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Klara Vichnevetskaia

Working Paper GFSS/WP/02

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FOREWORD

In late 1995, the FAO Forestry Department initiated the Global Fibre Supply Study (GFSS) with an outlook to the year 2050. The study was recommended by the FAO Advisory Committee on Pulp and Paper (now the Advisory Committee on Paper and Wood Products). The general objective of the study is to contribute reliable data, information, forecasts and analysis of industrial fibre sources in order to promote sustainable forest management.

The GFSS will include a compilation of the latest available inventory data, including recovered and non-wood fibre, focusing primarily on the sources of industrial fibre as raw material for the sawmilling, wood-based panels, and pulp and paper industries. It will also include a projection and analysis of future developments in fibre supply, based on explicit consideration of the major factors affecting supply.

The GFSS is unique among FAO studies in that special emphasis is placed on collection and compilation of fibre volume inventory and growth data for the developing regions - Africa, Asia-Pacific, and Latin America and the Caribbean. The study complements other FAO work, such as the Asia-Pacific Forestry Sector Outlook Study and the upcoming Forest Resources Assessment 2000. FAO is also updating its statistics on forest plantations and developing a method for estimating fibre volumes from non-forest areas in the tropical regions. Available data from these studies will be included in the GFSS.

The major products of the GFSS will include:

- A database accessible on-line through the Internet providing estimates of commercial wood volumes from natural, semi-natural and plantation forests;
- An on-line interactive fibre-supply model incorporating key determinants of supply;
- A statistical and descriptive report on the data and three fibre-supply scenarios which are based on factors deemed to be the most critical;
- A working paper describing in detail the methods for data compilation, gap filling, data validation, forecasting and definitions, survey forms and country list;
- A series of additional working papers on sustainable forest management, improved forest productivity from industrial forest plantations, fibre-supply modelling, recovered and non-wood fibre, and other topics; and
- An issue of *Unasylva*, FAO's quarterly journal on forestry and the forest industry, dedicated to the theme of global fibre supply.

This paper, solicited by the GFSS and prepared by Klara Vichnevetskaia, summarizes the world literature on productivity gains in plantations from tree improvement and better silviculture practices. We sincerely hope that it contributes productively to the world-wide dialogue on sustainable forest management for fibre and other values.

Olman Serrano
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PREFACE

Biophysical science is a necessary input into any dialogue on forest policy formulation. While it is necessary, it is of course insufficient - policy must also be informed by the social sciences and formulated in a consultative, participatory process. The most powerful forms of biophysical science for policy-making are those which take an anticipatory view of the world, that is, forms of science which attempt to glimpse into the future for insights into how the world functions and how we might choose and shape a desirable future.

The Global Fibre Supply Study (GFSS) of the Forestry Department at FAO is such a study. Its objective is to contribute reliable data, information and analysis of industrial fibre sources around the world for use in international forest-policy dialogues. In addition to the basic forest resources data and information, the GFSS will present a series of scenarios which depict possible futures for fibres supplies around the world. The projections are generated by a few biophysical accounting models that simulate, under specific assumptions, how much industrial fibre should be available through the year 2050.

The assumptions underlying each scenario are critical. We know that future fibre supplies will be affected by, among other things: (a) silvicultural and tree-breeding strategies; (b) the availability of non-wood and recovered fibres; and (c) restrictions on timber harvests due to considerations for social and ecological forest values. The process of making useful assumptions must be informed by what we know or surmise is both possible and probable in the future of such factors. In the case of tree improvement and silvicultural practices, we might well assume a business-as-usual scenario, where the future is an extension of the recent past and present. However, we might well also try out the assumption that the theoretical gains in fibre production shown by research to be possible are actually implemented across the board.

The underlying assertion, however, is that the forecasting exercise can be improved if we apply species- and region-specific gains from certain tree improvement and silvicultural measures, rather than just applying the same average gain for all species in all regions. For example, it is likely unreasonable to expect gains from improved tree spacing in plantations of *Eucalyptus spp.* in Africa to match those from improved symbiotic associations of *Acacia spp.* in Asia. Such a 'weighted average' approach should improve the overall reliability of the assumptions used to create the alternative scenarios. It was with this view in mind that the GFSS sponsored the literature review underlying this paper.

Peter Duinker
August 1997

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1. INTRODUCTION

This paper was prepared as a background report for Global Fibre Supply Study by FAO. The overall objective was to assess the impact of silviculture and tree improvement on current and future fibre supply. To gain a better understanding of this complex topic, an extensive literature search has been conducted. The current literature review is concerned with the positive impacts of some key factors on tropical forest plantation productivity. These factors are: matching species/provenances to site, tree improvement, initial spacing, symbiotic associations of trees with bacteria and fungi, tree seed pre-treatment, site quality, irrigation and fertilization. These factors are obviously not the only ones to affect plantation productivity, but they are certainly among the most crucial.

Tree improvement is a broad topic and powerful tool. Matching species/provenances to site is basically a starting point and an integral part of any tree improvement programme. Yet, it is discussed separately from the rest of tree improvement steps since the selection of suitable provenance(s) will usually give the biggest gain. Growth and yield increases have generally been 10-45 percent when comparing the best provenances of a given species [Palmberg 1989].

This study focuses mainly on tropical plantations of acacia (*Acacia* spp.), eucalypt (*Eucalyptus* spp.), teak (*Tectona* spp.) and pine (*Pinus* spp.), although a number of publications cited refer to subtropical and other southern regions and species. Three main regions are of interest: tropical Africa, tropical Latin America and the Caribbean, and tropical Asia and Pacific. Some publications cited discuss plantations located outside of these main regions (e.g. Australia, New Zealand).

This document cannot be considered a complete survey of the literature on the given topic. The limited time and budget allocated for this study (considering ambitious terms of reference) restricted the author to just a portion of the references available and a limited number of topics for discussion for each genus considered.

The present bibliography would be more complete if relevant references in Spanish, Portuguese, Thai, Chinese, Indonesian and other languages could have been utilized. Again, the limited budget of this study restricted the author to using references primarily in English.

The current study contains information on the results of large-scale plantation practices as well as young trials. One has to be careful with the results of young trials if the numbers are to be used for extrapolation purposes to cover the entire rotation.

The author came across another problem while trying to quantify the impact of various factors on plantation productivity. Ideally, mean annual increment (MAI) of volume production at rotation age should be taken as a parameter for comparing the actual yield of plantations [Pandey 1995]. This was not always possible since different authors cited have used various parameters while investigating the impact of silviculture and tree improvement on plantation yield. Among those parameters are: height of the tree, diameter at breast height (DBH), basal area (BA), yield, and volume (V). One should apply certain formulae to unify the data quoted. Some of the relevant formulae are given at the beginning of chapters on acacia, teak and pine.

2. ACACIA PLANTATIONS

Numerous factors affect productivity of tropical acacia plantations. Two of those factors - matching species/provenances to site and initial spacing - are reviewed below under the heading “Common factors” as they appear to affect productivity of other tropical species under consideration (eucalypts, teaks, pines) as well. Symbiotic associations and seed pre-treatment play a certain role in the success of many tropical species, but more so in acacia due to specific biological features of this species. Therefore, these two factors are reviewed below under the heading “Unique factors”.

2.1 PLANTATION YIELD ESTIMATION

Yield refers to the quantity of product that can be obtained from a stand of trees and is usually measured as wood volume per unit area. Volume of acacia can be estimated from DBH alone or in combination with total height. Soemarna and Bustomi [1986] sampled over 100 trees in 3-, 5-, and 7-year-old plantations and developed the following equations to estimate the clear bole volume as well as volume to 4 cm diameter:

$$V\ (\text{clear bole}) = 0.1217 * DBH^{(2.4697)}$$
$$V\ (4\ \text{cm}) = 0.1537 * DBH^{(2.4247)}$$

2.2 COMMON FACTORS

2.2.1 Species/provenances matching to site

2.2.1.1 Tropical Asia and Pacific

The success of plantation establishment and productivity is determined largely by the grower’s choice of species and seed source [Callaham 1964]. Provenance trials to evaluate growth performance, stem form, and susceptibility to pests and diseases are the first step in the genetic improvement programme component of plantation establishment. The primary aim of such trials is to identify suitable provenances for a large-scale planting locality. Provenance trials should consist of three phases: range-wide provenance screening, restricted provenance screening, and provenance proving [Awang and Bhuimibhamon 1993].

Acacia mangium is a major fast-growing tree species in forestry plantation programmes in Asia and the Pacific. This acacia is playing a growing role due to its versatility and ability to recapture grasslands dominated by the noxious weed *Imperata cylindrica*. For *A. mangium*, trials established in almost all countries where it has been introduced are still in the rangewide screening stage [Awang and Bhuimibhamon 1993]. Results of trials established in the 1980s and coordinated by the Food and Agriculture Organization of the United Nations (FAO) and the Australian Commonwealth Scientific and Industrial Research Organization (CSIRO) have been reported from China [Chung *et al.* 1990], Malaysia [Khamis 1991], Thailand [Atipanumpai 1989; Lawskul 1991], and Viet Nam [Huynh and Nguyen 1992]. Most of these have shown substantial differences in growth performance of different natural provenances.

Harwood and Williams [1991] completed comprehensive intersite analysis of those trials involving 24 provenances of *A. mangium* on 19 sites in seven Asia-Pacific countries. Significant differences were found in performance (height and DBH) between experimental sites, between provenance regions, and among the provenances within each provenance region. Growth was generally faster at sites near the Equator (with average annual increases in height of 3-4m) and slower at sites further from the Equator in Bangladesh, southern China, Taiwan (Republic of China), and Fiji. Papua New Guinea (PNG) provenances consistently performed best, closely followed by Claudie River provenance from Far North Queensland (FNQ). Provenances from the Queensland Cairns Region (QCR) and the CERAM and IRIAN provenance regions in Indonesia were almost always slower growing than those from PNG and FNQ. The biggest difference in MAI and DBH at a single site was observed between PNG (3.07) and IRIAN (Indonesia) (1.19) provenances at the site Nukurua, Fiji.

Provenance trials of *A.mangium* established in Indonesia by the Centre for Reforestation Technology in Banjarbaru showed that the best provenance for Riam Kiwa (Banjarbaru) was Claudie River (Queensland), which at 2.5 years old reached MAI of 38 m^3/ha/yr. The worst provenance was Sanga-Sanga (East Kalimantan), which at the same time attained MAI of 11.1 m^3/ha/yr. At 5 years of age, the Claude River provenance reached MAI of 58 m^3/ha/yr, while Sanga-Sanga had only 17.5 m^3/ha/yr. Other tests in Banjarbaru showed that at 35 months, provenances from PNG demonstrated MAI of 43 m^3/ha/yr, and Subanjeriji-palembang provenance attained MAI of only 27 m^3/ha/yr. A provenance trial in Riam Kiwa using 30 provenances of *A. mangium* showed that there were no differences among provenances for both height and DBH at 2 years [Suhaendi 1993].

Acacia mangium was considered the most promising acacia species in Viet Nam. It was clear that on the dry, bare hills in the midlands of northern Viet Nam (Dai Lai trial site), growth of *A. mangium* was much lower than at sites in southern Viet Nam (Ba Bang, La Nga). Promising provenances from these trials were Cardwell, Kennedy, Hawkins Creek, and Kuranda (all from Queensland, Australia). Numerous publications indicated that *A. mangium* can tolerate harsh sites better than any other species of acacia [e.g. Tan 1987].

Multi-site trials of *Acacia mangium* revealed a significant genotype x environment interaction effect on total wood production [Awang and Bhuimibhamon 1993]. The biggest difference in mean total wood weight of *A. mangium* at the age of 36 months was observed at Serdang site, Malaysia, between two provenances: PNG (10.24 kg) and Queensland (5.63 kg). The two provenances (Boite, PNG, and Iron Range, Queensland) were not stable across sites, suggesting the need to take into account characteristics such as biomass production, tree form, and growth performance in provenance selection. Provenances may respond consistently across sites in terms of height and diameter but not in other characteristics. However, the choice of selection traits depends very much on the planting objective. The existence of provenance x environment interactions can be exploited for higher genetic gain. This results in a choice related to site adaptability: one can select either a single provenance that is broadly adaptable over a range of sites, or the most productive provenance at each site. This choice depends on the relative costs and benefits, and the availability of resources [Nickles 1991].

Provenance affects the growth of a species at new sites where it is introduced. An example is provided by Awang and Bhuimibhamon [1993] from an unpublished Ph.D. thesis by Uddin: provenances of *A. mangium* collected from lower elevations performed very well at much higher elevations in the Philippines, a fact he attributed to higher rainfall. In contrast, provenances from higher elevations did not do well when planted at lower elevations. Among the provenances of *A. mangium* planted in Viet Nam, Kha and Nghia [1991] found that Kuranda and Bronted provenances grew best in La Nga where water drainage is very good during the rainy season. But in Bau Bang, where drainage is poor, the Kennedy provenance grew best. Latitude appeared to be an important consideration when matching seedlots to planting sites. The example was provided in the trial of *Acacia melanoxylon* in Queensland, Australia. The tallest nine seedlots growing at Kuranda site were from the north and performed better in their early growth stages at the low latitude (16° 45’ S) than further south [Applegate and Nicholson 1987].

Acacia auriculiformis and *A. mangium* in humid tropical Asia are good examples of importance of provenance research. In 1966, *A. mangium* was introduced into Sabah (E. Malaysia) from Queensland (Australia) and it grew so well that from 1973 it began to be widely planted (National Research Council 1983). *A. auriculiformis* had long been used as an ornamental but was of indifferent form. Both species occur naturally in northern Australia, parts of Indonesia, and PNG and trials as exotics in the 1980s have stimulated much interest in these ‘phyllode’ acacias.

