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MEAN ANNUAL VOLUME INCREMENT OF SELECTED INDUSTRIAL FOREST PLANTATION SPECIES

Based on the work of

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Consultants

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ABSTRACT

This paper provides a global overview of forest plantation growth rates, with a particular focus on mean annual volume increment (MAI) of the main species planted in developing countries. Documented growth data from both trials and plantations is presented, and the difficulty of translating trial data to commercial scale is highlighted. The main technical issues and pitfalls relating to MAI measurement and the preparation and growth models used are included. This paper concentrates primarily on presenting data for the most important industrial species. A brief description of major efforts to improve data on plantation growth performance and make it more accessible is described.

Currently, eucalypts and pines are the most commonly used species in tropical timber plantations; together, they account for 43 percent of all tropical plantation area. Pines dominate temperate and boreal plantations; 54 percent by area. Productivity of tropical plantation forests grown on short to medium-term rotation lengths varies greatly from 1-2 m^3 ha^{-1} yr^{-1} to 25-30 m^3 ha^{-1} yr^{-1}.

The large variability found on productivity is due mainly to species behaviour, site quality, genetic material, plantation age and silvicultural management. Growth increment and quality yields vary considerably even between varieties, as is the case of *P. caribaea*.

Eucalypts are recognized as the some of the fastest growing trees and some of them are preferred because of its high growth rate, short rotation length (10 years) and favourable pulpwood properties.

For the most fast growing species growth rates are highest with favourable temperatures and where there is high soil water-storage capacity and good fertility. However, sustaining tree productivity in the future will depend on maintaining soil fertility levels in subsequent plantation rotations.

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1. INTRODUCTION

Forest plantations, which are expanding rapidly in the tropics and sub-tropics will clearly play a very important role in the future world wood supply (see Working Paper FP/ paper 13). Currently, eucalypts and pines are the most commonly used species in tropical timber plantations (Evans 1992); together, they account for 43 percent of all tropical plantation area (FAO 1999). Pines dominate temperate and boreal plantations; 54 percent by area (FAO 1999).

Productivity of tropical plantation forests grown on short to medium-term rotation lengths varies greatly from 1-2 m^3 ha^{-1} yr^{-1} to 25-30 m^3 ha^{-1} yr^{-1} (Table 1 and Appendix 1). A similar range is found in temperate countries (Evans 1992, FAO 2000). Higher yields have been reported for some species and situations. However, while the potential for achieving high productivity is clearly evident, there are many constraints on yield (see Working Papers FP/3 and 15) and perhaps sustainability (see Working Paper FP/2) or environmental concerns.

Table 1. Productivity and rotation lengths for main forest plantation trees in selected tropical countries

Species	**Region**	**Country**	**Rotation length (yr)**	**MAI (m^3 ha^{-1} yr^{-1})**
Eucalypts	S. America	Brazil	8-10	18-20
	Africa	Burundi	8	1-2
		Congo	7	30
		Rwanda	8	8.5
		South Africa	8-10	18-20
Pines	S. America	Brazil	16-25	15-25
		Venezuela	10-20	10
		Chile	20-30	24
	Africa	Malawi	20-25	17
		Madagascar	15-18	6-10
		Mozambique	18-25	11
Teak	Asia	Bangladesh	60	2.6-3
		India	70	2.5
		Indonesia	50-70	1.3-2

Source: Brown *et al* 1997.

This paper focuses on the main tropical and subtropical forest plantation species. The key measurements discussed are mean annual increment and rotation length. Mean annual increment (MAI) is defined here as the merchantable stand volume at harvesting divided by the stand age (rotation length), although in some instances MAI for pre-harvesting stands are also discussed. Unless otherwise stated these are over-bark log volumes. It should be noted these do not take into account losses during conversion to sawn timber, plywood, pulp etc.

2. *EUCALYPTUS* SPECIES

The Australian eucalypts have been among the most widely used and successful plantation trees. Only a few 500 species have potential in industrial plantations (FAO 2000). Jacobs

(1981) suggested that a MAI of 10-15 m^3 ha^{-1} yr^{-1} was commonly obtained from the large scale plantations, but more recent experience suggests that on many sites faster growth rates are possible (Appendix 1). Eucalypts are recognized as the some of the fastest growing trees. The dominant trees on fertile sites at Gogol, near Madang, Papua New Guinea reached 38 m in height and 39 cm in diameter breast height over bark (DBHOB), at three years of age; this was equivalent to an MAI of 80-90 m^3 ha^{-1} yr^{-1} (Eldridge *et al*. 1993).

These faster growth rates result from using careful site selection, intensive cultural practices, selection of the best species and provenances, and genetic improvement (see also Working Papers FP/3 and 4). Small sample plots of eucalypt aged 6-8 years in East and West Africa, Brazil, and Papua New Guinea have had MAIs up to 100 m^3 ha^{-1} yr^{-1}.

More typical of fast growing stands, however, is the productivity of South Africa eucalypts (mainly *Eucalyptus grandis* and its hybrids). There the average productivity is 21 m^3 ha^{-1} yr^{-1} (MAI of 15-55 m^3 ha^{-1} yr^{-1}) (Du Toit *et al.* 1998).

In Brazil, where there are about four million hectares of eucalypts, the MAI is commonly between 5 and 35 m^3 ha^{-1} yr^{-1}, on rotations from 5 to 21 years. The majority of these plantations are *E. grandis* grown on 5-10 year coppice rotations (Turnbull 1999). Intensive breeding and silviculture has been reported as raising MAI from 33-70 m^3 ha^{-1} yr^{-1} for *E. grandis* and *E. urophylla*. In Chile, an example of more temperate climates, the MAI for *E. globulus, E. nitens or E camaldulensis* ranges from 10-40 m^3 ha^{-1} yr^{-1} at 10 years (Pinilla *et al*. 1999).

Growth rates tend to be lower in India. The productivity of eucalypt plantations in Kerala, for example, are estimated to be 5-10 m^3 ha^{-1}yr^{-1}. The causes are climate, soils, species used, (e.g. *E. tereticornis*) and silvicultural. One possible cause of the poor productivity is soil fertility deterioration from successive crop rotations (Sankaran 1998).

Species widely used in the tropics are described in more detail below.

