_{15} = H \frac{\left[1 - e^{-0.16 * 4}\right]^{1.53}}{\left[1 - e^{-0.16 * t}\right]^{1.53}}$

Figure 6.15 shows the scatter plots of top height-age for *Acacia* hybrid and *Eucalyptus urophylla* in the Binh Dinh Province, with the fitted mother curve for the Chapman-Richards equations in table 6.18. For *Acacia* hybrid, the top height ranges from 2 to 18 m and the age ranges from 1 to 7 years. For *Eucalyptus urophylla*, the top height ranges from 1 to 13.8 m and the age ranges from 1 to 5 years.

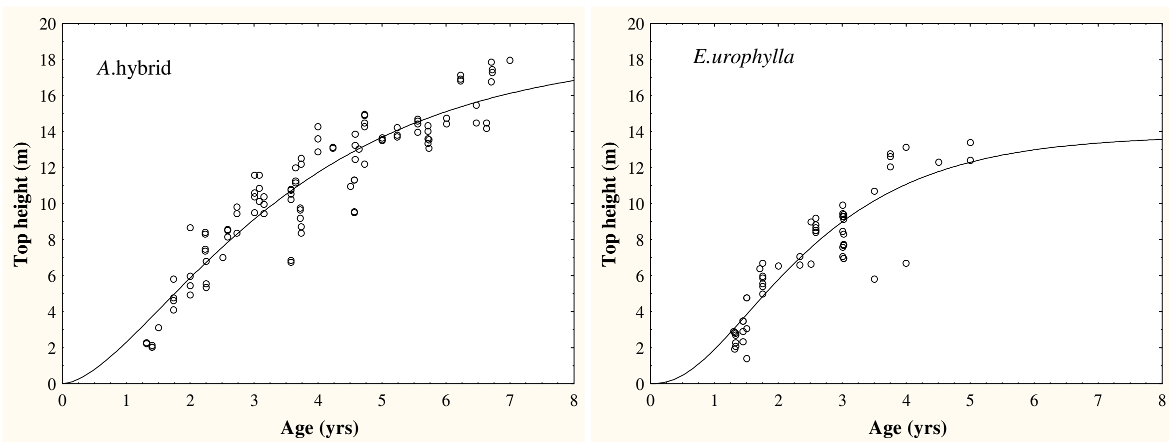


Figure 6.15: Scatter plots and fitted curves for top height-age relationship of *Acacia* hybrid, and *Eucalyptus urophylla* in the Binh Dinh Province.

Figure 6.16 shows the scatter plot of the top height-age relationship for *Acacia mangium, Eucalyptus urophylla*, *Cinnamomum parthenoxylon* and *Erythropholeum fordii* in the Phu Tho Province with the fitted mother curves for the Chapman-Richards equations in tables 6.19 and 6.20. Top height ranges from 2 to 18.5 m, 2 to 17 m, 2.5 to 12.5 m, 2.5 to 16 m and the age ranges from 1 to 7 years, 1 to 6 years, 2 to 17 years, 2 to 23 years, respectively.