As with many acacias, the phyllode species are able to grow on infertile soils and degraded grasslands and offer much promise both as industrial crop species and in agroforestry to assist soil enrichment. Results from Sabah, Malaysia, and southern China show that knowledge of provenance is essential to utilize the great potential of these species. Two species/provenance trials on different soils in Sabah are shown in Evans' monograph [1992], which compared local seed sources of *A. mangium and A. auriculiformis* with three new sources of these species from PNG. The results of these trials indicate that the Balamuk and Iokwa provenances of *A. auriculiformis* are significantly taller at the age of 4 years than the local sources. Two other phyllode acacias from PNG included in the trials, *A. crassicarpa* and *A. aulacocarpa*, are growing at least as well, with *A. crassicarpa* looking most promising. The poor showing of *A. mangium* from local sources probably arises from inbreeding depression since it is thought that all seed in the original 1966 importation to Sabah came from one tree. Similar poor growth is reported for Indonesian provenances of *A. mangium* owing to the very restricted extent of natural stands. International provenance trials of *A. mangium* show PNG origins to be best across the full range of sites.

Field trials of Australian acacia were planted at different sites across Thailand during the period 1985-1987. Trial sites were dispersed around Thailand from wet (e.g. Sai Thong) to seasonally very dry (e.g. Chiang Mai) sites. In most instances there was a perceived need for fuelwood in the area, or the sites were chosen to extend the climatic range of the test sites (e.g. Sakaerat) [Boland and Turnbull 1989]. Early results obtained for the trials have shown marked differences between species in growth and survival. Species having greatest DBH were those which grew tallest (e.g. *A. carssicarpa* and *A. auriculiformis)*. While *A. auriculiformis* has been planted elsewhere in Thailand due to its excellent performance. *A. crassicarpa* was first introduced to Thailand under the current programme and appears to have a big future because of its fast growth and wide adaptability to various site conditions. Smallest DBHs were recorded for *A. polystachya*, *A. falvescens* and *A. aulacocarpa* from more southerly latitudes. Among the poorest species in the trial was *A. melanoxylon*, which was all dead at one site and suffered heavy losses at other sites. Some species grew slowly but survived well (e.g. *A. oraria).* Provenance differences were observed for *A. crassicarpa* and *A. aulacocarpa*: seedlots from PNG grew much faster than their counterparts from North Queensland (Australia). The biggest and the smallest mean DBH (cm) at the age of 24 months that were recorded at each of six planting sites for *Acacia* species are as follows:

Ratchaburi (central-west):	Acacia crassicarpa - 5.43; A. polystachya - 1.39
Sai Thong (south)	A. crassicarpa - 10.30; A. melanoxylon - 1.98
Si Sa Ket (far northeast)	A. crassicarpa - 6.88; A. polystachya - 2.09
Sakaerat (northeast)	A. crassicarpa - 5.59; A. shirleyi - 0.77
Chanthaburi (central-east)	A. auriculiformis - 3.35; A. aulacocarpa - 0.78
Huai Bong (north)	A. auriculiformis - 3.38; A. polystachya - 0.28

Among the best in DBH growth were four provenances from PNG (sites 1, 2, 4, 5) [Pinyopusarerk 1989].

Other trials in Thailand also support the provenance data for *A. auriculiformis* showing PNG ones to be superior [Evans 1992], as do others such as at Qionghai on Hainan Island, China. Hainan is a large tropical island, the most southern province of China, where low soil fertility suggests the need for planting nitrogen-fixing leguminous species. Currently, there is one Chinese indigenous species planted (*Acacia confusa)* that has a good reputation for producing fuelwood and resisting typhoon damage. Since 1985, the Research Institute of Tropical Forestry has been establishing a series of acacia species and provenance trials with ACIAR support. Two series of acacia species and provenance trials were planted in 1986 and 1987 [Minquan *et al.* 1989].

The five provenances of *Acacia crassicarpa* were the fastest growing and had a high survival rate among the species in the trial on Hainan Island, China [Minquan *et al.* 1989]. Their wind resistance was poor. The best-growing provenance (13682) came from Oriomo River, PNG. At 20 months it grew to 6 m tall, with a trunk 5.8 cm DBH (Table 1). DBH (which is often used as a single parameter for wood volume estimation [Watts 1989, Bustomi 1988] of provenance 13682 of *A. crassicarpa* was 828 percent of the DBH of *A. confusa*, provenance 86002. Being the only indigenous acacia species, *A. confusa* served as a control in Hainan Island trials. Of the five provenances of *A. mangium* in the trials, the best provenance was 15063 from Mossman, Queensland. It reached 4.3 m in height with 4.1 cm DBH in 20 months. The average number of stems per tree was 1.6. The slowest provenance was 13622 from Sidei, Indonesia, which reached 3.5 m in height with 2.5 cm DBH. Average number of stems per tree was two. Among four provenances of *A. aulacocarpa*, the best one was 13689 from Oriomo River Province, PNG. This provenance had fast growth with a straight stem and strong apical dominance. There were seven provenances of *A. auriculiformis* including two control (local) provenances from Guangdong Province, China. The best provenance was 13686 from Iokwa, PNG. It attained 5.3 m in height with 5.2 cm DBH which were 120 percent and 144 percent respectively better than the controls (86001). The provenance with the best stem form was 13869 from Sprigvale Holding, Queensland. *A. cincinnata* produced some individuals with very straight stems; growth of three provenances was satisfactory. Both provenances of *A. leptocarpa* were fast-growing and single-stemmed but not very straight. Two provenances of *A. melanoxylon* were slow-growing and had poor stem form; they appear not to be suitable to the trial site. A special feature of *A. oraria* is the high survival rate and the uniform growth [Minquan *et al.* 1989].

Table 1: Results of tropical Australian acacia species/provenances trials on Hainan Island, China. (surveyed at 20 months after planting)

Seedlot No.	Species	Height (m)	DBH (cm)	Survival at 1 year (%)	Mean number of stems	Index of wind resistance
13863	*Acacia crassicarpa*	4.7	4.6	88	1.7	1.00
13683	*Acacia crassicarpa*	5.7	5.6	96	1.4	1.67
13682	*Acacia crassicarpa*	6.0	5.8	93	1.7	1.79
13504	*Acacia mangium*	3.8	3.8	89	1.4	1.08
13622	*Acacia mangium*	3.5	2.5	88	2.0	1.89
15063	*Acacia mangium*	4.3	4.1	86	1.6	1.05
13869	*Acacia auriculiformis*	4.1	4.1	98	1.0	1.00
13854	*Acacia auriculiformis*	4.5	3.8	96	1.7	1.00
13686	*Acacia auriculiformis*	5.3	5.2	97	1.5	1.03
13684	*Acacia auriculiformis*	4.3	4.2	99	1.5	1.01
14969	*Acacia aulacocarpa*	2.7	1.6	93	2.2	1.07
13689	*Acacia aulacocarpa*	4.9	4.8	85	1.5	1.48
13864	*Acacia cincinnata*	3.7	3.0	62	1.8	1.00
13878	*Acacia cincinnata*	3.8	2.8	74	1.5	1.00
13361	*Acacia cincinnata*	3.7	2.9	67	1.7	1.00
14176	*Acacia melanoxylon*	2.2	0.6	56	1.7	1.07
14766	*Acacia melanoxylon*	2.0	1.4	56	1.3	1.00
14961	*Acacia oraria*	1.9	0.9	89	3.2	1.00
86001	*Acacia auriculiformis*	4.4	3.6	96	2.6	1.00
86002	*Acacia confusa*	1.6	0.7	74	3.1	1.00

Source: Minquan *et al.* 1989.

Results of these trials show that *A. crassicarpa, A. mangium, A. auriculiformis* and *A. cincinnata* have good potential for larger-scale planting on Hainan [Minquan *et al.* 1989]. These species are fast-growing trees with moderately straight stems, and they tolerate tropical, low-fertility acidic soils. In particular, large provenance differences were observed for *A. aulacocarpa* and *A. mangium*. The most productive species in terms of DBH growth was *A. crassicarpa*. However, since Hainan Island is often threatened by typhoons, the wind resistance index is a very important parameter for evaluating species/provenance trials in this area. The fast-growing, large-leaved acacias (e.g. *A. crassicarpa*) may be particularly prone to wind throw.

Acacia crassicarpa demonstrated the best growth performance in another trial in Southern China. Mean DBH of this acacia at the age of 4 years in Hainan province was three times better compared to *A. cincinnata* (Table 2
Table 2).

Table 2: Comparison of diameter growth for five acacias at different sites in Southern China, at 4 years of age.

	DBH (cm)			
Species	Suixi *		Qionghai**	
	Mean	Max	Mean	Max
A. auriculiformis	4.37	5.11	7.33	8.60
A. crassicarpa	6.10	6.37	9.92	10.80
A. aulacocarpa	3.41	5.00	5.51	8.17
A. leptocarpa	4.04	4.07	7.50	7.60
A. *cincinnata*	1.81	2.33	3.26	3.50

* Guangdong Province.
** Hainan Province.
Source: Haishui and Zengjiang 1993.

Acacia mangium demonstrated superior growth performance compared to other species - *A. cunninghamii, A. auriculiformis,* and *A. concurrens* in Hainan province. Its DBH and volume were 137 percent and 229 percent respectively better compared to the same parameters of *A. concurrens.* However, survival of *A. mangium* was only 57.5 percent compared to 74.3 percent of *A. auriculiformis* [Haishui and Zengjiang 1993].

Another provenance trial in China was established with *Acacia meransii* in the central and southern districts of subtropical zones of this country. Imported seed from Australia, South Africa and Brazil were compared with a number of local provenances. Available early results have shown marked differences among provenances in many growth characteristics [Chuanbi 1989]. At the age of 18 months, several provenances attained 3 m in height and over 2 cm DBH. These included two local seedlots (C21, C24), six Australian (S14397 Bodalla, S14398 Batemans Bay, S14725 Bungendore, S14771 Cooma, S14922 Braidwood, S14925 Blackhill Reserve), two South African (S15087 and S15088) and the one Brazilian. One local provenance (C22) from Guangnan was the poorest in height and the second poorest in DBH. Two Australian provenances from New South Wales (S14769 Googong and S14924 Merimbula) were also growing slowly in both height and DBH. The best DBH growth was achieved in the local Sichuan (C24) provenance and South African provenance of Natal (15088). DBHs of these provenances were 192 percent and 184 percent respectively compared to the slowest in DBH growth, the Australian provenance Polacks Flat Ck (14770). Some provenances have performed significantly well since the nursery stage (i.e. two South African provenances and one Australian provenance from Bungendore). However, some provenances that were establishing poorly in the nursery grew very fast in the field (i.e. seed from Brazil and a local seed from Wenzhow).

In general, growth performance of more than a hundred introduced acacia species is quite variable in Southern China. However, the MAI of the superior species or provenances is about 2-3.5 cm in DBH, 1.8-3.8 m in height, and 20-30 ton/ha in biomass [Haishui and Zeng Jiang 1993].

In India, at Kanpur (Uttar Pradesh) provenance tests of *A. nilotica* ssp. *indica* from Banaskantha (Gujarat) showed better height, DBH, number of nodes and branch length than other provenances from Karnataka, Maharashtra, Andhra Pradesh and Uttar Pradesh [Shivkumar and Banerjee 1986].

Thirty-nine provenances of five *Acacia* species were put in trials in Viet Nam at Da Chong (Ha Tay province, 1990), Dai Lai (Vinh Phu, 1991), Dong Ha (Quang Tri, 1991), and La Nga (Dong Nai, 1991). The most promising provenances in terms of height and DBH growth were Pogaki E.M. of *A. mangium;* Coen River and Kings Plains of *A. auriculiformis;* and Pongaki E.M., Gubam and Mata Province of *A. crassicarpa.* The slowest growing were some provenances of *A. aulacocarpa* and *A. cincinnata* [Nghia and Kha 1993].

An example of provenance selection for suitability in a range of environments is the trial with *Acacia* species in Tandojam, Pakistan. In an effort to make the large tracts of saline waste lands throughout Pakistan productive for farmers by use of trees, a number of Australian acacias were recently introduced in Pakistan. Among the species tested on highly saline soils, *A. ampliceps and A. stenophylla* show potential. The best results in terms of DBH growth were achieved in case of *A. ampliceps*; mean DBH at 15 months was 3.75 cm. This was 3.5 times better than the DBH of *A. machanochieana* [Ansari *et al.* 1993].

Of all acacia species that have been tried on saline soils in Sri Lanka, the best growth was shown by *A. leucophloea*. Another trial at Sri Lanka was aimed at evaluating the relative performance of different acacias in the dry intermediate zone. The greatest DBH at 42 months was recorded for *A. mangium* (11.1 cm). The second was for *A. auriculiformis* (10.3). Other species having a large diameter included *A. crassicarpa* (8.6 cm). The poorest performance was shown by *A. polystachya* (DBH = 3.2 cm) [Vivekanandan 1993].

2.2.1.2 Tropical Africa

Australian acacias in dry tropical Africa have made great strides during the last 20 years. The first results showed that, on the whole, these species are sensitive to the severe drought conditions prevailing in certain trial locations. This is related to the coastal origin of the plant material introduced to date. The most encouraging results of these early introductions were obtained in coastal stations in Senegal. The species distinguishing themselves by their good performance in this zone are 1) *Acacia coriacea, A. sclerosperma,* and to a lesser extent, *A. bivenosa*; due to their drought resistance, these three species are most interesting in the prevention and control of erosion; and 2) *Acacia holosericea, A. trachycarpa,* and *A. tumida* for their good productivity and their fodder value; however, *A. tumida* is adapted to only a restricted number of sites because of its drought sensitivity. Species from southern Australia failed to adapt to Sahelian and Sahelo-Soudenian zones. These included *Acacia baileyana, A. cyclops, A. dealbata, A. mearnsii, A. microbotrya, A. pycnantha, and A. saligna* [Cossalter 1987].