2.1 Eucalyptus camaldulensis

Of all eucalypts, *E. camaldulensis* has the widest distribution in Australia (Lamprecht 1990). *E. camaldulensis* plantation yields in the drier tropics are often about 5-10 m^3 ha^{-1} yr^{-1} on 10-20 year rotations, whereas in moister regions, volumes up to 30 m^3 ha^{-1} yr^{-1} may be achieved (Evans 1992). Typical growth rates are given in Table 1.

Table 1. Annual volume increment in Eucalyptus camaldulensis plantations in different parts of the world, at rotations of 7-15 years

Country	MAI (m^3 ha^{-1} yr^{-1})
Argentina	20-25
Israel (irrigated plantation)	30
Turkey (heartwood growth)	17-20
Turkey (1st coppice generation)	25-30
Morocco	3-11
Portugal	2-10
Italy	6-7

Source: Lamprecht 1990.

Total volume production of 45 m^3 ha^{-1} at 3 years has been reported in Colombia (Newman 1981).

Otarola and Ugalde (1989) found the MAI for *E. camaldulensis* at 4.5 years varied between 12.5 and 17.6 m^3 ha^{-1} yr^{-1} in Guatemala, while in Nicaragua it ranged from 2.4-16.8 m^3 ha^{-1} yr^{-1}. The variation in MAI with age shown in Table 2 are from four spacing experiments (Leña and Madeleña Projects).

Table 2: MAI of E. camaldulensis at young stand ages in Nicaragua.

Stand age	MAI (m^3 ha^{-1} yr^{-1})
2.8	2.4-16.8
4.2	9.8-10.6
4.5	11.0-11.7
5.4	12.3-16.7

Source: Otarola and Ugalde (1989)

2.2 Eucalyptus deglupta

E. deglupta has great potential for planting in humid tropics. Growth rates are excellent on suitable sites (25-40 m^3 ha^{-1} yr^{-1} over 15 year in Papua New Guinea), and the wood and bark are good sources pulp fibre (Eldridge *et al*. 1993). Yields of 20-40 m^3 ha^{-1} yr^{-1} are common in several countries (National Academy of Sciences 1983). Some major industrial projects are now under way in the tropics based, at least in part, on reforestation using this species in fast-growing plantations, for short rotations of 10-12 years or less and considerable database has been assembled on its performance. The Philippines and Indonesia, followed by Brazil, have the most extensive plantations (Eldridge *et al*. 1993).

Despite *E. deglupta's* spectacular growth rate and suitability for pulp, initial enthusiasm for planting it has been somewhat tempered in many countries by plantations being poorly sited. It is extremely site-sensitive, very susceptible to fire, does no coppice readily, and is susceptible to a variety of pests and diseases (Eldridge *et al*. 1993). Costa Rica is a good example. Stands of 2-4 years old in Costa Rica had MAIs ranging between 2 and 39 m^3 ha^{-1} yr^{-1} (Sánchez 1994). The maximum recorded in Costa Rica is 89 m^3 ha^{-1} yr^{-1} over 4.5 years (Ugalde 1980). Chavarria (1996) has identified three site classes (Table 3).

Table 3: Site classes for E. deglupta in Costa Rica

Site Class	Average stand ages (yrs)	MAI (m^3 ha^{-1} yr^{-1})
I	9.5	28.5
II	7.0	11.7
III	8.4	4.4

Based on Chavarria (*1996*)

Paper Industries Corporation of the Philippines (PICOP) has extensive *E. deglupta* plantations in Mindanao. In plantations with an initial stocking of about 625-680 stems ha^{-1} an average yield of 25-30 m^3 ha^{-1} yr^{-1} (overbark to 10 cm top diameter) is expected over a ten year rotation. Much higher yields of 40-60 m^3 ha^{-1} yr^{-1} (total volume over bark) can be obtained from higher stocking on above average sites in Mindanao. This species is no longer planted commercially in Sabah, Malaysia, because growth slowed significantly after five years (Eldridge *et al*. 1993).

2.3 *Eucalyptus globulus*

E. globulus was the first of the eucalypts to become widely known outside Australia. The wood is used largely for pulpwood, firewood, and mine timbers. Plantations are often coppiced two or three times on rotations of about 8 to 12 years, or allowed to grow to a large size for sawn timber, although growth stresses result in low outputs of high-quality boards. MAIs of more than 20 m^3 ha^{-1} yr^{-1} (over 40 m^3 ha^{-1} yr^{-1} is reported) can be obtained on the best sites (Table 4). But generally, 10-15 m^3 ha^{-1} yr^{-1} is regarded as an achievable yield for this species over large areas (Jacobs 1981, Eldridge *et al.* 1993).

Table 4: Selected reported growth rates for E. globulus.

Location	Rotation (years)	MAI (m^3 ha^{-1} yr^{-1})	Reference
Argentina		30	Mangieri and Dimitri 1961
Australia – Tasmania	17	35	Hillis and Brown 1984
Australia – Western (SW)	10		O’Connell and Grove 1998
Ethiopia		30	Davidson 1989, Pohjonen and Pukkala 1990
Chile	15-16	13-44	INFOR 1986

In the south of West Australia, *E. globulus* is preferred because of its high growth rate, short rotation length (10 years) and favourable pulpwood properties. These plantations are established on agricultural land because productivity is much lower on recently cleared land and because farm forestry is being promoted. Growth rates are high due to favourable temperatures, abundant incident radiation and the deep-soil water-storage capacity required to maintain growth during the hot, dry summer period (Table 4). Sustaining tree productivity in the future will depend on maintaining soil fertility levels in subsequent plantation rotations (O'Connell and Grove 1998).

In Argentina, according to Mangieri and Dimitri (1961), *E. globulus* achieves MAIs of 30 m^3 ha^{-1} yr^{-1}, and in Chile 40 m^3 ha^{-1} yr^{-1}. Plantations are established on high quality lands, because yields and gains are more certain and risks lower, than they would be for cereal crops, alfalfa, etc.