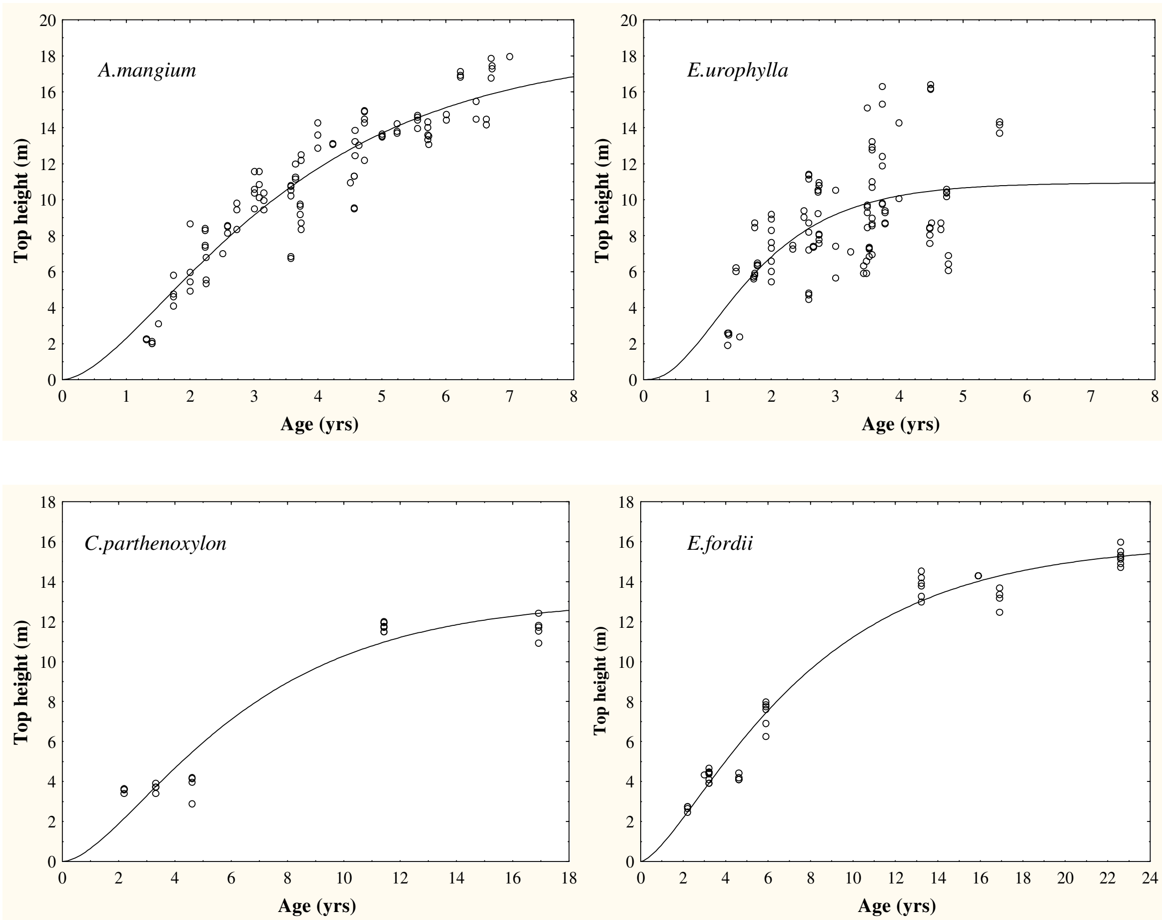


Figure 6.16: Scatter plots and fitted curves for the top height-age relationship of *Acacia mangium, Eucalyptus urophylla*, *Cinnamomum parthenoxylon* and *Erythropholeum fordii* in the Phu Tho Province.

Site index is a significant quantity in silvicultural studies. For that reason, site class developments are most important for management practices and are strongly related to site factor. For instance, volume tables are constructed for different site classes. The concept is well suited for growth and yield predictions and silvicultural prescriptions (Magnussen, 1999), although there appears to be no universal consensus on the type or number of site trees needed for its application (McRoberts, 1996). In British yield tables, the site classes are based on mean annual increment (MAI) (Van Laar and Akca, 1997). However, site classes are based on top height in this study.

The curves depicted in figures 6.17-6.22 are anamorphic and were obtained by the "guide curve method", the levels refer to the top heights attained at a reference age of 4 years for exotic species and 12 and 15 years for native species (SI_4, SI_{12} and SI_{15}) and thus indicate the site index. In the Binh Dinh Province, the site classes and site index curves for *Acacia* hybrid are shown in figure 6.17 and the site classes and site index curves for *Eucalyptus urophylla* are shown in figure 6.18. In the Phu Tho Province, the site classes and site index curves for *Acacia mangium* are shown in figure 6.19, *Eucalyptus urophylla* in figure 6.20, *Cinnamomum parthenoxylon* in figure 6.21 and *Erythropholeum fordii* in figure 6.22.