Among Australian acacias introduced into Tanzania for rural development, the most successful one was *Acacia mearnsii.* It grows best in a cool moist climate. Good growth has been achieved at high altitudes (1200-2150 m) and on soils derived from crystalline rocks compared to those derived from volcanic rocks. *Acacia melanoxylon*, in trials at Mamba, Moshi, revealed that at the age of 20 years the trees attained heights 24-32 m with 10-11 m of clean bole, and with a girth at breast height of about 1.5 m. Other species planted in Tanzania include *A. mangium, A. auriculiformis, A. saligna,* and *A. decurrens* [Kessy 1987].

Species/provenance field trials with Australian acacias were established at different sites in Kenya. Of all the species tested (*Acacia aulacocarpa, A. auriculiformis, A. flavescens, A. mangium, A. crassicarpa)*, the most promising results were obtained for *A. crassicarpa*. At a young age (3 months) it had the highest growth and survival in semi-humid to semi-arid areas. The poorest was *A. flavescens* [Milimo 1989].

Five exotic fast-growing tropical tree species were tested on four different sites in Zaire to assess their growth and adaptability. All parameters (height, DBH, number of stems, branch angle, stem straightness, survival percentage) were measured at 21 months. Ranking of the species for growth and adaptability over all sites was in the following descending order: *Acacia auriculiformis, Eucalyptus urophylla, A. mangium, Cassia siamea, Leuciana leucocephala.* The rank of species changed across sites, indicating significant species x environment interactions [Khasa *et al.* 1995].

The MAI of *A. auriculiformis* on very poor and acidic soils of the Bateke plateau in Zaire was 12 m^3/ha/yr at a 7-year rotation [Gerkens and Kasali 1988]. Productivity can be improved by using propagules of genetic superiority [Khasa *et al.* 1994]. In early evaluation of *A. auriculiformis* and *A. mangium* provenance trials in Zaire [Khasa *et al.* 1995], *A. auriculiformis* showed higher plasticity than *A. mangium*, and, therefore, more stability across the sites. It grew well from 110 m to 1300 m altitude. In the sites where *A. mangium* was physiologically suited, such as Bateke plateau, some provenances were outperforming those of *A. auriculiformis.* However, *A. mangium* was the least salt-tolerant species and did not thrive in saline soils at 6 km from the Atlantic coast with 100 percent mortality. In this site, two putative hybrids, showing morphological characteristics intermediate between these two species, grew well. They showed fine branching and apical dominance which may lead to good stem form as compared to pure *A. auriculiformis* trees which generally showed crooked stems [Khasa *et al.* 1994].

Variability in *Acacia albida* Del. (syn. *Faidherbia albida* Del.) growth was caused by variability in soil properties across relatively short distances in Niger. Good sites within a plantation near Niamey had higher clay contents and base saturations, and lower exchangeable acidity than poor sites. The tallest trees in the field were associated with the proximity to abandoned termite mounds. Seedlings planted on sheet-eroded sites caused by run-off from microtopographically high sites grew poorly. The variability in *A. albida* growth in plantations within Niger is hypothesized to be due, in part, to pre-existing soil conditions. These results also suggest that the 'albida effect' might be partially caused by these pre-existing 'islands of fertility'. This site-determined variable growth of *A. albida* could be exploited with a proper seedling placement strategy [Geiger *et al.* 1994].

2.2.1.3 Tropical America

The *Acacia mearnsii* De Wild. breeding programme, in southern Brazil, aims to increase tannin and timber yield. Recently introduced germ-plasm is being studied in a combined provenance and progeny trial planted in two sites. Batemans Bay provenance is showing best growth, followed by Bega and Bodalla. Genetic variability for DBH, height and survival in these introduced provenances was greater than that determined for existing germ-plasm. Genetic variation for these traits was highly significant, but the genotype x environment interaction was not [Higa and Resende 1994].

2.2.2 Spacing

The choice of initial spacing is determined mainly by the end use of the plantation material, and to some extent by the tree form. It is commonly observed that *A. mangium* grown at wider spacing produces multi-shoots, and more and heavier branches that prune poorly and persist for long periods [Srivastava

1993]. For chipwood and fuelwood, form may not be important; in fact production of multi-shoots and heavier branches may even result in higher volume, although it may increase harvesting costs. Plantings intended for sawlogs need sufficient numbers of trees to enable selection for excellent form at the end of the rotation. According to Mead and Miller [1991], density may vary with site (and even among microsites) and with seed source. Various initial spacings have been used for the same species at different locations even within the same country; this indicates lack of information on optimum spacing for different objectives [Srivastava 1993].

In Sabah, Malaysia, 3 x 3 m is the most common spacing used for *Acacia mangium* [Udarbe and Hepburn 1987], although Udarbe [1984] stated that this can be reduced to 2.5 x 2.5 m to take advantage of fast initial growth. Two types of spacing were tested for *A. mangium* in commercial plantations at Sabah Softwoods - 3 x 3 m, and 2.4 x 2.4 m (National Research Council 1983). MAI at the same location (Brumas) varied from 13.8 m^3/ha/yr (spacing 3 x 3 m) to 44.58 m^3/ha/yr (spacing 2.4 x 2.4 m).

SAFODA (Sabah Forestry Development Authority) adopted a spacing of 4 x 2 m (1250 stems/ha), moving away from square to rectangular spacings after their trials at Begkoka found little difference in growth between the two options, with considerable cost savings due to fewer lines per ha. Although there was no significant difference in diameter growth among the different treatments in the SAFODA square spacing trial, comparison of mean heights indicated that spacing of 2 x 2 m and 2.5 x 2.5 m (8.4 m and 7.6 m respectively) are significantly different from control - 3 x 3 m (6.9 m) [Srivastava 1993]. A 4.5-year-old plantation in Sarawak, Malaysia, had a density of 1084 trees/ha and a top height of over 20 m; the DBH ranged from 4.3 cm to 24.2 cm and averaged 14.3 cm; MAI was 18.2 t/ha [Lim 1986].

Wider spacing in *Acacia mangium* plantations was adopted in Malaysia by the Compensatory Forest Plantation Project (CFPP). Trees planted at 3 x 3.7 m (900 stems/ha) resulted in good site occupancy within the first year [Mead and Miller 1991]. Weinland and Zahaidi [1992], however, recommended higher initial density to maintain strong lateral competition for producing thin, self-pruning branches. According to them, a sequence of slow initial diameter growth under strong lateral competition, followed by relatively late fast diameter growth under minimal competition, is probably the key to reduced fungal infection and enhanced log quality.

Low-density plantings showed better growth on banks and along roads than high density in an *A. mangium* trial in Viet Nam, at Tan Tao Station (Ho Chi Minh City). At 4.3 years of age, average annual height increase of 2.6 m and DBH of 3.4 cm was observed at 4 x 6 m spacing, while at 1.5 x 1.5 m spacing these parameters were 2.1 m and 2.1 cm respectively [Nghia and Kha 1993].

In PNG, the two timber companies that have taken up *A. mangium* as the main species for reforestation - Japan-New Guinea Timber Pty., Ltd (JANT) and Stettin Bay Lumber Co. (SBLC) - most commonly employ a 4 x 4 m spacing (625 trees/ha), although 4 x 3 m (830 trees/ha) has been tried on some sites [Srivastava 1993]. In both cases, the management objective is to produce pulpwood.

In Queensland, Australia, at the seed production areas, the initial spacing of 3 x 1.8 m was too dense to allow *Acacia mangium* trees to reach sufficient size for accurate selection prior to thinning [Harwood *et al.* 1993]. An initial spacing of 5 x 2 m was considered satisfactory, as it would allow effective selection and access by a “cherry-picker” for seed collection.

A study of *A. mangium* planted at different spacings has been conducted at the field station in Kalitabu Tanjung Bintang, Lampung province in Indonesia [Siregar and Djaingsastro 1988]. There was no significant difference among three spacings applied (1 x 2 m, 1 x 3 m, 1 x 4 m) in heights or diameters of the seedlings.

In field trial sites in Thailand, *A. mangium* and *A. auriculiformis* were grown at 6 spacings: 1 x 0.5 m, 1 x 1 m, 1 x 1.5 m, 1 x 2 m, 1 x 3 m, 1 x 4 m. The biomass reported for *A. mangium* and *A. auriculiformis* grown at 1 x 1 m spacing (10 000 trees/ha) was 53 and 52 m^3/ha/yr, respectively, at the age of 3 years [Yantasath 1987]. An increase in height, DBH and biomass per tree was observed with an increase in spacing. However, the total biomass production was higher with the closer spacing.

The effect of stand density on the wood yield in an *Acacia auriculiformis* Cunn. plantation was investigated in Thailand. The highest density plots (1250 trees/ha) had the highest survival rate and the plots with 625 trees/ha (4-year-old) had the lowest. Biomass per tree of each fraction of the *A. auriculiformis* plantation was directly proportional to the stand density [Sahunalu 1983].

Another study of the yield-density effect of *Acacia auriculiformis* in Thailand was carried out in 2-, 3-, and 4-year-old plantations in the Agroforestry Research and Demonstration Plots at Kantrarom, Srisaket. The experimental stands were initially planted at densities of 1250, 625, 417, and 278 trees/ha. Biomass of each fraction per tree, mean fuelwood biomass and mean stem volume of the plantations were inversely correlated to the stand density. Dry matter yield of each fraction, yield of fuelwood and stem volume of the plantations were directly correlated to the stand density. Net primary production averaged over 24 years for plantations of density 1250, 625, 417 and 278 trees/ha were found to be 12 351, 11 735, 12 497, and 8420 ton/ha/yr respectively. Average stem volume increments were 11 980, 8756, 11 316, and 7905 m^3/ha/yr respectively [Kietvuttinon 1985].

Stand growth, development and economic return of 5-year-old *Acacia mearnsii* in China, planted at spacings ranging from 1 x 1 to 1 x 2 m, were examined. Height and DBH increment at age 3-5 years decreased as density increased; bark and wood yield per unit area increased with increased stand density; and economic returns (judged using output-input methods) at the wider spacings were better than at the denser spacings [Zheng *et al.* 1994]. Lower densities are considered desirable for longer rotations, under which conditions the stand needs lower investment and produces greater log volume and economic returns. In contrast, higher densities are more suitable for short-term management, but incur higher establishment costs, produce lower log volume and poorer economic returns, although maturing early.

In Sri Lanka, *Acacia decurrens* was grown at a spacing of 4 x 4 m [Vivekanandan 1993]. In trials of afforestation of denuded land in Peninsular Malaysia, *A. auriculiformis* was established at a spacing of 2.4 x 2.4 m [Yap 1987]. In Karnataka State, India, *A. auriculiformis* planted on degraded open sites at a spacing of 1 x 2 m produced MAI in total biomass of 60.77 t/ha at the age of 5 years [Reddy and Sugur 1992]. *A. melanoxylon* has been grown in Kenya for the production of saw timber at a spacing of 2.7 x 2.7 m with 1372 stems/ha and a wider spacing of 3 x 3 m with 1111 stems/ha [Kaumi 1987].

2.2.3 Factors unique for acacia plantations

2.2.3.1 Symbiotic associations

Acacia's success in the tropics is partly due to its ability to adapt to adverse sites, acidic soils of less than pH 4, areas subjected to periodic drought, and soils low in nitrogen and phosphorous. The species' ability to grow in degraded grasslands, where nutrients - particularly nitrogen and phosphorous - are deficient, may be attributed to its dual symbiosis with the nitrogen-fixing bacterium *Rhizobium* and vesicular-arbuscular mycorrhizal (VAM) fungi [dela Cruz and Yantasath 1993]. The tree roots provide these organisms with excess carbohydrates and other metabolites; in turn, the mycorrhizae and rhizobium make soil nutrients available to the tree, particularly nitrogen and phosphorous [Supriadi and Valli 1988].

Rhizobia are soil micro-organisms found in root nodules of leguminous trees and plants. They can "fix" atmospheric nitrogen. Most *Acacia* species nodulate with *Rhizobium* to fix nitrogen [Nokos 1977]. The legume plant root recognizes only selected kinds of *Rhizobium* among other bacteria; the nodulating *Rhizobium* recognizes only the selected legume roots among all other roots that may occur in the environment. Many nitrogen-fixing tree species particularly depend on mycorrhizae for absorbing nutrients required for plant growth and efficient nitrogen fixation [dela Cruz and Yantasath 1993]. In general, two major groups of mycorrhizae are recognized on the basis of infection morphology: ectomycorrhizae and VAM. VAM are by far the most widely distributed mycorrhizae. They are harder to recognize than ectomycorrhizae as they have no fungal sheath and cause little change to the external appearance of the roots. Reddell and Warren [1987] compiled the list of *Acacia* species that were found to be ectomycorrhizal (e.g. *A. aneura, dealbata, melanoxylon, platycarpa, salicina*), VA mycorrhizal (*albida, aulacocarpa, auriculiformis, concurrens, holocericea, mangium, nilotica, saligna*), and both (*myrtifolia, redoxylon, rothii, simsii)*. Mycorrhizae are particularly important for the uptake of nutrients that are immobile in soils (e.g. P, Zn, Cu, NH_4^+), although they are probably also important for uptake of more mobile nutrients (e.g. NO_3^-, SO_4^{2-}, K) in highly competitive situations and in young plantations where trees have low rooting intensities [Bowen 1985].