2.4 *Eucalyptus grandis*

E. grandis is probably most widely planted eucalypt for industrial wood production, with an estimated plantation area of about 2 million ha in 1987 (Burgess 1988). Most of these are in Brazil and South Africa, but there also large plantation areas in Argentina, Australia, India, Uruguay, Zambia and other countries (Eldridge *et al*. 1993). In Africa, *E. grandis* volume yields higher than 25 m^3 ha^{-1} yr^{-1} are often achieved, provided site conditions are favourable, and appropriate silvicultural treatments are applied (Eldridge *et al*. 1993). Table 5 summarises selected growth data from a number of countries. It also illustrates how growth varies with site and silviculture.

There is evidence, particularly in Kenya, that the second coppice rotation out-yields the seedling rotation; the initial crop averaged 178 m³ ha-¹ at 6 years, while subsequent coppice crops averaged 277 m³ ha-¹ for the same period (National Academy of Sciences 1980). The usual rotations in Kenya are 6 years for domestic woodfuel, 10-12 years for industrial woodfuel, and 7-8 years for telephone poles (National Academy of Sciences 1980).

Table 5: Selected reported growth rates for E. grandis.

Location	Rotation or stand age (years)	MAI ($m^3ha^{-1}yr^{-1}$)	Reference
Australia - NSW	29	16	Hillis and Brown (1984)
Brazil – Aracruz Florestal	7	55	Evans (1992)[a]
Costa Rica	2-4	1-49	Sánchez (1994)
Costa Rica	6.5	49-112	Vásquez & Ugalde (1995)[b]
South Africa		35	NAS 1980
Swaziland – Shiselwene Forestry	9	18	Evans (1992)
Uganda		17-45	NAS 1980
Zimbabwe		40	NAS 1980[c]

a. Clonal plantations – some were higher than this
b. Experiment with fertilizer and spacing
c. With irrigation

2.5 *Eucalyptus robusta*

E. robusta trials have been established in many different countries (Fenton *et al*. 1977).

Table 6: Selected reported growth rates for E. robusta.

Location	Rotation or stand age (years)	MAI ($m^3ha^{-1}yr^{-1}$)
Brazil		10-35
Chile		10-35
Florida	10	16.8
Hawaii	23-38	26
Madagascar		10-35
Mauritius		10
Malawi		21
India		21
Malaysia		21
Papua New Guinea		21
Zaire		20-30

Source: NAS 1983

2.6 Eucalyptus saligna

There are large plantations of this species in many parts of Africa (e.g. Angola), South America (e.g. Brazil), and elsewhere (Lamprecht 1990). With 25-year rotations, average volume increments are between 36 and 53 m^3 ha^{-1} yr^{-1} on suitable sites. Under less favorable conditions, e.g. in poor soils, the increments can be considerably lower (Lamprecht 1990).

A MAI of 89.5 m^3 ha^{-1} yr^{-1} at 7 years old has been reported from Brazil (Betancourt 1987).

2.7 Eucalyptus urophylla

The largest *E. urophylla* plantations are in Brazil. In recent years the popularity of this species has increased markedly for plantations in humid and sub-humid tropical climates that endure several months of drought annually (the wet/dry tropics) such as parts of Indonesia, Brazil and southern China (Eldridge *et al*. 1993). Yields of 20-30 m^3 ha^{-1} yr^{-1} have been reported under favourable growing conditions.

Provenance selection is very important with low-altitude provenances usually giving the highest yields (National Academy of Science 1983). In a trial near Edea, Cameroon, Africa an 8-year *E. urophylla* rotation on a suitable, well-prepared site obtained a MAI of 30 m^3 ha^{-1} yr^{-1} following provenance screening (Eldridge *et al*. 1993). At Mangombe, Cameroon (altitude 30 m, rainfall 2,600 mm) the MAI from a low-altitude source near Mt Egon, Flores was 83 m^3 ha^{-1} yr^{-1} at age 8 years (Eldridge *et al*. 1993). In Loudima, in the Republic of Congo, growth of the Mt Lewotobi provenance from Flores was approximately 40 m^3 ha^{-1} yr^{-1} at 5 years (Eldridge *et al.* 1993).

In southern China there are about a million hectares of eucalypt plantations, mainly *E. urophylla*, *E. grandis* and *E. camaldulensis,* most of which have been established since the 1980s. Because past land use has degraded the soils, productivity has been very low (5-10 m^3 ha^{-1} yr^{-1}), and highly variable (3 to 30 m^3 ha^{-1} yr^{-1}) (Bai and Gan 1996). Both genetic improvement and fertilizer applications are required to sustain or improve productivity (Xu *et al*.1998, Turnbull 1999).

3. *PINUS* SPECIES

Tropical pine species play an especially important role in modern plantation forestry. Several species, mostly originating from the American or Asian tropics and subtropics are now widely cultivated (Appendix 1). Pines enjoy such great popularity because:

- the large number of species allow choice for widely varying environmental conditions;
- many thrive on a wide range of sites;
- many flourish in dry, nutrient-poor soils or degraded sites;
- the volume production of some species can be high to very high, even under unfavourable site conditions;
- being robust pioneer species, pines are well suited for reforestation and for simple silviculture (monocultures and clear-felling);
- wood qualities that are otherwise in limited supplies in the tropics - of uniform coniferous wood valued for production of lumber, chemical pulp, paper, particleboard, etc (Lamprecht 1990).

In the Southern Hemisphere the Central and North American pines predominate; *Pinus patula*, *P. taeda*, *P. elliottii*, *P. caribaea* and *P. radiata*. For example, the first three species are planted in South Africa in summer rainfall zone and their average productivity is 15 m^3 $ha^{-1}yr^{-1}$ (Du Toit *et al.* 1998). *P. radiata* is widely used in summer-dry climates. Brazil, with its humid summers, largely uses *P. caribaea, P. taeda* and *P. elliottii.* Pines in Brazil produce 8-30 m^3 ha^{-1} yr^{-1} on rotations of 20-25 years.

3.1 *Pinus caribaea* var. *caribaea*

P. caribaea plantations are found throughout the tropics and in some parts of the subtropics: in Africa from Nigeria to South Africa; Latin America from Puerto Rico to Brazil; Asia from Malaysia to India; and in Oceania from New Guinea to Australia (Lamprecht 1990). A MAI of 21-40 m^3 ha^{-1} yr^{-1} can be achieved on suitable sites for up to 13 years of age (National Academy of Sciences 1983), but average growth rates are often lower than the upper figure (Appendix 1, Evans 1992).