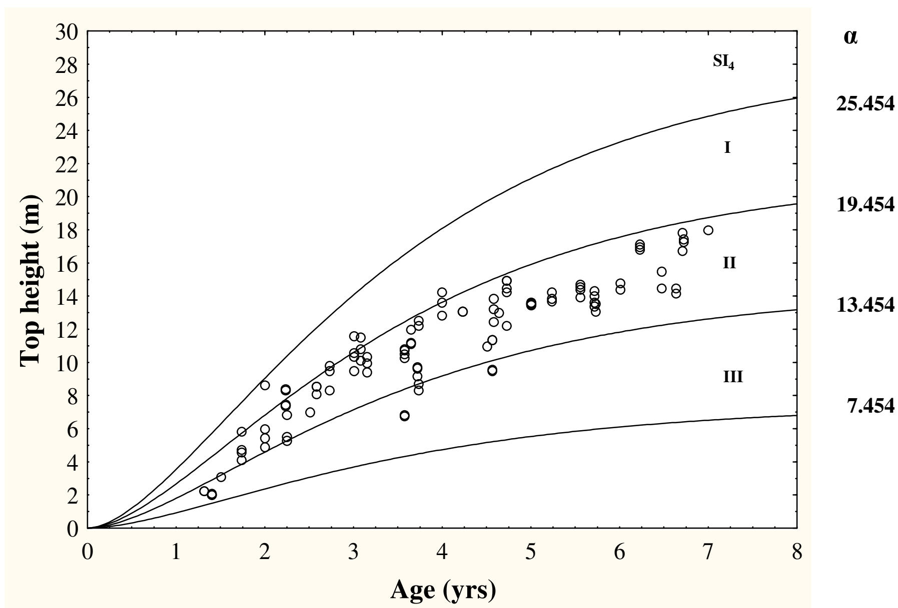


Figure 6.17: Site classes and site index curves for *Acacia* hybrid in the Binh Dinh Province (α = top height in meter for each site class).

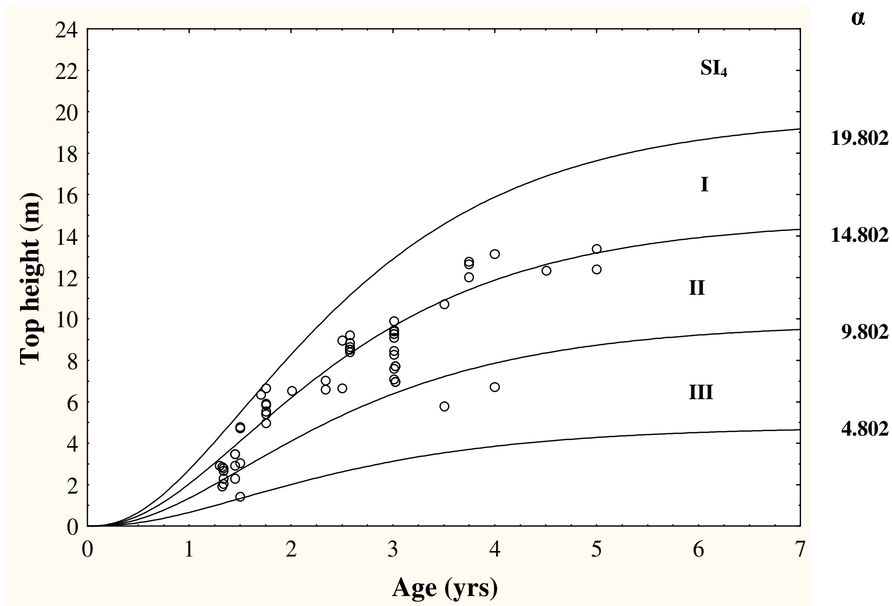


Figure 6.18: Site classes and site index curves for *Eucalyptus urophylla* in the Binh Dinh Province (α = top height in meter for each site class).