As with rhizobia, studies have shown that under some conditions, mycorrhizal fungal inoculation can increase growth of trees in plantations [Marx 1980; Garbaye and LeTakon 1986, Momoh and Gbadegesin 1980]. In the tropics, however, the potential for improving growth of hardwoods through mycorrhizal inoculation has often been neglected [Mikola 1980]. Most of the increase in tree growth related to mycorrhizal inoculation can be attributed directly to increased nutrient uptake, but mycorrhizae can also benefit trees by reducing the effects of stress related to drought and transplantation [Parke *et al.* 1983], extreme soil conditions of high soil temperatures, high aluminium, and low soil pH [Bowen 1985], and some soil-borne pathogens [Marx 1973]. Factors which influence tree response to mycorrhizal inoculation in the field include: 1) the tree species - some species are more dependant on mycorhizzae than others, often a reflection of their rooting intensity and nutritional requirements; 2) the fertility of the planting site - the less fertile the site, the larger the response tends to be; 3) the species composition and the population level of the naturally occurring mycorrhizal fungi; and 4) the persistence, competitiveness and effectiveness in promoting plant growth of the introduced fungus compared with the naturally occurring fungal population [Bowen 1985]. The most dramatic increases in tree growth occur following mycorrhizal inoculation of introduced species that have not been previously grown in the area [Momoh and Gbadegesin 1980] or where the planting site has been severely disturbed and lacks a native mycorrhizal population. Nevertheless, even in situations where there is an existing population of mycorrhizal fungi, beneficial growth responses to inoculation can occur [Marx 1980].

2.2.3.2 Rhizobium and nitrogen fixation in Acacias

Annual nitrogen fixation rates for acacias range from 10 to 32 kg/ha/yr [Adams and Attiwill 1981]. In a nursery experiment on the effect of liming and inoculation of *A. mangium* in the presence or absence of NPK fertilizer, Cali [1991] reported that inoculation independently improved height, shoot biomass, nodule weight, and nitrogen content and uptake of *A. mangium*. In Adtuyon clay loam (pH 6.2), the local *Rhizobium* isolate Am_2 could replace about 91 percent of the N requirement for *A. mangium* growth. Cabahug [1991], studying early growth of *A. mangium* in a grassland soil (pH 6.4) found that increased levels of N gave a general trend of improved growth performance and nodulation. In the presence of N at the rate of 100 kg/ha, inoculation improved nodulation by 193.6 percent over the unfertilized inoculation treatment.

Some strains of *Rhizobium* were found to be more effective with certain species of *Acacia*. *Acacia* species can be classified into three groups according to effective nodulation response patterns with fast- and slow-growing tropical strains of *Rhizobium*. The first group nodulates effectively with slow-growing, cowpea-type strains; the second nodulates with tropical, fast-growing strains; and the third group nodulates with both fast- and slow-growing strains [Dreyfus and Dommergues 1981].

Souvannavong and Galiana [1991] collected, isolated, and characterized *Rhizobium* strains from the natural range of *A. mangium* in Australia, as well as in Côte d'Ivoire, Senegal, Congo, China, and French Guyana, where it had been introduced. Of the 42 strains isolated, those nodulating *A. magium* were all found to belong to the *Bradyrhizobium* group. *In vitro* and greenhouse tests, as well as nursery and field trials established in Benin, Côte d'Ivoire, and the Cook Islands, indicated variable efficiency among the strains, with the Australian strains being the most efficient.

Dart *et al*. [1991] isolated 12 *Rhizobium* strains from *A. mangium*. None of the 12 strains nodulated *A. auriculiformis* effectively, leading the authors to conclude that *A. mangium* was more specific in its *Rhizobium* affinities than *A. auriculiformis.* Their studies suggest that many of the strains present naturally in soil are only partially effective with many species of *Acacia,* and that responses to inoculation can be obtained with young seedlings. After outplanting, the competition between inoculant strains and native rhizobium populations changes as the inoculant strains need to colonize newly formed roots. This report stresses the need to inoculate seedlings with rhizobia that are more effective in fixing atmospheric nitrogen and aggressive enough to compete with less-effective native strains.

Techniques for mass production of rhizobial inoculants are available. According to dela Cruz and Yantasath [1993], inoculants containing effective strains of *Rhizobium* for *Acacia* species are available from: the Nitrogen Fixation in Tropical Agricultural Legumes (NiFTAL) Project in Hawaii, USA; the Biological Nitrogen Fixation Resource Centre for South and Southeast Asia in Thailand; and from BIOTECH, at the University of the Philippines at Los Baños (UPLB).

2.2.3.3 Combined effects of mycorrhiza and rhizobium in acacia.

It is difficult to isolate the effect of mycorrhizae on the growth of acacia trees without also considering the effect of *Rhizobium*. Thus, many reports in the literature include dual effects of mycorrhizae and *Rhizobium.*

VAM seem to be predominant in *Acacia* species. Reddell and Warren [1987] described several experiments with *Acacia* in pots and under field conditions following inoculation of seedlings in the nursery. It was found that in a pot experiment with a phosphorous-deficient soil that had been sterilized to kill the native population of mycorrhizal fungi, inoculation of *Acacia raddiana* and *A. holosericea* with VAM fungus *Glomus mosseae* increased shoot weights by 170 percent and 859 percent respectively, and nodule weights by 10-12-fold (all pots were also inoculated with *Rhizobium*). This study also indicated a beneficial effect of mycorrhizae in enhancing the drought tolerance of *A. raddiana.*

Nursery and field responses to inoculation of *Acacia holosericea* with both VAM and *Rhizobium* in Senegal were recorded by Cornet and Diem [1982]. Compared to plants inoculated with *Rhizobium* only, dual inoculation increased seedling growth in the sterilized nursery soil by 50 percent. The relative effect of mycorrhizal inoculation diminished with time and 7 months after outplanting, dual-inoculated plants were only 8 percent larger than those inoculated with *Rhizobium* only. This diminishing mycorrhizal effect was probably due to infection of the uninoculated plants by the natural population of VAM at the planting site. Even though the effect of the inoculation with the mycorrhizal fungi was only temporary, its short-term influence on plant growth may make the difference between initial success or failure of seedling establishment, especially in semi-arid areas and other stressful environments [Reddell and Warren 1987]. A further finding of the study was that following outplanting there was much less variability in growth amongst plants inoculated in the nursery with a mycorrhizal fungus than amongst the uninoculated plants. A somewhat similar effect in which ectomycorrhizal infection masked genetic differences in plant growth between several genotypes of *Pinus elliottii* has been shown [Marx and Bryan 1971]. This suggests that perhaps mycorrhizal fungi compensate for genetic differences that occur between individual trees in their efficiency of root function [Reddell and Warren 1987].

Only plants dependent on mycorrhizae for their growth show positive responses to inoculation with VAM fungi in growth and nutrient uptake [Yantasath and Poonsawad 1991]. Chemical fertilizers can improve tree growth, but once the fertilizer is exhausted, growth will decrease. Fortunately, native VAM populations where trees are planted (especially in logged-over areas and degraded grasslands) are often adequate for at least minimal growth [dela Cruz and Yantasath 1993]. Tambalo-Zarate and dela Cruz [1991] found *A. mangium* to be mycorrhizal dependent; that is, it would not survive in soils of marginal fertility without forming VAM associations. Introduction of *A. mangium* in some parts of the tropics has thus been successful partly due to the presence of native VAM fungi [dela Cruz and Yantasath 1993]. VAM fungi are not specific in their associations with crops.

The major factor limiting the large-scale use of mycorrhizae in establishing *Acacia* species has been the scarcity of cheap but effective mycorrhizal inoculants. Unlike ectomycorrhizal fungi, VAM fungi have not been isolated *in vitro* in the laboratory, thus making mass production of inoculants for nursery use difficult. dela Cruz and Yantasath [1993] listed some commercial VAM inoculants available on the market: NUTRI-LINK (produced in Salt Lake City, Utah, USA); and MYKOVAM 1 and 2 (produced by BIOTECH at UPLB, Philippines).

Some VAM fungi are more effective than others in promoting *Acacia* growth. dela Cruz *et al.* [1988] found in a greenhouse experiment conducted in pots with soil collected from degraded grasslands in Philippines that *Glomus fasciculatus* + *Rhizobium* and *Gigaspora margarita* + *Rhizobium* were most effective for *A. mangium;* stem diameter of seedlings at 4 months was 28 mm and 26 mm respectively, which was significantly different from the uninoculated control - 15 mm. *Scutellospora persica + Rhizobium, Gigaspora margarita + Rhizobium,* and *Glomus fascilatus + Rhizobium* were most effective for *Acacia auriculiformis* with seedling diameters 27, 25, and 28 mm respectively, compared to 14 mm in the control. Consistently poor growth was attained by seedlings inoculated with *Sclerocystis clavispora* + *Rhizobium, or Rhizobium* alone.

dela Cruz and Yantasath [1993] summarized the results of another study testing inoculation of *A. mangium* with three VAM species in the nursery, followed by outplanting in a degraded grassland. Inoculation with any of the three VAM species resulted in large increases in both height and diameter. Uninoculated seedlings were shortest and showed symptoms of nutrient deficiency. Seedlings inoculated with *Glomus etinicatum, G. macrocarpum,* and *Gigaspora margarita* at the age of 15 months were 82.9, 78.59, and 75.22 cm in height respectively, while uninoculated seedlings reached only 26.73 cm. After 24 months in the field, all uninoculated seedlings were dead.

Lorilla *et al.* [1992] tested inoculation of *A. mangium* in the nursery using three VAM species and five levels of chemical fertilizer. After 5 months, seedlings were outplanted in a degraded grassland. The most effective VAM fungus was *Scutellispora calospora*. The best growth was obtained by seedlings inoculated with this VAM and fertilized with 50 g complete fertilizer/plant in the field. Height growth of seedlings was 249.7 cm versus 147 cm in the uninoculated control. *G. margarita* replaced 54 percent, *G. etunicatum* 88 percent, and *S. calospora* 100 percent of the chemical fertilizers required for growth in the field.

Research in the Philippines is now incorporating VAM into traditional silvicultural technologies for growing *Acacia mangium.* In a direct-seeding experiment, dela Cruz *et al.* [1992] placed *A. mangium* seeds into fabricated direct-seeding blocks (DSB) and inoculated them with either *G. macrocarpum, G. margarita*, or a combination of both fungi. Seeds received one of the three pre-soaking treatments. Seeds soaked for one minute in hot water, then soaked overnight in tap water, and then inoculated with *G. margarita* alone attained best height and diameter growth - 525 mm in diameter growth compared to 180 mm in the control (DSB + same pre-soaking treatment, but uninoculated with VAM).

Some publications report no need for fertilizer in *Acacia* plantations (e.g. National Research Council 1983) since *Rhizobium* and VAM are capable of fully replacing the chemical fertilizers required for tree growth in the field [e.g. Lorilla *et al.* 1992]. However, a word of caution is added to acacia silviculture in other publications, e.g. that of Midgley and Vivekanandan [1987]. They suggested that if a species has the ability to fix atmospheric nitrogen, it does not follow that application of fertilizer is not necessary. For rapid growth and successful early establishment, fertilizer is helpful especially on marginal sites.

In conclusion, of all the tree genera discussed in this review, *Acacia* is by far the most effective in symbiotic associations with *Rhizobium* bacteria and mycorrhizae, and the most effective in fixing atmospheric nitrogen. Data on plantation yield increases as a result of symbiotic associations of acacias with some micro-organisms were not available to the author at a time this review was compiled. Nevertheless, it is clear from the publications reviewed that, used together, effective *Rhizobium* strains and effective VAM fungi can increase early seedlings growth in areas of marginal fertility and can economically substitute for large portions of early chemical fertilizer requirements in such areas. This eventually will lead to enhanced productivity and sustainability of acacia plantations.

2.2.4 Seed pre-treatment

Seeds of *Acacia* species are known to have hard coats that completely prevent the inhibition of water and exchange of gases, thus preventing initiation of the germination process [Khasa 1993b]. Such physical seed-coat dormancy occurs most frequently in species adapted to alternating dry and wet seasons. To accelerate germination of *Acacia* seeds, various pre-treatment methods have been assayed including nicking, soaking in hot or boiling water, and sulphuric acid scarification [Doran and Gunn 1987]. The proportion of hard-coated seeds in a sample may be influenced by environmental conditions during the growth of the plant, the degree of the maturation of the seeds when collected, and duration and type of seed storage [Willian 1985]. Hence, it is difficult to prescribe an optimum treatment that is highly effective in stimulating germination in most *Acacia* seeds [Doran and Gunn 1987]. However, it is vital to practice efficient, easily applied seed pre-treatment methods that can be used in industrial nurseries for managed plantations of *Acacia.*

One of the simplest and most direct methods is to cut, drill or file a small hole in the seed coat before sowing. This was done on *Acacia* seeds in Honduras [Willian 1985]. In laboratory trials in Sweden, sandpaper scarification followed by a 3-hr cold water soak was the most effective treatment for *Acacia farnesiana.*

Khasa [1993a] investigated different methods of overcoming seed-coat dormancy of *Acacia auriculiformis* (provenance KZNO) from Zaire. Of the water pre-treatments tested, soaking seeds in boiling water (heat source removed) gave the best germination (77.5 percent after 20 days of germination). Immersing the seeds in boiling water for one minute gave the second highest result for water pre-treatments (51.0 percent). While the control seeds germinated at a rate of 23.5 percent, immersion in boiling water for 3 and 5 minutes gave the worst results (12 percent and 7 percent respectively), killing many embryos and encouraging fungal growth. All acid scarification methods produced earlier and better germination than water treatments. Scarification in concentrated H_2SO_4 (95-98 percent) for 15 minutes gave the best germination (93 percent). This method was adopted in an industrial tree-planting project on the Bateke Plateau by HVA-Holland Agro Industries in Zaire. Sulphuric acid treatment has been reported to be effective for *Acacia albida (*20 minutes), *Acacia nilotica* (60-80 minutes), *Acacia senegal* (40 minutes), and *Acacia planifrons (*2 hours) [Willian 1985].