Within its native habitat, this variety of *P. caribaea* has low standing volumes and growth increments. An inventory performed on nearly 7,000 ha in Guatemala found the standing volume was 46.3 m^3 ha^{-1} (± 26%), with a MAI of 2.6 m^3 ha^{-1} yr^{-1} (Lamb 1973). Annual increments between 3 and 37 m^3 ha^{-1} have been measured on plantations in Queensland, Australia. The lower figure indicates that *P. caribaea* plantations were not justified on all sites. However, on suitable sites between 30° N/S latitude a MAI of between 17.5 and 21 m^3 ha^{-1} yr^{-1} (under bark) can be expected until the trees are 15 years old (Lamb 1973). In 15 to 20-year-old trees the bark accounts for 20-30% of total stem volume (Lamprecht 1990).

3.2 *Pinus caribaea* var. *hondurensis*

Growth increment and quality yields vary considerably between the two varieties of *P. caribaea*. In general var *hondurensis* is faster growing but of poorer quality (Lamprecht 1990, Martin 1971, Lamb 1973, Rollet 1980). Thus the average MAI for *Pinus caribaea* var *hondurensis* is between 20 and 50 m^3 ha^{-1} yr^{-1} compared to 10-20 m^3 ha^{-1} yr^{-1} for *P. caribaea* var *caribaea* (Appendix 1).

In South Africa, this species has average MAIs of 22 m^3 ha^{-1} yr^{-1} (v. Meyenfeldt *et al.* 1978); on the best sites it has attained an annual increment of 35-42 m^3 ha^{-1} yr^{-1} at age 14 years (Lamprecht 1999). In Panama growth rates tend to be slower. Here the MAI fluctuates between 5 and 22 m^3 ha^{-1} yr^{-1} (outside bark) with an average of 11 m^3 ha^{-1} yr^{-1} at age 7-11 years (Gewald 1986).

Table 7 illustrates how the MAI in *P. caribaea* var *hondurensis* continues to rise up to 24-25 years of age (Wadsworth 1997).

Table 7: Mean annual volume increment of Pinus caribaea var hondurensis in Trinidad as related to age and site quality

Age (years)	MAI (m^3 ha^{-1} yr^{-1})
Site I	
0	-
10	14
15	17
20	19
25	20
Site II	
0	-
12	12
18	14
24	16

Source: Wadsworth 1997.

3.3 *Pinus oocarpa*

The natural range *of P. oocarpa* extends from 12° N in Nicaragua to 28° N in northwestern Mexico (Lamprecht 1990). In Costa Rica, the mean annual volume increment for a 12 year-old trial stand is 22 m^3 ha^{-1} yr^{-1} (unthinned trial stand); this value can be considered representative of the average yield obtained on *P. oocarpa* plantations (Lamprecht 1990). Plantation-grown trees have MAIs ranging from 10-40 m^3 ha^{-1} yr^{-1} (Appendix 1).

3.4 *Pinus patula*

Pinus patula is native to Mexico where its range is limited and disjointed. *P. patula* plantations are concentrated in eastern, central and southern Africa, which together account for over 95% of the total area planted with this species (Lamprecht 1990). Depending on site factors and intermediate treatment, the mean annual volume increments with 30-40 year rotations vary between 8 and 40 m^3 ha^{-1} yr^{-1} (Appendix 1). Examples from a range of countries are given in Table 8.

The possibility of a decline of productivity with successive rotations of this species has been studied in Swaziland and no evidence has been found (see Working Paper FP/2).

Table 8. Examples of the MAI for Pinus patula growing in different countries.

Country	Age (years)	MAI (m^3 ha^{-1} yr^{-1})	Reference
Brazil		21-36	Wormald (1975)
Columbia	10	20 (thinned plots)	Ladrach (1986)
South Africa		15-20	Lamprecht (1990)
Swaziland	14	20	Wadsworth (1997)
Tanzania	25	18.2 (heavy thinning) 21.8 (medium thinning)	Sommer and Dow (1978)
West Bengal, India	19	25.0	Sommer and Dow (1978)
	33	22.2	
	38	37.1	

3.5 *Pinus radiata*

Pinus radiata naturally occurs only on the Californian coast (35-37°N) and 800 km further south on Guadeloupe Island. For over 80 years it has been grown as large plantations in the temperate Southern Hemisphere countries of Australia, New Zealand, South Africa and Chile (Lamprecht 1990). The MAI over 25 years is often 25-30 m^3 ha^{-1} yr^{-1} (Lamprecht 1990). However in New Zealand growth rates of up to 50 m^3 ha^{-1} yr^{-1} having been recorded on the best sites and as low as 11 m^3 ha^{-1} yr^{-1} on very dry sites (Burdon and Miller 1992). On average New Zealand has higher growth rates than the other major growers of this species, despite the heavier thinning schedules.

4. OTHER SPECIES

4.1 *Acacia mearnsii* and *A. auriculiformis*

In South Africa *A. mearnsii* is planted as a dual-purpose crop for timber and tanbark. The average productivity is 12 m^3 ha^{-1} yr^{-1} (Du Toit *et al.*1998). In Indonesia, short rotations of 7-10 years or less, are the most economical. This produces MAIs of 10-25 m^3 ha^{-1} yr^{-1} (National Academic of Sciences 1980). In Rio Grande do Sul, Brazil, 100,000-140,000 ha of 7 years-old stands produce 160 m^3 of piled wood for cellulose, 20 m^3 piled wood for firewood and 16 tonnes of green bark for tannin (personal communication, A. Higa, Brazil).

A. auriculiformis occurs naturally in humid areas of Australia, Papua New Guinea and Indonesia. A MAI of 15-20 m^3 ha^{-1} at 10-12 years can be expected from *A. auriculiformis* plantations under favourable conditions but production is lower on infertile soils where there is a prolonged dry season. Selection of suitable provenances can increase plantation productivity (Pinyopusarerk 1990). In humid, fertile areas of Indonesia and Malaysia, MAI are 17-20 m^3 ha^{-1} yr^{-1} on rotations of 10-12 years; on poor soils this reduces to 10 m^3 ha^{-1} yr^{-1}. However, in semiarid West Bengal on shallow soils, yields were only 5 m^3 ha^{-1} yr^{-1} at the 15th year (National Academic of Sciences 1980).