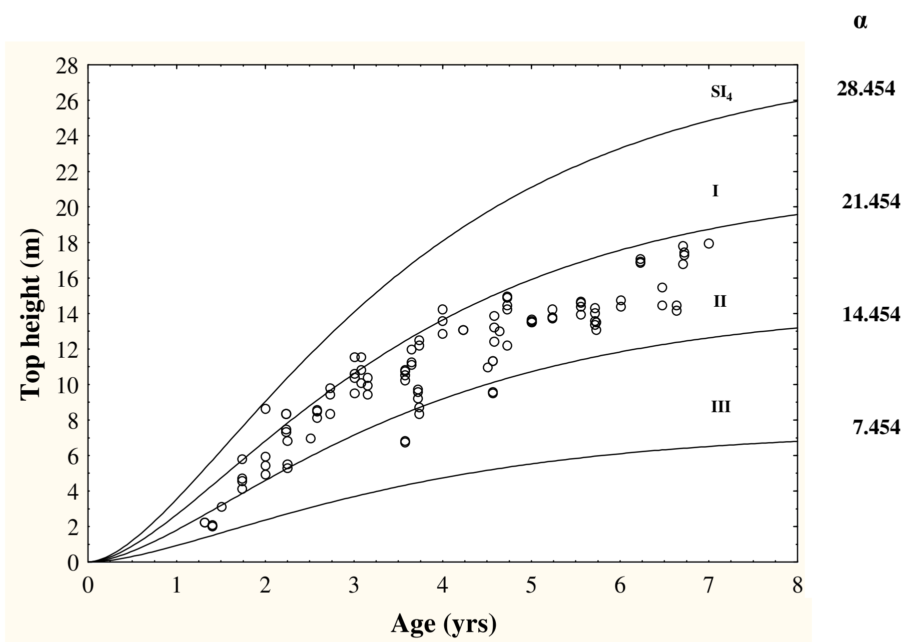


Figure 6.19: Site classes and site index curves for *Acacia mangium* in the Phu Tho Province (α = top height in meter for each site class).

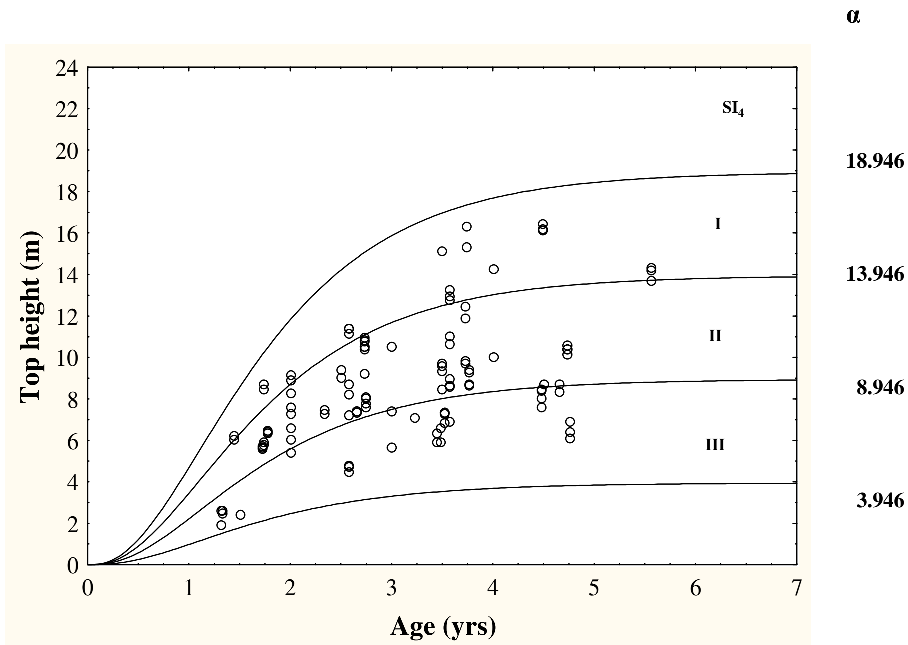


Figure 6.20: Site classes and site index curves for *Eucalyptus urophylla* in the Phu Tho Province (α = top height in meter for each site class).