Acid scarification is considered to be more effective method for many African acacias and is in regular use throughout Africa [Doran *et al.* 1983]. Cavanagh [1987] suggested that acid treatment may well be more suitable for those lots which are adversely affected by heat. Acid scarification, however, has seen little use in Australia, most likely because of the effectiveness of easier and safer methods of pre-treating local *Acacia* seeds [Doran and Gunn 1987].

The effectiveness of nine methods of stimulating germination in Australian acacias was tested at ACIAR [Doran and Gunn 1987]. Sixteen species of high potential for widespread planting were chosen as candidates for this experiment, including *Acacia ampliceps, A.aneura, A. cincinnata, A. crassicarpa, A. mangium, A. mearnsii, A. melanoxylon,* and *A. stenophylla.* Three methods were found to be worthy of adoption as standard techniques for pre-treating hard-coated Australian acacias. They are: 1) manual nicking - recommended for the treatment of seed for germination tests and when propagating small and valuable research lots; 2) boiling water immersion for one minute - recommended as a standard treatment appropriate for many hard-coated *Acacia* seedlots; as well as being highly effective in breaking dormancy, it is easy to apply and reproduce with a minimum of equipment; and 3) hot water (90°C) for one minute - recommended for hard-coated seedlots that are suspected of being sensitive to boiling water treatment (e.g. *Acacia stenophylla).* Untreated seed of the species tested gave low levels of germination, usually in the range of 0-10 percent after 27 days of incubation. As a result of seed pre-treatment, germination of *Acacia spp*. increased up to 100 percent. According to Cavanagh [1987], immersion of seeds in boiling water may stimulate germination by causing rupture of the lens tissue, thereby allowing water to enter the seeds.

Typically “Australian” methods of seed pre-treatment for acacia were introduced to Africa together with some Australian acacias. Pre-treatment of *Acacia mearnsii* seeds by boiling water gave faster and more uniform germination in Tanzania [Kessy 1987].

A number of methods have been used in Sabah, Malaysia, to break the dormancy of *A. mangium* seeds caused by the hard seed coat. The most common and practical pre-treatment method now in use in almost all nurseries for *A. mangium* seeds is the hot- water treatment. Adjers and Srivastava [1993] reported large increases in germination rates after the following procedure: seeds were dropped into ten times their volume of heated water for 30 seconds, and then immersed in 20 times their volume of cold water, where they imbibed for 18 hours. Seeds of *A. mangium* pre-treated with boiling water of 100°C for 30 seconds germinated at a 91 percent rate, while those pre-treated with water of 30°C germinated only at a 5 percent rate. Pre-treated seed can be dried (to 6 percent moisture content) and stored for later use, at which time no further treatment is required. Pre-treated seed can be stored in a cold store (4-10°C) for as long as 2 years without significant loss in viability [Liang 1987].

Increased germination rates are not the only objective of seed treatment. Seedling uniformity within the nursery is crucial [Foster *et al.* 1995]. Non-uniform seed germination or slower growth due to variability in vigour results in a large disparity in seedling size. In a study on loblolly pine, Boyer and South [1988] found that a one-day delay in seedling emergence from the seed caused reductions in several traits of the seedlings: 0.5-0.8 cm in height, 0.12-0.16 mm in diameter, 0.22-0.47 g in shoot dry weight, and 0.3-0.6 g in total weight. Therefore, a variable germination rate will lead to a lower percentage of high quality seedlings. In a World Bank Project in northern Sabah, Malaysia, the contracting company, Groome Poyry, developed means by which all the *Acacia mangium* raised in the nursery were from the same germination peak, producing a homogeneous planting population, which eventually improved wood production per hectare [Foster *et al.* 1995].

3. EUCALYPT PLANTATIONS

Jacobs [1979] listed factors affecting yield of *Eucalyptus* plantations. Among them are site (geographic location and quality), choice of species, provenance/site matching, silvicultural treatment (fertilization, weeding, irrigation, etc.), pests and diseases, and interactions of all the factors. Some of the factors (species/provenance matching to site, spacing and tree improvement) that could be important for yield increases in *Eucalyptus* plantations are discussed below. No unique (for eucalypt plantations only) factors that affect plantation productivity were identified at this point.

3.1 COMMON FACTORS

3.1.1 Species/provenances matching to site

The evolution of the eucalypts has produced species and provenances fitted to an enormous range of environmental conditions within the natural range of the genus. On the other hand, eucalypts are highly variable genetically and adaptable to changing environmental conditions. Jacobs [1979] reviewed several properties of the genus *Eucalyptus* that can limit the choice of sites for productive plantations. Among them are tolerance of periodic flooding, tolerance of salinity, tolerance of calcareous soils, drought resistance, adaptability, and resistance to cold.

3.1.1.1 Tropical Asia and Pacific

A *Eucalyptus* species and provenance trial was established in tropical areas of the People’s Republic of China. Although the trial was still young [18 months), it was tentatively concluded that *E. camaldulensis* and *E. tereticornis* from northern Australia were well-adapted, fast-growing species suitable for the poor site conditions of this tropical part (Quionghai County) of China [Wenlong and Jiayu 1989]. Both have performed better than *E. exserta* which is commonly planted on Hainan Island. All three species belong to the red gum group of eucalypts (section *Exsertaria*). Among the 14 provenances of *E. camaldulensis* tested, eight were placed in the ten best provenances for height growth, and three in the ten best provenances for diameter growth. For *E. tereticornis* these figures were two and one respectively. *E. urophylla* also grew fast with very straight stems and is a species worth considering for plantations in southern China, perhaps in areas having a much shorter dry season. This is because *E. urophylla* is found naturally in Indonesia in areas having a shorter dry season than that experienced on Hainan Island. Nevertheless, of the species tested in section *Transversaria*, *E. urophylla* appears to tolerate the tropical dry periods much better than *E. grandis* and *E. saligna.* The best provenance (15052) of *E. camaldulensis* performed 312 percent better in terms of DBH growth than *E. saligna* (provenance 13263), and 128 percent better than local *E. exserta.*

Field trials of Australian eucalypts planted at six sites across Thailand showed marked differences among species and provenances [Pinyopusarerk 1989]. The most promising species at 24 months after planting were *E. camaldulensis and E. pellita*. *E. camaldulensis* has been planted with acceptable performance elsewhere in Thailand, and the results for this species in the present trials vindicate the high priority accorded to it in current tree-planting programmes in Thailand. Other interesting eucalypts included *E. tereticornis, E. urophylla, E. raveretiana, E. citriodora,* and *E. exserta.* The results reflect the wide adaptability of this genus to all site conditions which makes it so successful as a plantation species in many countries. Some eucalypts (e.g. *E. houseana, E. cloeziana, E. dunnii, E. microcorys, E. torelliana)* were slow-growing compared to those species mentioned above. Of all species and provenances tested at the six sites, the most promising growth in DBH at 24 months was achieved by

E. camaldulensis (provenance 14537) - at three sites up to 163 percent better than the slowest provenance of *E. torelliana*, and *E. pellita* (provenance 12013) - at two sites up to 157 percent better.

Five tropical provenances of *E. camaldulensis* were included in a species trial planted in 1973 on contrasting sites in northern and southern Thailand. After one growing season the height and survival of *E. camaldulensis* provenances were clearly superior at both localities compared with 30 seedlots representing 15 other eucalypt species. Statistical analysis indicated significant variation between the provenances at each site although no provenance was clearly superior to the others and the ranking differed at each site [Pousugg 1975].

Species/provenance trials were established in Sri Lanka [Weerawardane 1989]. Species were ranked according to their DBH at 42 months in the following way: *Eucalyptus tereticornis, E. torreliana, E. alba, E. camaldulensis, E. microtheca, E. crebra, E. melanophloia*, with the most promising seedlot of *E. tereticornis* being 247 percent better than *E. melanophloia.*

The magnitude of Australian provenances' differences of *Eucalyptus camaldulensis* was indicated by the fact that at the Gan Hadar plot in Israel, volume yields in the best and worst provenances were in the ratio 8 to 1 at age 10 years [Jacobs 1979].

E. grandis is resistant to the deadliest of eucalypt diseases - the pink disease - and also produces the best quality pulp for the paper industry. Multi-location trials involving 69 provenances of *E. grandis* from Australia were tested in India at different locations in Kerala State. The provenances were evaluated at the half-rotation age of 5 years. The provenance number 11681 was found to be resistant to pink disease and also exhibited a good growth rate. Among other provenances, numbers 12409, 13326, and 13365 were also found to be promising. Another trial with Australian provenances in India was performed in Punjab with 5 provenances of *E. tereticornis.* All the plants survived and the growth was appreciable. The trial revealed that provenances of the Laura area and 20 km North of Mount Mollowy were significantly different from the provenances of Kennedy River for tree height and DBH [Tewari 1992].

3.1.1.2 Tropical Africa

Field trials with Australian eucalypts were established in semi-arid to humid areas in Kenya. Early results showed that *Eucalyptus saligna* and *E. grandis* had the best growth and survival in humid areas [Milimo 1989].

It is clear that there was a great difference in the growth of the different Australian provenances of *Eucalypt camaldulensis* at the age of 6 years at the Afaka plot in Nigeria. The best provenance at Afaka - Petford - had yielded over three times the volume of timber produced by the worst - Walpole. The MAIs recorded for these provenances were 17.3 and 5.1 m^3/ha/yr respectively. The most productive provenances were from the tropical part of Australia with a pronounced summer rainfall. At Afaka the Petford provenance yielded the most, but it has a very narrow crown and in older plantations invasion by savanna grasses may be a problem. It was followed by the Bullock Creek and Katherine provenances (15.3 and 14.1 m^3/ha/yr respectively); the former tended to outyield the latter but was of poorer form. Lake Albacutya was among the best provenances and maintained its superiority in several plantations in Nigeria, Zambia, and Madagascar. In contrast to Afaka, the only provenance with reasonable survival in the extremely harsh conditions at Yambaya in the Sudan zone was that from Katherine. In an irrigated trial at Malam Fatori, the Silverton provenance from New South Wales (Australia) performed best, although it was one of the worst on all non-irrigated sites [Jackson and Ojo 1973].

3.1.1.3 Tropical Latin America and Caribbean

Most early plantings in the extensive pulpwood plantations of Aracruz Florestal in Espiritu Santo (19°S) were of a local hybrid eucalypt, referred to as *E. 'alba'*, and some *E. saligna*. Both species grew poorly in the humid tropical climate, averaging 22 m^3/ha/yr on a 7-year rotation. Also both were susceptible to the canker *Cryphonectria cubensis*. 80 percent of the trees were infected, and coppicing ability was poor. It was considered desirable to change to *E. grandis* which was known to be faster growing and possibly more resistant to canker. The first seed of *E. grandis* tried came from Coffs Harbour, New South Wales, Australia (26-31°S) and, though growing faster, still suffered canker damage on 40 percent of the trees. In 1973, seed from a more northerly and tropical source near Atherton in Queensland, Australia (17°S), were tried along with improved seed imported from Zimbabwe (of Coffs Harbour origin, which, through selection, had become well-adapted to Zimbabwe conditions, i.e. it was a land race). The Atherton provenance of *E. grandis* achieved a growth rate of 35-40 m^3/ha/yr and was significantly less susceptible to canker. This provenance, the land race from Zimbabwe, and *E. urophylla* from Timor were the main plantings of the late 1970s. Since then vegetative propagation of selected vigorous trees, free of disease, has created mixed clonal plantations averaging 55 m^3/ha/yr and many up to 70 m^3/ha/yr. Elite trees from hybrid crosses of *E. grandis x E. urophylla* are planted to increase yield even further [Evans 1992].

3.1.1.4 Australia, Tasmania

Growth performance of *E. cloeziana*, *E. grandis* and *E. resinifera* were compared in a trial established on a degraded pasture at Pomona near Gympie, Queensland, Australia. Trees were planted at a spacing of 2.4 x 2.7 m (1540 stems/ha) and subsequently pre-commercially thinned. At the age of 29 years, *E. cloeziana* had shown better growth than the two other species. Mean DBH was recorded as follows: 44.3 cm in *E. cloeziana* (stocking 208 stems/ha), 41.1 cm in *E. grandis* (stocking 168 stems/ha), and 32.0 cm in *E. resinifera* (stocking 178 stems/ha) [Borough *et al.* 1984].

Eucalyptus species selection for planting at high elevation on the north coast was performed at the arboretum at Chichester near Dungog, New South Wales, Australia. Mean DBH at the age of 15 years in eucalypts planted at 2.4 x 2.4 m spacing (1740 stems/ha) was as follows: 33.3 cm in *E. obliqua* (stocking 667 stems/ha), 19.7 cm in *E. grandis (*stocking 1265 stems/ha), 20.4 cm in *E. laevopinea (*stocking 1551 stems/ha), 22.7 cm in *E. fastigata* (stocking 782 stems/ha), and 18.0 cm in *E. saligna* (stocking 1371 stems/ha) [Borough *et al.* 1984].

Growth and survival of 64 provenances of *Eucalyptus delegatensis* R.T. Baker from the whole natural range of the species in south-eastern Australia were assessed in four field trials in Tasmania and New South Wales [Moran *et al.* 1990]. At 3 years from planting there was significant variation in height, DBH and volume among mainland Australian, Tasmanian and New Zealand provenances. The better provenances across all sites came from the mainland, and in particular from Victoria. The biggest difference in DBH between the best (Mt Ewen, 3.03 cm) and the worst (Fingal Tier, 1.10 cm) provenance was observed at Tarraleah site. In general, the Tasmanian provenances had poorer survival and grew slower on the mainland. General susceptibility to frost, lower survival, and significantly lower growth rates seemed a sound basis for excluding Tasmanian provenances from mainland breeding programmes. Further it was noticed that the source of superior provenances for plantations in Tasmania would be from southern Victoria. Also it was suggested that it would be beneficial to introduce new material to New Zealand from superior mainland provenances in Australia.