4.2 *Araucaria angustifolia* and *A. cunninghamii*

The natural range of *A. angustifolia* is concentrated in the three southernmost Brazilian states of Paraná, S. Catarina and Rio Grande do Sul (Fähser 1981, Lamprecht 1990). *A. angustifolia* is an economically valuable tree species with even the first thinnings yielding marketable wood. In plantations with nutrient-rich, well-drained soils MAIs of 20 m^3 ha^{-1} yr^{-1} have found; a typical range is from 8-24 m^3 ha^{-1} yr^{-1} (Appendix 1). According to Hosokawa (1976), the rotation period for maximum yield in terms of volume is 35-40 years, but at least 90 years for maximum yield in term of value. Yield tables suggested that the MAI occurs at about year 20 regardless of site (Heinsdijk 1972). In Brazilian plantations, with 40-year rotations and increments of between 6 and 20 m^3 ha^{-1}, 5 thinnings are carried out at ages 10, 13, 16, 20 and 25 years (Nock 1981, Lamprecht 1990).

Wood (cited in Burley and Wood 1976) lists cases where the MAI was over 45 m^3 ha^{-1} yr^{-1} for plantation grown *A. cunninghamii* (Lamprecht 1990). However, typically growth rates are from 10-18 m^3 ha^{-1} yr^{-1} (Appendix 1).

4.3 *Casuarina equisetifolia*

C. equisetifolia occurs naturally in coastal areas of Australia. It is cultivated throughout the tropics and subtropics, especially in coastal and semiarid regions, but also in mountainous zones (Lamprecht 1990). On favourable sites, *C. equisetifolia* can yield MAIs of 15 m^3 ha^{-1} at 10 years (Pinyopusarerk and House 1993). Height growth tapers off when the trees are 7 year old, and volume increments at about 20 years (Table 8). While trees can attain ages of 40-50 years, rotations of 8-15 years are used for production of woodfuel (Lamprecht 1990). Depending on site quality, a MAI of 6-20 m^3 ha^{-1} yr^{-1} can be expected (Appendix 1, Table 9).

Table 9. Reported MAIs for Casuarina equisetifolia.

Country	Age (years)	Height (m)	D. b. h. (cm)	MAI (m^3 ha^{-1} yr^{-1})	Reference
Asia	5	7-10	6-10	3-4	Lamprecht (1990)
	10	13-15	12-15	5-6	
	15	17-19	20-25	6-8	
	20	21-23	30-40	7-10	
	25	24-28	40-45	7-10	
Southern China	10-15*	-	-	4-5	Turnbull (1983)
Columbia	3	-	-	8	Newman (1981)
West Bengal, India	12-15*	-	-	11	Ray (1971)

. * Rotation age

4.4 *Cordia alliadora*

C. alliadora occurs widely in Latin America, from 25°N in Central Mexico to 25°S in the Argentine provinces of Misiones. It is primarily cultivated within its native range, but is also grown in Mauritius, Nigeria and Sierra Leone (Lamprecht 1990). *C. alliadora* produces a highly marketable wood (Lamprecht 1990).

This species also thrives well in associations with cocoa. At age 15 years and 180 stems per hectare a standing volume of 308 m^3 ha^{-1} at Siquirres, Costa Rica (CATIE 1979). The usual MAI is 10-20 m^3 ha^{-1} yr^{-1} (Appendix 1).

4.5 *Cupressus lusitanica*

C. lusitanica is native to Central America extending southwards from 21°N, encompassing Mexico, Guatemala, El Salvador and Honduras. Outside its native range, it is grown extensively in Spain, Portugal, southern and eastern Africa, and in South America (Lamprecht 1990). On 40-year rotations the MAI is usually 8-15 m^3 ha^{-1} yr^{-1}, although the range of increments is greater than this (Appendix 1). In southern and eastern Africa the final yield is approx. 350-560 m^3 ha^{-1} (plus about 150 m^3 from thinnings) (Lamprecht 1999).

Table 10. Reported MAIs for Cupressus lusitanica.

Country	Age (years)	MAI (m^3 ha^{-1} yr^{-1})	Reference
Sao Paulo, Brazil	-	24.5	Soares (1973)
Africa	-	6.8-20	Soares (1973)
Costa Rica	-	21.6-23.6	Alfonso *et al.* (1965)
Costa Rica	15	25	Bucarey (1967)
	20	23	
	30	23	
	35	23	
	40	22	

Bucarey (1967) estimated mean annual volume increments of 22 m^3 ha^{-1} yr^{-1}, under Costa Rican conditions, with extraordinary values of up to 41 m^3 ha^{-1} yr^{-1}. Furthermore, MAI was slightly higher at age 15 years than at ages 20, 30, 35 and 40 years (Table 10).

Generally under good conditions the MAI for *C. lusitanica* should reach 20 - 30 m^3 ha^{-1} yr^{-1}. Lower figures indicate unsuitable sites, poor genotypes, or inadequate management. Chaves and Fonseca (1991) suggest that a well-managed stand should achieve increments higher than 30 m^3 ha^{-1} yr^{-1}.

4.6 Dalbergia sissoo

D. sissoo is planted in many parts of India and Pakistan and shows promising results, with irrigation, in the Sudan. It has been less successful in Ghana, northern Nigeria, northern Cameroon, and Togo; however, it is being increasingly planted as a street tree in southern Florida. There are experimental forestry plantings in Puerto Rico, the West African Sahel, South America, and the Middle East (National Academy of Sciences 1983).

Yield on 10 year rotations can reach 9-15 m^3 ha^{-1} yr^{-1} but lower yields are more typical (Appendix 1). Growth is strongly dependent on soil conditions.

4.7 Gmelina arborea

Gmelina arborea is native to the Indian subcontinent, southern China, Southeast Asia and the Philippines. *G. arborea* plantations have been established throughout the humid tropics where it only attains high MAI of 20-25 m^3 ha^{-1} on fresh, well-drained, fertile soils (Lamprecht 1990). Rotations of 5-8 years seem most common; MAI is usually between 12 and 50 m^3 ha^{-1} yr^{-1} (Appendix 1).