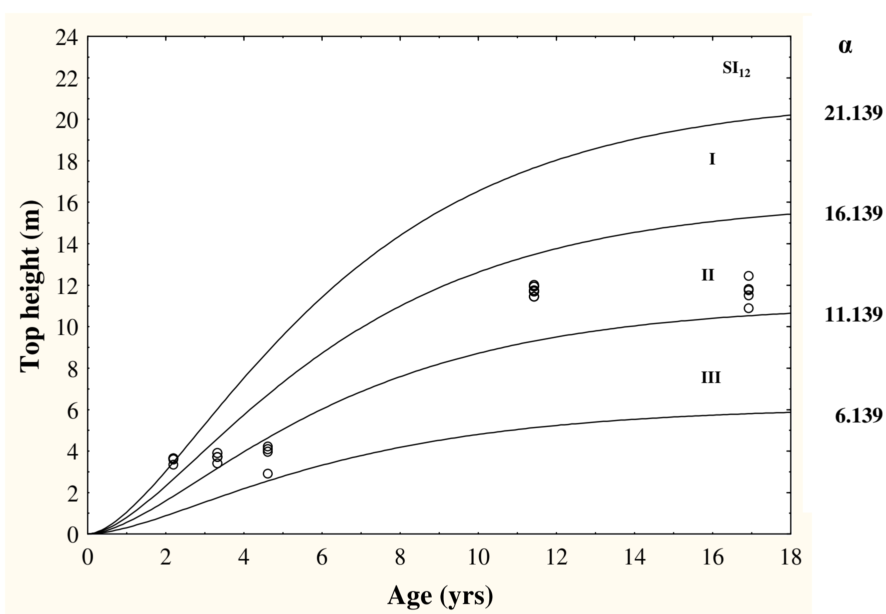


Figure 6.21: Site classes and site index curves for *Cinnamomum parthenoxylon* in the Phu Tho Province (α = top height in meter for each site class).

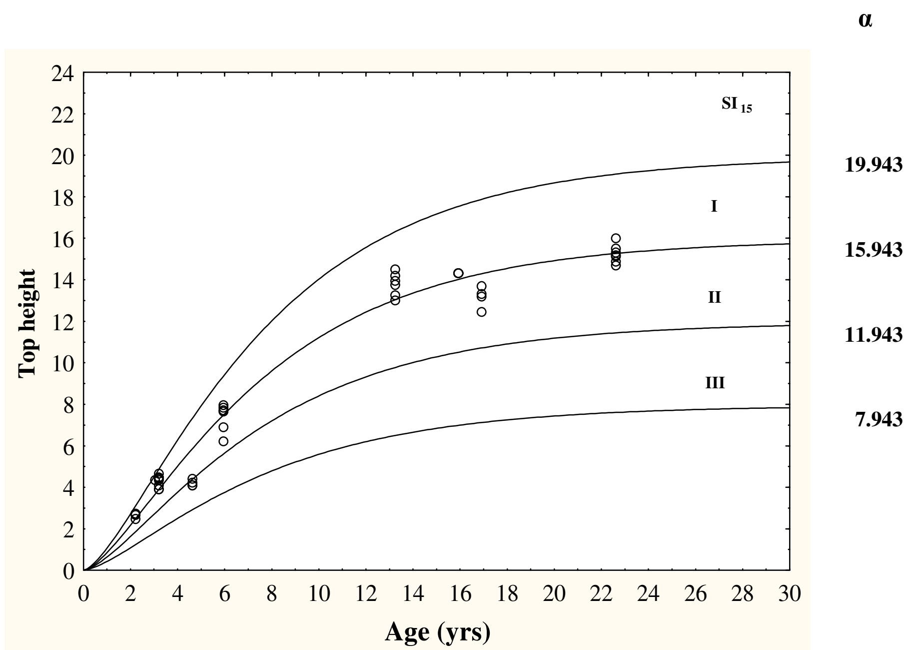


Figure 6.22: Site classes and site index curves for *Erythropholeum fordi* in the Phu Tho Province (α = top height in meter for each site class).

In Vietnam, trees are grown in more or less similar site conditions. It is very difficult to categorize stands under different classes for management purposes if the classes are not so widely placed.