Four eucalypt species, *Eucalyptus delegatensis*, E. *globulus, E. nitens,* and *E. regnans*, were established at each of four plantations situated between 60 m and 650 m above sea level (asl) in southeastern Tasmania. *E. grandis* and *E. pauciflora* were also established at the lower and upper two plantations respectively. Two provenances of each species were tested. In general, *E. globulus* and *E. nitens* of subgenus *Symphyomyrtus* grew faster than *E. delegatensis* and *E. regnans* of subgenus *Monocalyptus*. Survival was also greater in *Symphyomyrtus* than *Monocalyptus* species except at the uppermost (650 m) site where snow and frost killed *E. globulus*. The faster diameter growth across all sites at age 5 years was from the Upper Toorongo provenance of *E. nitens* with mean DBH between 10.5 cm (60 m asl) and 9.6 cm (650 m asl). The lowest DBH at 60 m asl was observed in *E. delegatensis*, Maydena provenance (7.5 cm). The lowest DBH was observed in *E. pauciflora* at 440 m asl (1.7 cm) [Turnbull *et al.* 1993].

Provenances can differ not only in growth parameters but in others as well. Heritable variation in insect resistance has been observed within and between many species of *Eucalyptus*. The level of damage to foliage of *Eucalyptus blakely* and *E. camaldulensis* caused by *Cardiaspina albitextura, C. retator, Phylacteophaga froggatti* and *Mnesampela privata* was recorded for a range of provenances in plantations near Seymor and Tatura in Victoria, and in a natural stand near Tumut in New South Wales (Australia) [Floyd *et al.* 1994]. The most resistant provenances of *E. camaldulensis* were from the Lake Frome catchment and Lake Bolac, while the most susceptible provenances were local to the Seymour and Tatura plantation sites. Significant variation in resistance was observed within and between most provenances, offering an opportunity for genetic improvement as a means of reducing insect damage in commercial hardwood plantations. For example, the Lake Albacutya provenance of *E. camaldulensis* has consistently good growth and form characteristics in Australia, as well as in other parts of the world (see section on Africa above). The weakness of this provenance, however, is its poor insect resistance. Some individuals of this provenance planted near Seymour were superior in all three traits [Floyd *et al*. 1994]. The progeny of such individual trees could be expected to have superior levels of insect resistance and growth performance and could be used as a basis for genetic improvement programmes.

Growth in eucalypts varies greatly according to climate and soil. Volume yields of 20-25 m^3/ha/yr are reported for *Eucalyptus camaldulensis* from Argentina, and on the very best sites in Israel as much as 30 m^3/ha/yr may be obtained. In Turkey 17-20 m^3/ha/yr can be obtained on good sites in the initial seedling rotation and 25-30 m^3/ha/yr in subsequent coppice rotations. However, on the poorer and drier sites much lower yields can be expected. Morocco records a range between 3 and 11 m^3/ha/yr and Uruguay a range between 4 and 18 m^3/ha/yr. On the driest sites in Israel only 2 m^3/ha/yr are obtainable. In southern Africa the average is between 7 and 14 m^3/ha/yr. In India, which has the biggest area of plantations of *E. tereticornis.*, the average MAI at 8 years of the better plantations in eight states is about 18 m^3/ha/yr; the average of the poorer plantations in the same states is 4 m^3/ha/yr [Jacobs 1979].

3.1.1.4.1 Provenance x environment interaction in eucalypts

Provenance x environment interactions are a problem as they can lead to the choice of a less-than-most-productive seed source (provenance) for planting at a particular site [Matheson and Raymond 1984]. The most productive provenance in a provenance trial may not be the most productive provenance at another site nearby. If it is decided to plant the overall 'best' provenance everywhere, then the operational costs of a subsequent breeding are a great deal less than the costs of having a separate breeding programme for every region. But the biological cost of planting the same provenance everywhere is that advantage is not taken of the specific characteristics of each site. In other words, production from every site may be less than could be obtained. It is not known yet which way of solving the problem is the optimal.

In *Eucalyptus camaldulensis* it has been widely recognized that generalizations are possible about the behaviour of provenances. Lacaze [1977] reported on 30 plantations of *E. camaldulensis* in 14 countries, and stated that the lake Albacutya provenance is almost always among the best provenances for vigour and form, both in the Mediterranean area and in the tropics. It was the tallest in Zambia, Spain, and Algeria, as well as at five sites in Nigeria. Martin [1977] recommended the use of mid-western Queensland (e.g. Flinders River) provenances for use in the dry tropics.

In a trial of 26 provenances of *E. camaldulensis* and 23 provenances of *E. tereticornis* planted at nine sites in South Africa, Darrow [1983] found Palmer River provenance (*E. tereticornis)* to perform well at most sites. For *E. camaldulensis* the Petford and Katherine provenances performed well in the more humid zone while the more southerly provenances performed better in the winter rainfall zone.

In Colombia, Ladrach [1980] found that the best provenances of *E. camaldulensis* varied with the altitude of the trial site (ranging from 0 to 1935 m asl). Burgess [1975] found in a provenance trial of *E. pilularis* planted on eight sites in eastern New South Wales (Australia) that some provenances from high quality sites grew best at all locations. Similarly, Ades and Burgess [1980] reported that *E. grandis* from the Coffs Harbour region in New South Wales grew best in a trial on two sites at different elevations. They stated that this experience is consistent with results from Brazil although there is some variation between provenances in the Coffs Harbour Region. A similar result was obtained by Roeder [1980] for a number of sites in South Africa.

Darrow and Roeder [1983] found no evidence of provenance x site interaction for either five provenances of *E. alba* or seven provenances of *E. urophylla* planted at three sites in South Africa but not all provenances were represented at each site. For *E. alba* provenances from Lennard River, Western Australia and Flores Island, Indonesia, performed well. For *E. urophylla* the best provenances were from Bobinaro and Ermera in Timor.

In general, analysis of information on provenance x environment interactions in some tropical eucalypt plantations suggests that there are significant changes in rank between different environments [Matheson and Raymond 1984]. However, most research reports that for each species there are some provenances which seem to grow better than the others almost everywhere.

3.1.2 Spacing

Overall, more widely spaced plantations are probably cheaper to grow [Evans 1992]. Allan [1977] cited a comparison of eucalypts planted at 3 x 3 and 3 x 1.5 m, and reported that at the closer spacing costs were 83 percent higher during the first year due to both greater planting costs and weeding costs because of less opportunity for mechanized weed control.

A wide range of initial spacing has been tried in countries where eucalypts are planted (Table 3). The more stems per hectare, the greater the total volume yield in the early stages, and the greater the cost of planting stock and planting. Owners must decide on a spacing which suits their management objectives and site fertility. In general, poor sites should have wider spacings and good sites a closer spacing but one which permits the rapid development of high-quality crops of pulpwood. Another important factor that should influence the owner’s decision on spacing is the likely use of mechanical equipment for cultivation and harvesting [Jacobs 1979].

Table 3: Range of espacements used by the main eucalypt-planting countries

Initial espacement (m)	Trees/ha	Object of management
2 x 2	2 500	pulpwood, mine-timber, light posts
2 x 2.5	2 000	pulpwood, mine-timber, light posts
2.5 x 2.5	1 600	pulpwood, mine-timber, light posts
3 x 2	1 670	pulpwood, light and heavy posts
3 x 2.5	1 330	pulpwood, light and heavy posts
3 x 3	1 110	sawlogs, light and heavy posts, mine-timber and pulpwood
3.33 x 2.25	1 330	sawlogs, light and heavy posts, mine-timber and pulpwood

Source: Jacobs 1979.

Examples of spacing used in tropical eucalypt plantations [Evans 1992] are:

- *Eucalyptus globulus* poles in Ethiopia - spacing 1 x 1 m or less, growing space/tree 1 m^2, number of trees/ha - 10 000;
- *Eucalyptus grandis* in Aracruz, Brazil - 3 x 3 m, 9.0 m^2, 1111 trees/ha;
- *Eucalyptus deglupta* in the Philippines - 4 x 4 m, 16.0 m^2, 625 trees/ha;
- *Eucalyptus deglupta* grown for sawnwood in PNG - 4.5 x 4.5 m, 20.25 m^2, 494 trees/ha.

Jacobs [1979] provided more examples of spacings used in different eucalypt-planting countries: 3.33 x 2.25 m in Australia; 3 x 2 m, 2.7 x 2.7 m, 3 x 1.7 m, 2.5 x 2.5 m in Brazil; South Africa is tending to a normal espacement of 2.4 x 2.4 m with a wider row of 3.7 m at intervals of ten rows to admit trucks; New Zealand Forest Products Ltd., planting for pulpwood, aims at an initial stocking of 1700 stems/ha with bare-rooted stock which permits the widths between rows to be up to 3.3 m to allow better access for treatment, and will consider an initial stocking of 1100-1200 trees/ha when establishment techniques have improved.

3.1.2.1 Tropical Asia and Pacific

Wider spacings usually lead to some loss in total volume production per hectare but individual trees grow larger. This can be explained in the following way. A stand of trees planted far apart will have a lower photosynthetic surface area per hectare to intercept light in the early years and consequently lower yield - at least to begin with. But a wide spacing enables individual trees to develop and maintain large crowns and their root systems to occupy a large volume of soil before competition starts, both of which enhance growth. Data from a spacing trial of *Eucalyptus deglupta* in PNG (Table 4) illustrates these effects [Evans 1992].

Table 4: Effect of initial spacing progressively up to 5 years of age in stands of *Eucalyptus delgupta*

	Age in years							
Initial spacing	2		3		4		5	
(m)	dg	G	dg	G	dg	G	dg	G
1.83	5.58	3.56	8.63	8.16	12.00	14.35	14.55	17.27
2.44	4.35	1.86	7.67	5.66	11.32	11.24	14.99	16.33
3.05	5.40	1.45	8.92	3.93	13.56	8.92	16.83	12.64
3.66	5.56	1.30	9.41	3.57	14.77	8.67	18.45	12.27

dg = diameter of tree of mean basal area (cm).
G = basal area per hectare (m^2).
Source: Evans 1992.

Total volume production per hectare in the above trial correlates with G which is 141 percent higher in the plots with closer spacing (1.83 m as opposed to 3.66 m) at the age of 5 years.

Spacing adopted for planting eucalypts in India varied from 1.8 x 1.8 m to 3.6 x 2.4 m or 3 x 3 m [Tewari 1992]. The effect of spacing on survival, diameter growth, height and volume production was observed in the study conducted in Uttar Pradesh, India [Lohani, 1980]. A trend of decline in survival was found when the spacing was reduced from 3 x 3 m (91 percent) to 1 x 1 m (56 percent). The diameter growth strongly correlated with spacing; as the spacing increased, average DBH also increased (e.g. at age 6 from 9.32 cm under spacing 1 x 1 m to 14.25 cm under spacing 3.16 x 3.16 m or 14.56 cm under spacing 1 x 10 m). A similar trend was observed for heights. The diameter growth in square spacing was found higher as compared to rectangular spacings. In general, total volume production decreases with increase in spacing. The highest MAI was observed at the age of 6 years, with spacing 3 x 1/3 m - 48.06 m^3/ha/yr; total volume production in 6 years was 288.38 m^3/ha. The lowest MAI was recorded at the age of 7 with spacing 4 x 6 m - 3.11 m^3/ha/yr; total volume production in 7 years was 21.80 m^3/ha. Even a less dramatic change in spacing - from 3 x 1.5 m to 2 x 1.5 m - led to an increase in MAI up to 275 percent (from 4.97 to 13.66 m^3/ha/yr). The results of the study indicated that close spacing of 1 x 1 m gave high volume production up to the age of 3 years, and 2 x 2 m gave high volume up to the age of 6 years, but wider a spacing of 2.5 x 2 m showed increased volume production at higher ages of 8 to 10 years. Any spacing closer than 1.5 x 1.5 m was considered not acceptable economically.

Bhatia [1980] reported that a wider spacing of 3 x 3 m gave better height and diameter growth and number of branches over closer (1.5 x 1.5 m) spacing in a *Eucalyptus* hybrid plantation. Diameter at wider spacing was 12.60 mm versus 6.65 mm at closer spacing (age of the plantation, type of diameter, and MAI were not reported).

Various spacing trials with eucalypts were conducted in Thailand. Stem diameter and crown width of *E. camaldulensis* grown at Changwat SiSaKet plantation in Thailand increased from narrow to wider spacings or with decreasing stand density. Dry matter and stem volume decreased from narrow to wider spacings. Total stem volume in plantations planted at 1 x 2 m, 1 x 4 m, 2 x 2 m, 2 x 4 m, 1 x 8 m, 4 x 4 m, 2 x 8 m, and 4 x 8 m were 20.084, 11.516, 10.599, 8.240, 7.164, 5.710, 4.006, and 2.421 m^3/rai respectively. Average yield per tree increased from narrow to wider spacings [Vacharangkura 1988]. Spacing trials with *E. camaldulensis, E. deglupta,* and *E. tereticornis* conducted at Takuapa, Phang Nga Province in Thailand, demonstrated that each species of eucalypt growing with narrow spacing (2 x 2 m) produced more biomass than growing with wider one (3 x 3 m and 4 x 4 m) [Sahunalu 1984b].

3.1.2.2 Australia

Various studies conducted in Australia on initial spacing of eucalypt species indicated similar trends. For example, a reduction in spacing (i.e. an increase in initial density) usually reduces mean height (but not necessarily mean dominant height), mean DBH, branch size, and taper, but increases basal area and total stemwood volume (but not necessarily merchantable volume). The results of the spacing trial of *Eucalyptus pilularis* at the age of 11.5 years in New South Wales demonstrated rapid growth in height and diameter with an increase of stem density, quick suppression of a large number of trees in the denser plots, and considerable effects of competition on the growth of dominants. Mean DBH increased from 17.6 cm at a density of 1249 stems/ha to 32 cm at a density of 121 stems/ha, while total basal area decreased from 34.7 to 9.8 m^2/ha [Opie *et al*. 1984].