Experiences from three South American countries emphasise the wide range of growth rates. In Brazil, *G. arborea* was reported to be yielding 38 m^3 ha^{-1} yr^{-1} on a 10-year rotation. In Colombia total volume production was 27.5 m^3 ha^{-1} at 3 years (Newman 1981). In Costa Rica MAI ranges between 7.1 and 55 m^3 ha^{-1} yr^{-1} (Vásquez and Ugalde 1994).

In *G. arborea* plantations at Ston Forestal,Costa Rica, Zeaser (1999) used permanent plot data to study the growth dynamics of the species. The maximum MAI in these unthinned stands occurred about age 5 (Class 1A, 1, 2 and 3) or 6 (Class 4) years (Table 11). This is in contrast to a study in the Philippines where the MAI was still increasing at age 8 years (Nanagas and Serna (1970). The MAI, for the Costa Rica study, of site quality 1A and1 converged after 7 years while the lower site qualities (Sites 3 and 4) apparently converged after year 8 (Table 11). This affect was attributed to reducing basal area growth, at high stockings, occurring earlier on more fertile sites. Total chipwood and sawlog volumes at age 8 years on good sites are about double those on poor sites (Table 11).

Table 11. Effect of site on merchantable volumes at age 8 years and MAI, by age, for G. arborea in Costa Rica.

Age (year)	Class 1A	Class 1	Class 2	Class 3	Class 4
	----------------------------MAI ($m^3 ha^{-1} yr^{-1}$)----------------------------				
2	49.8	48.3	30.8	23.9	10.0
3	56.3	51.5	36.8	30.7	17.1
4	59.9	53.2	40.8	34.7	22.0
5	60.6	53.4	42.8	35.9	24.7
6	58.6	52.1	42.9	34.3	25.2
7	53.7	49.2	41.1	30.0	23.5
8	45.9	44.9	37.2	22.9	19.6
	----------------------Pulpwood volume ($m^3 ha^{-1}$)------------------------				
8	385	372	319	225	173
	------------------------Sawlog volume ($m^3 ha^{-1}$)--------------------------				
8	183	170	156	129	78

Source: Zeaser (1999).

4.8 *Leucaena* spp

Leucaena originated in tropical Latin America, probably in Mexico. It was introduced very early on (16 to18th century) to the Pacific islands, the Philippines, Indonesia, Papua New Guinea, Malaysia and East and West Africa (Lamprecht 1990).

More than 100 varieties are known. According to the National Academy of Sciences (1977), these can be assigned to 3 groups:

a) Hawaiian group;
b) Salvadoran group;
c) Peruvian group.

The Salvadoran group produces industrial woodfuel and pulpwood on 8-year coppice rotations; the MAI is 30-40 $m^3 ha^{-1} yr^{-1}$ with a maximum of 100 $m^3 ha^{-1} yr^{-1}$ (Lamprecht 1990). Others have suggested dense leucaena stands often achieve 40-50 $m^3 ha^{-1} yr^{-1}$ (National Research Council 1984).

4.9 *Swietenia macrophylla*

The natural habitat of *S. macrophylla* is between 20° N and 18° S, extending from the Yucatan in Mexico, across Central America, Colombia and Venezuela to the western Amazonian lowlands in Ecuador, Peru, Brazil and Bolivia. Today it is cultivated throughout the tropics on 40-60 year rotations with a likely MAI of 7-30 $m^3 ha^{-1} yr^{-1}$ (Appendix 1). On the

Antilles a MAI of 15-20 m^3 ha^{-1} yr^{-1} have been achieved with 40-50 year rotations (Lamprecht 1990).

Pure mahogany plantations in Indonesia reach a maximum MAI of 18 m^3 ha-^{1} yr-^{1} in 20 years on the best sites; on poor sites, the maximum MAI of 13 m^3 ha-^{1} yr-^{1} may not be achieved until 50 years. Plantations in Martinique have a maximum MAI of over 30 m^3 ha-^{1} yr-^{1} on the best sites (Tiller 1995), although 14-25 m^3 ha-^{1} yr-^{1} are more usual. Plantations in neighbouring Guadeloupe are less productive, with the best giving 17 m^3 ha-^{1} yr-^{1} over the first 25 years (Soubieux 1983, Mayhew and Newton 1998).

4.10 Tectona grandis

The natural distribution of Teak (*T. grandis*) is in South and Southeast Asia. Examples from a range of countries are given in Table 12.

Table 12. Examples of the MAI for Tectona grandis growing in different countries.

Country	Age (years)	MAI (m^3 ha-^{1} yr-^{1})	Reference
India	60-80	4-8*	Evans (1992)
Costa Rica	4-8	5-27	Vázquez and Ugalde (1994)
Guanacaste, Costa Rica	21	15-20	Lamprecht (1990)
Java	80	2-15	Wadsworth (1997)

* Possible range in growth rates is considerably larger than this.

In parts of Asia, extremely poor growth rates of between 2 and 3 m^3 ha-^{1} yr-^{1} have been reported. It is estimated that the average yield obtained in Kerala and Bangladesh could be doubled, while in Indonesia it is considered a six fold increase is possible (Pandey 1992).

As in parts of Asia there are very few well-managed teak plantations in Central America and the Caribbean. The aim should be to obtain at least 8 m^3 ha-^{1} yr-^{1} which is feasible on all suitable sites (Keogh 1996).

4.11 Terminalia ivorensis **and** *T. superba*

The range of *T. ivorensis* is smaller than *T. superba* being confined to 4-10° N, between Guinea and Cameroon. The natural distribution of *T. superba* stretches from Sierra Leone, through Ivory Coast, Ghana, Togo, Benin, Nigeria, Cameroons and well inland into the Central African Republic and the Congo (Lamprecht 1990, Fenton *et al*. 1977).

Few growth and yield data have been published. The average MAI of *T. ivorensis* have been reported as 8-17 m^3 ha-^{1} yr-^{1}, and *T. superba* between 10 and 14c [1]m^3 ha-^{1} yr-^{1} (Wadsworth 1997; Appendix 1)

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[1] The letter "c" shown after the MAI figures indicates that the species reportedly coppices well enough for one or more coppice crops. These commonly exceed in yield the seedling crops cited in the MAI figures.