In the Nuwara-Eliya division, the Chapman-Richards generalisation of Bertalanffy's growth model for even-aged conifers was observed to be the most appropriate model for *Eucalyptus grandis*. Von Gadow and Bredenkamp (1992) used the same model (but the parameter values were different) in a height growth study of *Eucalyptus grandis* on a particular site. This model was withdrawn in the form of site index (SI) to show the top height of a stand at the reference age for different species. The reference age was 30 years, when clear felling usually starts. The observed maximum top height was 63 m and the minimum was 8 m. The age extended from 3 to 55 years, other than one stand at 72 years. The equation for site index of *Eucalyptus grandis* in Nuwara-Eliya is as follows:

$$SI = \alpha\left[1 - e^{-0.09109}\right]^{1.262}$$

Developing site classes is a critical characteristic in a managed plantation. The growth structure of a species for a specific site will not change if the site conditions are more or less the same and all other factors remain constant. Therefore, site class differentiation is a valuable tool for smallholders to build the volume table for a specific species at different sites. Site class development differs from country to country. For example, in Britain, Van Laar and Akca (1997) observed that the classes developed for the yield tables were dependent on mean annual increment. However, the principle process of classifying site classes is by the age-top height relationship in this study.

In this study, site classes were divided into three classes for both exotic and native species: class (I) referred to the best site quality, class (II) had moderate quality and class (III) had poor quality. As an example, the lower and the upper limits of *Acacia mangium* curves (top height) at the reference age of 4 years were 7.5 and 28.5 m, so the three classes could be divided into 7-m classes; for example, *Acacia mangium* would have a 21.5 to 28.5-m class I, 14.5 to 21.5-m class II and 7.5 to 14.5-m class III. Using different site classes of selected species in the Binh Dinh and Phu Tho Provinces, smallholders can build volume tables of the respective species.

7. Summary

This research has been carried out in the context of a CIFOR (Center for International Forestry Research) project. The purpose of the project is to strengthen rural institutions and promote innovative partnerships to increase productivity, profitability, and access to land, credit, and markets for smallholders participating in industrial tree-planting programs in Vietnam and Indonesia.

The government of Vietnam is carrying out a large-scale ‘reforestation program’, with the aim of improving local livelihood security, environmental sustainability and industrial wood supply. Smallholders are involved in plantation timber production through various schemes. Generally, these reforestation efforts have been effective: eventhough smallholders often lack the appropriate technical knowledge and management skills. Therefore, the proper research on silvicultural and management aspects of fast growing species and also native species are necessary. In this study, three exotic species, *Acacia mangium*, *Acacia* hybrid, *Eucalyptus urophylla* and two native species, *Cinnamomum parthenoxylon*, *Erythropholeum fordii* were selected to conduct stand structure and stand volume analyses in different ages.

The data of these five species were collected, namely: age, size and site condition by visiting the local commune office of the Binh Dinh and Phu Tho Provinces. In the assessment of pure plantations, the following plot-related data were obtained: stem quantity and quality and overall tree condition, spacing, elevation, slopes, aspect at the plot centre and the accessibility and adjacent land uses. Diameter and tree height were measured. The heights of the five nearest trees to the sample central points were measured and the remaining was estimated using the Prodan height-diameter relationship.

The following main results are obtained:

1. Different age stands from the species above were chosen and diameter distributions were constructed. Among the fitted functions, the three-parameter WEIBULL distribution was found to be superior. It was observed that the probability density for each stand

decreased with increasing age. Due to low crowding, differentiation was observed in *Acacia* hybrid in the Binh Dinh Province. The mean diameters of the stands were not as distinct in the Binh Dinh and Phu Tho Provinces. This may be due more likely to site differences among the stands. Knowing the diameter of the selected stands will aid in making proper management decisions by allowing smallholders to accurately depict stand structure and to decide for the most profitable species in both provinces.

2. For the diameter-height relationship, the Prodan function gave the best fit for the 5- year old stands in the Binh Dinh Province and Phu Tho Provinces. In pooled analysis (neglecting age) the Prodan function also showed better fit than compared functions in both provinces. In the Binh Dinh Province, *Acacia* hybrid exhibited a fast diameter and height growth as does *Eucalyptus urophylla* in the Phu Tho Province. Among the native species *Erythropholeum fordii* showed very good height growth compared to *Cinnamomum parthenoxylon* (chapter 6.1.1.2).