A trial aimed at assessing the suitability of *E. viminalis* for intensive wood production regimes with rotations less than 10 years was conducted near Toolangi, Victoria. A yield of 25.4 t/ha was obtained at the site with an initial spacing of 0.3 x 0.3 m, while at a spacing of 0.6 x 0.6 m it was only 10.9 t/ha [Borough *et al.* 1984].

Growth of a stand of *E. cloeziana* at Gympie showed the effect of initial spacing on subsequent development. The stand was planted at 1068 stems/ha and different plots were thinned to about 425, 300, 205, and 126 stems/ha at age 3.5 years [Borough *et al.* 1984]. Data from an assessment of the trial at age 21 years (Table 5) show the profound effects of the early thinning on diameter, basal area and merchantable volume.

Table 5: Growth of *E. cloezizna* by age 21 years following thinning at age 3.5 years to a range of stockings at Gympie, Queensland

	Stocking (stems/ha)	Mean DBH	Basal basal area	Standing merchantable volume
Treatment		(cm)	(m^2/ha)	(m^3/ha)
a	848	20.6	28.1	114
b	419	26.6	23.4	170
c	299	30.2	21.5	179
d	206	33.2	17.8	159
e	126	32.8	10.7	95

Treatment:
a - unthinned control;
b - thinned to a spacing of about 5 x 5 m;
c - thinned to a spacing of about 6 x 6 m;
d - thinned to a spacing of about 7.5 x 7.5 m;
e - thinned to a spacing of about 8.9 x 8.9 m.
Source: Borough *et al.* 1984

3.1.2.3 Tropical Africa

Production of *Eucalyptus globulus* was studied in the Harage Highlands, in eastern Ethiopia, by measuring MAI in plots with densities of 2000 and 1500 trees/ha. MAI of sites with higher density were significantly higher. For example, at the Arale location of the trial, MAI of the plot with 2000 trees/ha was 12.6 m^3/ha/yr, while at the plot with density 1500 trees/ha it was 9.4 m^3/ha/yr.

3.1.3 Tree improvement

Davidson [1975-76] listed five tropical countries in which national eucalypt breeding programmes were being vigorously pursued. These were South Africa (*E. grandis)*, Brazil (*E. grandis* and *E. urophylla)*, Zambia (*E. grandis* and *E. tereticornis*), Philippines (*E. deglupta)*, and PNG *(E. deglupta)*. In addition to these, Congo has developed an advanced breeding strategy, based mainly on species hybrids; hybrids are also considered for large-scale planting in India [Jacobs 1979].

Most tree improvement programmes can be divided into 4 major parts: selection, mobilization, orchard establishment, and genetic testing [Foster *et al.* 1995]. Jacobs [1979] listed several major steps of *Eucalyptus* tree improvement strategies:

Step 1	Species and provenance selection
Step 2	Selection and management of seed stands
Step 3	Individual selection
Step 4a	Progeny and clonal testing
Step 4b	Seed orchards
Step 5a	Controlled crossing
Step 5b	Massed production of improved material by vegetative propagation

Information on realized gains from eucalypt-improvement programmes is still scarce. Physical gains through genetic improvement were discussed by Foster *et al.* [1995]. Overall, yield increases averaged 20-25 percent for tropical eucalypts. Some examples of volume gains from tree improvement in eucalypts as listed in this publication are as follows:

- improved seed - 60 percent of volume gain;
- open-pollinated progenies - 8.5 percent;
- unpedigreed seed orchard (SO) - 7.8 percent;
- half-pedigreed SO - 7.8 percent;
- rogued SO (forward selection) - 18.2 percent;
- unpedigreed SO (initial selection) - 17.4 percent;
- CSO (backwards selection) - 22.6 percent.

Among biological characteristics of eucalypts influencing choice of breeding strategy, Griffin [1989] listed breeding systems, inbreeding depression, flowering and seed production, hybridizing ability and ease of vegetative propagation. In the scope of this study, examples of some of them can be provided.

3.1.3.1 Vegetative propagation

Vegetative propagation of eucalypts has assumed a great importance in tree improvement to ensure immediate yield gains. If superior clones of eucalypts, selected carefully from the natural or breeding populations, can be propagated in large numbers at low cost, then the ramets from these selected clones can be used directly in plantations to ensure that the superior growth characteristics of the clone are retained. The vegetative propagation of eucalypts, thus, would ensure improvement in the yield and quality, thereby shortening the rotation period [Tewari 1992]. The potential of vegetative propagation for yield improvement in eucalypts was realized when Aracruz Florestal, in Brazil, could increase the yield from 36 to 64 m^3/ha/yr in *Eucalyptus grandis* [Zobel and Ikemori 1983]. Various methods of vegetative propagation of eucalypts exist, such as rooting stem cuttings, air-layering, and grafting [Tewari 1992]. Cuttings programmes with *E. grandis, E. urophylla, E. tereticornis* and their hybrids have been successfully developed at a production-scale level in Brazil [Brandao *et al.* 1984] and Congo [Martin and Quillet 1974].

3.1.3.2 Hybridizing ability

Griffin [1989] recently reviewed the occurrence of natural and manipulated inter-specific hybrids within the genus *Eucalyptus*. Within sub-genera there are generally no strong barriers to the production of hybrid seed following cross-pollination, though in nature this may only occur at low frequency and selection may also operate against hybrid seedlings. In cultivation, where natural geographic and phenological isolating barriers are broken down, spontaneous hybridization can occur much more frequently [Griffin 1989].

Hybrids are desirable because they are heterotic or because they combine traits that previously were not found together in either parental species. Some authors, for example Van Buijtenen [1970], considered hybrid vigour with respect to growth to be the exception rather than the rule in forest tree species, and suggested that positive cases could be traced to environmental factors. It is in marginal conditions which are not tolerated by vigorous species, such as the poor sandy soils of the Congo-Brazzaville savannah, where eucalypt hybrids have shown strong heterosis [Chaperon 1984]. Van Wyk [1977] reported that hybrids of *E. grandis* with *E. Urophylla*, *E. camaldulensis* and *E. tereticornis* were showing good growth performance on sites in South Africa which, because of drought, are marginal for growing pure *E. grandis.* Some examples of hybridization in pursuit of combinatorial advantages are: *E. grandis x E. urophylla* hybrids which are more resistant to canker disease in Brazil [Campinhos 1980]; and the combination of frost hardiness of *E. nitens* with the higher pulp yield, coppicing and branch-shedding capacity of *E. globulus* in Australia [Griffin 1989]. Some of the common hybrids reported in the literature are *E. tereticornis x E. grandis, E. robusta x E. tereticornis, E. camaldulensis x E. tereticornis, E. botryoides x E. camaldulensis, E. grandis x E. tereticornis* [Tewari 1992].

Studies to estimate the growth rate of hybrids were undertaken as early as 1954. Venkatesh and Sharma [1977] compared the growth rate of two reciprocal interspecific crosses between *E. camaldulensis* and *E. tereticornis* and their parental species. The study indicated relatively greater heterotic vigour with regard to height and diameter growth, particularly when *E. camaldulensis* parental control rows in the experimental field trial of FRI 4 were not pure *E. camaldulensis* but hybrids between the species that had naturally been formed. This was designated as FRI 5. The observed differences in their growth rates were attributed to only genotypic and not environmental variance. At 26 months, progenies of FRI 5 had grown the most in height (206 percent of the Et parent height), followed by FRI 4 (126 percent), and the Ec parent (116 percent). At 52 months FRI 4 and FRI 5 were much superior to the parental checks with respect to diameter. Between the two hybrids, FRI 5 was relatively superior to FRI 4.

Arya and Sharma [1990] reported a second generation trial of FRI 4 and FRI 5 utilizing open-pollinated F2 seeds collected from the randomly selected trees of the F1 generation. The percentage of superiority of F2 in respect of height, DBH and volume was 59.97 percent, 90.00 percent, and 463.93 percent over the mid-parent.

More than 5,000 hybrids, arising from natural and controlled hybridization of *E. grandis x E. urophylla*, had been cloned by 1987 in the State of Espirito Santo in Brazil. By 1990, nearly 126 million rooted cuttings of selected clones of *E. urophylla x E. grandis* hybrids had been planted. Significant gains and rapid increases in volume productivity, as well as gains in desirable wood characteristics for pulp production, have been achieved. Volume productivity has gone up from 36 m^3/ha/yr to 45-75 m^3/ha/yr resulting in 25 percent to 108 percent gains. MAIs up to 100 m^3/ha/yr have been achieved with some of the outstanding clones on good sites, which means gains in per-ha volume up to 178 percent [Campinhos and Claudio-da-Silva 1990].

It is important to clarify here that a “hybrid/vegetative propagation” strategy is not sufficient on its own, but needs to be carried out in parallel with, and as an integral part of, a breeding programme which uses sexual reproduction for the generation of material for testing and eventual duplication by vegetative means [Palmberg-Lerche 1997].

3.1.3.3 Diallel progeny tests

Van Wyk [1977] conducted diallel progeny tests in *E. grandis* in South Africa using parent trees selected from even-aged stands with an emphasis on desirable characteristics for the production of sawn timber. Grafts from the parent trees were established in a clone bank where pollination work was done. A complete diallel mating design was adopted. At 15 months, the best family produced 4.86 dm^3 more in volume than the poorest which constituted a 15 percent volume increase.

3.1.3.4 Clonal selection

Sixty clones of *E. grandis, E. urophylla,* and *E. grandis x E. urophylla* have been included in the commercial plantations programme in San Paolo State, Brazil, to develop fast-growing disease-resistant eucalypt clones. Costs of clonal rooted nursery plants of US$ 120/1000 compared to US$ 35/1000 seedlings. Average plantation productivity is 27 m^3/ha/yr but MAIs up to 60 m^3/ha/yr have been obtained on good sites with clonal planting stock, leading to a gain of 122 percent in per-hectare volume [Lal 1994].

Thirty-five fast-growing and disease-resistant clones of *E. tereticornis* have been identified on the basis of plus tree selection in Andhra Pradesh State, India. These clones were multiplied on a large scale through rooting of cuttings. MAI of 16 m^3/ha/yr at 3 years of age has been recorded by some of these clones under rainfed conditions. Productivity is expected to rise by year 7 to 20-25 m^3/ha/yr. This will mean a 50 percent improvement in productivity compared to plantations based on improved seeds of orchard origin and a nearly four-fold increase in yield over eucalypt plantations raised from unimproved seed [Lal 1994].

Among other methods for genetic improvement in eucalypts, Tewari [1992] listed selection, introduction, plus-tree selection, establishment of seed production areas, establishment of seed orchards, and clonal seed orchards.

4. TEAK PLANTATIONS

The factors affecting teak plantation productivity reviewed below include matching species/provenances to site, site quality, irrigation and fertilization, and tree improvement. Irrigation and fertilization are discussed under the same subheading since in some experiments the combined effect of both treatments has been reported. Although provenance selection is one of the major steps in any tree improvement programme, it is considered separately in this review due to its obvious importance for success of any plantation. No unique (for teak plantations only) factors that affect plantation productivity were identified at this point.

4.1 PLANTATION YIELD ESTIMATION

The relationships of yield, basal area, number of trees per unit area and average DBH on age and height for teak plantations in Thailand were expressed by the following regression equations [Sahunalu 1984a]:

V_s = - 73.04435 - 0.08039 Age + 10.72483 Ht (r = 0.465);
BA = -2.00352 - 0.00953 Age + 0.82028 Ht (r = 0.9767);
DBH = 0.42371 + 0.18850 Age + 0.81749 Ht (r = 0.9253);
ln No = 6.60743 - 0.03199 (DBH) (r = 0.4923);
where
V_s = Stem volume (over bark) (m^3/ha);
BA = basal area (m^2/ha);
DBH = average diameter at breast height (cm); and
No = number of trees (trees/ha).

An equation based on data from sources for Trinidad [Keogh 1979] is as follows:

$$V = 72.2 - 14.22\,(h) + 0.86\,(h^2)$$

where
V = volume in m^3/ha (under bark);
h = average height of dominant trees in metres.

4.2 COMMON FACTORS

4.2.1 Species/provenances matching to site

4.2.1.1 Tropical America

Teak has come from Myanmar, Thailand, India and Africa (Nigeria, Cameroon, Côte d'Ivoire and Gambia) to tropical America. The most important introductions, apparently, were those made between 1913 and 1916 from Tenasserim, Myanmar (formerly Burma), to Trinidad and in 1926 from Sri Lanka to Summit Gardens in Panama. The Tenasserim-Trinidad strain has been generally regarded as being a "good" one [Keogh 1979]. Two countries in the region participated in the international provenance trials of the Danish/FAO Forest Tree Seed Centre: Cuba and Venezuela. An unpublished report on teak provenances in tropical America [Keogh 1978] included separate information for 12 countries of the region: Trinidad, Panama, Honduras, Cuba, Nicaragua, Puerto Rico, Venezuela, Costa Rica, Guatemala, Colombia, Belize, and El Salvador. As a general conclusion, Keogh [1979] recommended Trinidad as an area of superior seed source.

4.2.1.2 Tropical Asia and Pacific

Choice of species between indigenous and exotic ones is hotly debated. In India it was the need to maximize yield which led to the planting of eucalypts and pines instead of indigenous trees like teak over large areas. Although there are limitations in comparing the productivity data of different tree species in different plantations, it is apparent that exotic tree species may not always be superior to indigenous ones in terms of biomass production. It is the short-rotation management invariably associated with these exotics, as opposed to long-rotation management of indigenous species, which increases the utilizable biomass from the exotic species. Biomass available from multiple harvests through short-rotation plantation forestry of eucalypts over a period of 40 years is lower than the biomass available from a single harvest of indigenous species like teak under a single rotation of 40 years [Rao and Saxena 1991].