5. DIFFICULTIES TRANSLATING TRIAL DATA TO THE FIELD

Experiments are much more worthwhile if they have predictive value applicable to large areas or regions. However, this basic requirement is commonly either overlooked or given so little thought, that many experiments are sometimes not truly representative. It is dangerous to extrapolate results to conditions that are very different from those of the study area. This often occurs because experiments are located in accessible or convenient areas, a practice usually advisable only for exploratory research (Wadsworth 1997).

The interpretation of research results should consider all the important values such as wood quality and non-wood products. Plantation productivity, for example, is usually expressed in terms of volume (or aboveground biomass) per unit of area and time. However, under some circumstances, the maximum volume yield per unit investment or per unit of employment may be most meaningful (Wood 1974, Wadsworth 1997).

Excessive site heterogeneity and strong border effects can results unless these are considered during the experimental design. Long-term (> 10 years) research, needed to provide reliable recommendations, requires:

1) A diversified agenda that includes a "basket of research alternatives", including extreme treatments, to respond to unpredictable conditions, a varied clientele and changing perceptions;
2) Replicated experiments with good error control, located over a range of sites. This allows for losses due to natural disasters, human interference or shifts in motivation, plus sound application of results and perhaps future modelling;
3) Large plots (e.g. 36 x 36 m) to allow for possible thinning, with adequate treated borders (Powers *et al.* 1994, Somarriba *et al*. 2000).

6. GROWTH MODELS

Forest volume growth and yield are often viewed as functions of site quality, age, and some measure of stand density, as well as interactions among these variables. Stand density, in turn, is taken to be a function of site quality, age, and an initial measure of stand density. Site quality, expressed by site index, depends on the development of dominant height in relation to age (Clutter *et al*. 1983). It is apparent that forest growth and yield modellers deal with an interdependent system with underlying growth processes. Each equation in such a system describes a different relationship among a different set of the variables in the system, but all relationships are assumed to hold simultaneously. However, in most cases, the interdependence inherent in stand dynamics is ignored in model fitting. It is customary in forest procedures to obtain parameter estimates for each model separately, within a model system (Borders and Bailey 1986).

Growth models are of limited use on their own, and require ancillary data to provide useful information. With suitable inventory and other resource data, growth models provide a reliable way to examine silvicultural and harvesting options and to determine the sustainable timber yield for different areas and management strategies (Vanclay 1994). Growth models may also have a broader role in regional forest management and in the formulation of forest policy.

Sommer and Dow (1978) suggested there is often an evolutionary trend in the development of growth and yield data:

a) production statements;
b) production series;
c) provisional yield tables;
d) normal yield tables;
e) empirical yield tables;
f) variable density yield tables;
g) yield regulation and management tables;
h) growth simulation models

Few tropical and subtropical countries have sufficient plantation experience with most exotics to reach the stage of yield regulation tables. Consequently their data falls mostly into the first two categories. Some countries have produced provisional or tentative yield tables of one kind or another but only those with long experience and a large database are in a position to construct comprehensive yield-regulation tables or management manuals (Sommer and Dow 1978). However, advanced computer simulation models are available for some species (see below).

The greatest obstacle to developing advanced simulation models for many tropical forests is that suitable data is not available. Often yields are estimated by extrapolating models developed elsewhere or using generalised information such as is presented in this report.

Forest growth models fall into a number of groups, each of which is characterized by a central design paradigm, and each of which is most suitable for a particular situation. The selection of a modelling paradigm is driven mainly by currently or potentially available data, and the objectives for which the model is to be constructed (Alder 1995). Vanclay (1994) noted that there is no best method for forest growth models.

A completed model must undergo a process of validation or testing. This is both an ongoing and terminal activity. Ongoing validation is an integral part of the development of a model, whilst terminal validation seeks to define the limits of predictive capability (Alder 1995).

Simulation modelling has been motivated by the financial and policy structures of plantation forestry with close industrial link. This electronic method permits the construction of growth models by iterative solution. Such models can be manipulated to provide appropriate technical solutions for optimal management objectives (Sommer and Dow 1978).

A simultaneous growth and yield model for *P. elliotti* plantations was developed by Pienaar and Harrison (1989) using Correlated Curve Trend (CCT) data from the coastal regions of Zululand. The model includes equations for predicting height, basal area, total stem volume, marketable volume and tree survival, on a stand level (von Gadow and Bredenkamp 1992). A range of similar models, including looking at how growth, silviculture and stem quality impact on end-use, have been developed in New Zealand for *P. radiata* (Burdon and Miller 1992). Other growth models for this species have been developed in Chile and Australia.

The "Langepan" model is a well-documented growth model for *Eucalyptus grandis* stands, based on CCT spacing trial on an excellent growing site near KwaMbonambi in Zululand. The Langepan model dramatically illustrates the effect of planting spacing on diameter and height. Langepan model predictions for mean tree heights and volumes are possible for use in different climatic zones (von Gadow and Bredenkamp 1992).

7. IMPROVING ACCESSIBILITY TO PLANTATION GROWTH DATA

TROPIS, the *T*ree G*ro*wth and *P*ermanent Plot *I*nformation *S*ystem sponsored by Center for International Forestry Research (CIFOR), seeks to help forest scientists make better use of existing tree growth information by:

1. Supporting a network of people willing to share permanent plot data and tree growth information through a variety of ways, including the sources hosted at this site (newsletters, links, etc.);
2. Maintaining a searchable index of people and institutions holding permanent plot data in both plantations and natural forests;
3. Making a database management system available to promote more efficient management of permanent plot data (Mirasilv, developed by CATIE) (Ugalde 1999);
4. Providing a way to identify comparable sites in other regions, allowing data from elsewhere to be used when no local growth information exists (under development, more information), and
5. Offering access to an inference system to allow growth estimates to be made in the absence of empirical data (Plantgro and Infer).