3. In this study, the following model was selected to estimate the stand basal area of five selected species.

$$G = a * N^{\alpha} * H_d^{\beta} * t^{\delta}$$

As a result of the coppice system, the largest maximum basal area was found in *Eucalyptus urophylla* in the Binh Dinh Province. In the Phu Tho Province, *Acacia mangium* occurred as the largest basal area producing species obviously because of favourable soil condition. For native species, the largest basal area was observed for *Erythropholeum fordii.*

4. In even-aged stands, the pragmatic thinning schedule can be described by the stand density index developed by Reineke (1933) showing the relationship between the number of trees and the mean diameter. The fitted curves of selected species, according to the Reineke model represent impressive forms of ‘limiting lines’ which are feasible for both provinces (chapter 6.1.2.2). Many variations of mean diameter and maximum

number of stems per hectares exist because of the gaps in some plots (as a result of mortality).

5. The maximum number of observed trees per hectare was found to be 3165 at the age of 2 years for *Acacia* hybrid with relative spacing value of 0.9 in the Binh Dinh Province and 5857 for *Eucalyptus urophylla* at the age of 2 year with relative spacing value of 0.8 in the Phu Tho Province. For native species, the maximum number of observed trees per hectare was 2578 for *Erythropholeum fordii* at the age of 2 year with relative spacing value of 0.74. Using relative spacing index (chapter 6.1.2.3), smallholders can define the thinning intensity.

6. Going to the relationship between single tree volume and basal area, the allometric regression was applied. This regression was carried out for different species separately. In the Binh Dinh Province, *Acacia* hybrid and *Eucalyptus urophylla* had samilar r^2 values. The best volume bearer among the exotic species was *Acacia mangium* and *Erythropholeum fordii* for native species in the Phu Tho Province.

7. Based on data availability, four different volume models under different situations (age, top height and site index) were found to be good estimates of existing volume and their volume variation was between 51% and 94% (chapter 6.1.3.2).

8. Mean annual increment also provides important information regarding the yield development of a stand over time at specific sites. The 'Arc shape' fitted curves fitted with different maximum mean annual increment values at different ages of selected species. The maximum MAI occurred at young aged stands of *Acacia* hybrid in the Binh Dinh Province and *Eucalyptus urophylla* in the Phu Tho Province. For the reason that the two native species are slow growing species, their maximum MAI were captured in older aged plantations. For exotic species, high variation of MAI was recorded in same aged stands due to the use of different sources of seedlings (chapter 6.1.3.3).

9. For site class evaluation, top height is used. The Champman-Richards generalisation of Bertalanffy's growth model was observed to be the most appropriate among the different asymptotic models introduced for age and top height data of the selected species grown in the Binh Dinh and Phu Tho Provinces. The reference age was considered to be 4 years for exotic species and 12 and 15 years for *Cinnamomum parthenoxylon* and *Erythropholeum fordii*, respectively. Three site classes: the best site quality (class I), moderate quality (class II) and poor quality (class III) were built through the guide curve method for five selected species (chapter 6.1.4).

According to the above results, the smallholders can benefit as follows:

-From the diameter distributions of the selected species, smallholders can analyse their horizontal stand structure,

-Smallholders can be aware that favorable soil condition and coppice management can produce high timber quality,

-Smallholders can estimate the optimized stand density and spacing by using the fitted curves of Reineke model and relative spacing index,

-Due to the result of the high MAI of genetically improved trees, smallholders can decide the suitable seedling origin to enhance productivity,

-Smallholders can build volume tables of the selected species by using the different site classes.

In conclusion, this study demonstrates that site conditions have a direct influence on the growth of the stands. Moreover, some silvicultural management activities, i.e genetic improvement for plantation establishment and coppice management enhance the productivity of the stands as well.

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DECLARATION OF ORIGINALITY AND
CERTIFICATE OF OWNERSHIP

I, Chaw Chaw Sein, hereby declare that I am the only author of this dissertation entitled "Growth and Site Conditions of *Acacia mangium*, *Acacia* hybrid, *Eucalyptus urophylla*, *Cinnamomum parthenoxylon* and *Erythropholeum fordii* for Livelihood Security of Smallholders in Industrial Tree Planting Programs of Vietnam". All the references and data sources that were used in this dissertation have been appropriately acknowledged. I furthermore declare that this work has not been submitted elsewhere in any form as part of another dissertation procedure.

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