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*Appendix 1. Production potential for selected industrial forest plantation species and countries with experience of afforestation with exotic or local species**

Species	**Countries****	**MAI (m^3 ha^{-1} yr^{-1})**
Eucalyptus		
E. deglupta	BRA, COB, COL, CR, CUB, FIJ, HAW, I, (IND), IVC, MAL, NIG, (PHI), (PNG), SAB, SL SLK, SOL, SUR, ZAI,	14-50
E. globulus	ALG, ARG. (AUS), BRA, CHI, COL ECU, ETH, I, ITA, KEN, NZ, PER, POR, SA, SP, TAN, URG, USA, ZIM	10-40
E. grandis	ANG, ARG, BRA, COB, COL, I, KEN, MLW, MOZ, NIG, RWA, SA, SP, TAN, UGA, URG, ZAI, ZAM, ZIM	15-50
E. saligna	ANG, ARG, BRA, BUR, CAM, GRE, HAW, I, IND, KEN, MLW, MOR, MOZ, NIG, NZ, RWA, SA, TAN, UGA, URG, ZAI, ZAM, ZIM	10-55
E. camaldulensis	ALG, ANG, ARG, BRA, CHL, COB, CYP, GRE, I, ISR, ITA, KEN, LBY, MAD, MOR, NIG, PAK, POR, SA, SP, TAN, TUN, TUR, URG, USA, ZAM, ZIM	15-30
E. urophylla	ARG, AUS, BRA, CAM, COB, FIJ, (IND), IVC, MAD, MAL, NIG, PNG, SOL	20-60
E. robusta	ANG, ARG, (AUS), BRA, CHL, CHN, CAM, COB, CR, FIJ, GRE, HAW, I, IND, KEN, MAD, MAL, MAU, NIG, NZ, PER, PHI, PNG, PR, SA, SLK, UGA, ZAI	10-40
Pinus		
Pinus caribaea var. *caribaea*	ARG, AUS, BRA, (CUB), MAD, SA, SUR, UGA, ZAI, ZAM	10-28
Pinus caribaea var. *hondurensis*	AUS, (BEL), BRA, COB, CR, I, IND, FIJ, JAM, KEN, LIB, MAD, MAL, MLW, MOZ, NH, NIG, SA, SLK, SUR, SWZ, TAI, TAN, TRI, UGA, VEN, VN, ZAI, ZIM	20-50
Pinus patula	(MEX), ANG, ARG, ECU, I, KEN, MAD, MLW, MOZ, NG, PER, SA, SWZ, TAN, UGA, ZAI, ZIM	8-40
Pinus radiata	ARG, AUS, BOL, BRA, CHL, COL, ECU, KEN, MLW, NZ, POR, SA, SP, TAN, UGA, URG, ZIM	12-35
Pinus oocarpa	BRA, COB, COL, FIJ, IND, LIB, MAL, PR, SA, SLK, SOL, TAI, ZAM	10-40
Other species		
Araucaria angustifolia	(ARG), AUS, (BRA), KEN, SA, TAN, UGA, ZIM	8-24
A. cunninghamii	(AUS), I, KEN, MAL, MAU, NIG, (PNG), TAN, TRI, UGA, ZIM	10-18
Gmelina arborea	BRA, CR, FIJ, GHA, I, IVC, MAL, MLW, NIG, PHI, SL, UGA, VEN	12-50
Swietenia macrophylla	(BEL), FIJ, HAW, I, IND, MAL, MAR, (MEX), NIG, PHI, PR, SLK, TRI	7-30
Tectona grandis	BAN, BEN, (MYA), COL, CUB, ECU, GHA, (I), (IND), IVC, MAL, MAU, PR, SL, SLK, (TAI), TAN, TOG, TRI, VEN	6-18
Casuarina equisetifolia	ARG, BRA, CHL, CHN, EGY, I, KEN, MEX, MAU, PR, SLK, TAN	6-20
C. junghuhniana	TAI, IND	7-11
Cupressus lusitanica	ARG, AUS,BRA, CHL COL, CR, ECU, I, KEN, (MEX), MLW, POR PR, SA, SP, TAN, UGA, VEN ZA, ZIM	8-40
Cordia alliadora	(BRA), COB (COL), (CR),(ECU), FIJ, IVC, MAU, NH, NIG, (PR) SL, SOL, TRI, UGA, (VEN)	10-20
Leucaena leucocephala	AUS, GUA, (HAW), IND, MAU, (MEX), NIG, PR, PHI, ZAM, ZAN	30-55
Acacia auriculiformis	(AUS), I, (IND), MAL, NIG, (PNG), SAB, UGA, ZAN	6-20
Acacia mearnsii	I, KEN, SA, SLK, TAN, ZIM	14-25
Terminalia superba	ANG, (CAR), (COB), FIJ, (GHA), (IVC), (LIB), NH, (NIG), SOL, TAN, (TOG), TRI, UGA, (ZAI)	10-14
Terminalia ivorensis	FIJ, (GHA), (IVC), (NIG), (SL), SOL, TAN, TRI, UGA	8-17
Dalbergia sissoo	ECU, (I), MEX, (PAK), SUD, ZIM	5-8

Source: Webb *et al.* 1984, Wadsworth 1997.

* Local species in parentheses. Some promising trials are included. However, many countries other than those listed carry out trials.

**Key to country abbreviations:

ALG Algeria
ANG Angola
ARG Argentina
AUS Australia
BAN Bangladesh
BEL Belize
BEN Benin
BRA Brazil
BUR Burundi
CAM Cameroons
CAR Central Africa Republic
CHL Chile
CHN China
COB Congo
COL Colombia
CR Costa Rica
CUB Cuba
CYP Cyprus
ECU Ecuador
ETH Ethiopia
FIJ Fiji
GHA Ghana
GRE Grecia
HAW Hawaii
I India
IND Indonesia
ISR Israel
ITA Italia
IVC Ivory Coast
JAM Jamaica
KEN Kenya
LBY Libya
LIB Liberia
MAD Madagascar
MAL Malaya
MAU Mauritus
MEX Mex
MLW Malawi
MOR Moroco
MOZ Mozambique
MYA Myanmar
NH New Hebrides
NIG Nigeria
NZ New Zeland
PAK Pakistan
PER Peru
PHI Philippines
PNG Papua New Guinea
POR Portugal
PR Puerto Rico
RWA Rwuanda
SA South Africa
SAB Sabah
SL Sierra Leone
SLK Sri Lanka
SOL Solomon Islands
SOM Somalia
SP Spain
SUD Sudan
SUR Surinam
SWZ Swaziland
TAI Thailand
TAN Tanzania
TOG Togo
TRI Trinidad Tobago
TUN Tunisia
UGA Ugand
URG Uruguay
USA U. S. A.
VEN Venezuela
ZAI Zaire
ZAM Zambia
ZIM Zimbabwe

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