Kadambi [1972] described results of provenance tests of teak in Java (Indonesia). Teak of Malabar (India) origin grew fastest, followed by trees of local and Indo-China origins. Next were Thailand and Myanmar origins, and the last were of central India whose performance was poor. In another provenance test in Java, the local provenance of teak attained better height and girth than provenances from India, Myanmar, Thailand, and Indo-China. Generally teak trees of dry seed-origin grow more slowly and attain smaller sizes than those of imported origins with similar climate, but there are many exceptions.

Trees in the All India Teak Seed Origin plantations in Uttar Pradesh at age 20-22 years varied in height from 20 m to 23 m, and in DBH from 22 cm to 29 cm. The provenances tested in this study came from North Myanmar, South Myanmar, Madras (moist), North Bombay (dry), South Bombay (moist), and Madhya Pradesh. The South Myanmar provenance was the best one of all. Another provenance test conducted in Tamil Nadu showed variation in height at the age of 4 years from 4.96 m (S. Myanmar) to

6.58 m. Comparable height variation occurred in Kerala at the age of 3, from 5.36 m (N. Myanmar) to 6.49 m (S. Bombay) [Kadambi 1972].

In another teak provenance trial in Madhya Pradesh, India [Suri 1984], the performance of 50-year-old trees was analysed. Seeds came from Maharashtra [Kanara], Myanmar, Kerala (Nilambur), Madhya Pradesh (Betul and Tenduchua), and Karnataka (Kakankoti). The top height appeared to be a function of site quality rather than seed origin. The study indicated the superiority of Nilambur seed for use in this locality.

Provenance variation was demonstrated in a 15-year-old teak provenance trial at Huai Tak, Thailand. Seven provenances out of 30 were genetically superior to the others [Pinyopusarerk 1986].

Provenance x environment interactions in teak plantations were reviewed by Matheson and Raymond [1984]. Considerable changes in provenance rankings from site to site were observed in the trials conducted in Côte d'Ivoire, Sri Lanka, Nigeria, Ghana, and India.

4.2.2 Site quality

4.2.2.1 Tropical America and Caribbean

The importance of site quality for high yield of teak plantations cannot be overestimated. Keogh [1979] suggested that individual countries must examine their situations (in terms of adequate site availability) before commencing or continuing planting programmes with teak. Those with lower population densities and low land pressures have the greatest opportunities and may be able to establish small teak plantations. Those with higher population densities and greater land pressures will find it more difficult. Results will be patchy and teak will be forced onto the poorer sites. However, if the better sites cannot be given to this species, it is advisable to consider alternative species.

The site classification chart for *Tectona grandis* constructed by Keogh [1979] may be used as a practical guide to the classification and prediction of teak growth throughout Tropical America and the Caribbean. Three volume-height formulae from different countries of the region and the regional site classification chart were used to estimate total volume production per unit area through time. The formulae are as follows:

(A) That calculated by Keogh [1977] for El-Salvador.

$V = 3.394\ (h) - 0.344\ (h^2) - 62.78$

where

V = stem volume in m^3/ha, under bark, between 0.3 m above ground level and to a minimum diameter of 8.0 cm under bark;

h = top height, in meters, defined as a mean height of the 100 largest-diameter trees per hectare.

(B) That based on work by Fries [1972] for Jamaica.

$V = 0.3889\ (h^2) - 0.8989\ (h) + 0.5031$

where

V = volume in m^3/ha to 10 cm top diameter;

h = top height, in meters, corresponding to the 100 largest-diameter trees per hectare.

(C) Equation based on data from sources for Trinidad [Keogh 1979].

$V = 72.2 - 14.22\ (h) + 0.86\ (h^2)$

where V = volume in m^3/ha under bark;

h = average or mean height of dominant trees in metres.

An estimate of total volume production was divided by the relevant age to obtain MAI (Table 6). It must be remembered that volume and height definitions vary.

Table 6: Mean annual increment (MAI) compared through time for different regional site classes and for three equations

Regional site class	I			II			III			IV			V		
Equation	A	B	C	A	B	C	A	B	C	A	B	C	A	B	C
Years	MAI in m^3/ha														
5	9	12	7	4	8	4	-	5	3	-	3	3	-	2	-
10	17	16	16	12	12	10	7	8	6	3	5	3	-	3	2
15	16	15	17	11	11	11	7	7	6	4	5	3	1	3	1
20	14	13	16	10	10	11	7	7	6	4	4	3	1	2	1
25	13	12	15	9	9	10	6	6	6	4	4	3	1	2	1
30	11	10	13	8	8	9	6	5	5	3	3	3	1	2	1

Source: Keogh [1979].

The greatest difference in MAI, as calculated using equation C, among site classes was recorded for age 15 years. MAI of site I was 17 times higher than that of site V.

Keogh [1979] concluded that poorer sites (part of Class III and all of IV and V) should not be planted to teak. To avoid these, sites that contain deep (1-2 m), well drained, flat or slightly sloping alluvial loam soils which tend to have a homogeneous profile should be sought. Good soil is a prime requisite for teak. Secondly, the area should be influenced by a 3- to 5- or 6-month dry season ("dry month" being defined as one with 50 mm or less precipitation). Thirdly, the site should have an annual precipitation of over 1500 mm. As precipitation increases, somewhat higher growth rates are to be expected.

4.2.2.2 Tropical Africa

Vigour, growth and yield of teak differed considerably according to site conditions in Western Africa. In 5- to 11-year-old *Tectona grandis* plantations at Glaro, Cavalla, and Bomi Hills, Liberia, soil pH and rooting depth accounted for 92 percent of the variation in height growth intensity [Zech and Drechsel 1991]. The relationships between these parameters were described by the formula:

height growth (m/yr) = 0.294 pH + 0.0577 rooting depth (dm) - 0.758 (SE = 0.15 m/yr)

The height growth rate of 0.50 m/yr was achieved at sites where the topsoil base-saturation coefficient multiplied by the rooting depth equals 25, while the sites where the coefficient was 700 produced a growth rate of 1.80 m/yr. Thus, a 360 percent growth-rate increase was observed between the chlorotic teak grown on the former sites compared to healthy teak on the latter sites. Deficiency symptoms as well as soil and plant analyses indicated that differences in growth intensity are mainly related to topsoil acidity and foliar calcium status. Calcium deficiency seems to be caused by low soil reserves in highly weathered soils as well as by reduced uptake caused by root growth inhibition at waterlogged sites. Additionally, there are mineral disorders concerning the nitrogen, phosphorous and manganese supplies for teak. The recommendations to improve the current situation include: improvement of humus status by promotion of a low-growing and non-climbing understory (e.g. *Leucaena* spp.); avoidance of mechanical site clearing and mulching during the establishment of young plantations, thus reducing nutrient losses caused by erosion and leaching; low-intensity controlled burns to increase the quantities of N, P, K, and Ca in the soil; and retention of bark in the plantation during timber harvest since large amounts of Ca are stored in the bark.

Similar trends were observed in young teak plantations in Benin and Liberia [Drechsel *et al.* 1990/91]. Differences in growth were mainly related to topsoil acidity, foliar-Ca status, and microrelief in Liberia (Ferrasols). In Benin (Vertisols), waterlogging (followed by root decay) reduces the uptake of Mg, K, and N. In Liberia a mean annual growth rate of only < 0.6 m/yr was recorded on the top of the hills; young leaves were chlorotic, and several trees had died. On the slopes the growth rates were 1.2 to 1.8 m/yr. A growth rate of only 0.4 to 0.5 m/yr was observed on gleyic bottom soils. In Benin 1.5-year-old teak locally differed in height (1.8 to 4.7 m) and vigour within a few metres of each other.

4.2.2.3 Tropical Asia and Pacific

Height and DBH of 26-year-old teak trees at one mixed (60 percent *Tectona grandis*, 30 percent *Dipterocarpus turbinatus*, 7 percent *Syzygium grande*, and 3 percent *Amoora rohituka*) and two teak plantations at Kaptai (Bangladesh) were measured [Haque and Osman 1993]. Teak trees were significantly larger; their height in the mixed plantation averaged 18.30 m, and DBH was 35.59 cm. However, in pure teak plantations height was 16.17 m and 18.91 m for pure teak 1 and pure teak 2, and DBH was 23.14 cm and 24.59 cm. The poor growth of teak in pure teak sites was attributed to strong soil acidity and resulting low available phosphorous content; greater soil erosion was noticed at these sites. The authors concluded that plantations with teak should be limited to the most suitable sites such as gentle slopes, less erodible and deep fertile soils, and more absorptive surfaces. Mixed plantations should be preferred to pure teak plantations due to erosion hazards and better growth of teak.

Reduced growth in the second rotation of pure teak plantations has been reported in India, Indonesia and Senegal, and led to research into what was termed “the pure teak problem”. Excessive soil erosion was found to be the main reason for the reduction in growth [Evans 1992]. However, in Madhya Pradesh, India, organic C, N, P, and K were all found to be higher under teak plantations than adjoining forest probably because plantations are better protected from grazing, litter collection, fire and so on [Choubey *et al.* 1987].

A study of the site index and yield of a teak plantation was carried out at Lampang province, Thailand, in 1984-85 [Sahunalu 1984a]. The best site qualities (site index 30) were Huay-Prao and Mae-Sai-Kum plantations at 10 years old and Huay-Tak plantation at 40 years old. From the recorded data, the relationships of stem volume and average DBH were expressed as regression equations, as well as the relationships of yield, basal area, number of trees per unit area, and DBH on age and height. The estimated yield per hectare of teak plantation in Lampang province shows that stem volume (over bark) at the rotation age 60 years is 51.68, 116.47, 181.24, 246.13, and 310.91 m^3/ha for site indices 10, 15, 20, 25 and 30 respectively.

Soil in six teak (*Tectona grandis*) plantations (14-65 years old) of different site quality were studied in Kerala, India [Alexander *et al.* 1987]. Experimental plots were of 4 classes: site quality (SQ) 1 (30.5-36.6 m); SQ 2 (24.4-30.4 m); SQ 3 (18.3-24.3 m); and SQ 4 (12.2-18.2 m). There were significant differences in soil properties between groups. Increases in gravel and exchange acidity and decreases in sand, silt, pH and exchangeable bases resulted in a lower SQ. In a multiple linear regression analysis, soils variables accounted for 31 percent of the variation in top height, and age for 63 percent.

4.2.3 Irrigation and fertilization

4.2.3.1 Tropical Asia and Pacific

A critical assessment of growth response of teak plantations to irrigation has been carried out by the Forest Development Corporation of Maharashtra in the Northern Konkan coastal zone in India [Gogate *et al.* 1995a]. Height gain over the previous year in each plantation (1990, 1991, 1992) was compared (May 1993 over May 1992 and October 1994 over May 1993) and differences computed and compared in percentiles over the earlier benchmarks are as below (Table 7).

Table 7: Height increments in irrigated plants over non-irrigated plants

	1992	1991	1990
First year	4448%	-	-
Second year	141%	113%*	-
Third year	-	120%	1 024%
Fourth year	-	-	397%

* Poor response is related to shallow soil.
Source: Gogate *et al.* 1995a.

Irrigated trees certainly benefited: there was a definite gain over rainfed plantations in heights as well as in girth. Gain in girth varied from 193 percent to 276 percent. The positive effect of irrigation was maximum during the first year of the plantation. The irrigated crop was more homogeneous than the non-irrigated crop for both height and girth. Except during the juvenile stage, response to irrigation was not uniform throughout the year as there are definite signs of dormancy from the second and third years onwards. Soil attributes of the site are equally important and put severe restrictions of responses to irrigation and fertilization [Gogate *et al.* 1995a].

Discharge of sewage water is a primary source of pollution, especially near big cities. But its potential to provide water and nutrients to crops can be harnessed for production of arboreal biomass. In Maharashtra and adjoining states, many farmers are establishing irrigated teak (*Tectona grandis)* plantations. Use of the sewage water in this context will not only decrease plantation costs by saving expenditures on manuring, but will reduce the pollution as well. In a case study of teak plantations irrigated with sewage water (that is reported to be rich in N, P, K and S), it was observed that growth in terms of height and girth were significantly higher than the growth from plots irrigated with well water. MAI in three plots irrigated with sewage water was 6.78, 5.83, and 4.82 m^3/ha/yr as against 3.07 m^3/ha/yr in a plot treated with well water. However, mortality was higher in the plots irrigated with sewage water [Gogate *et al.* 1995b].

Introduction of *Tectona grandis* as an exotic species to PNG was successful only on fertilized plantations. In 1968 after 4 years of growth, mean height of teak trees grown in unfertilized plantations was only 0.21 m, and by 1971 all trees were dead. Plots heavily fertilized with 500 kg/ha of NPK (17:5:22) produced trees of 2.60 m in height, and by 1971 they reached 3.04 m [Evans 1992].

4.2.3.2 Tropical America and the Caribbean

The application of technically prescribed fertilizer to establish plantations of teak in Puerto Rico increased crop increment by 60 percent [Briscoe and Ybarra Coronado 1971]. This suggested a prospect for much shorter rotations if corresponding soil research and amendments are applied to teak plantations.

4.2.4 Tree improvement

Individual selection on the basis of phenotypic superiority forms the basis of any tree improvement programme. The success of individual tree selection largely depends on the magnitude of genetic variation. Where the magnitude of variation is high, the realized gain estimated from the difference between the progeny of the selected tree and the random sample of any base population will be high. In a genetic study on teak plantations in the southern part of India (States of Karnataka, Tamil Nadu, and

Kerala), the base population was highly variable and the estimations were made between the selected tree and the mean of five codominant trees [Bagchi 1995]. The higher selection differential thus obtained was indicative of higher gain. The characteristics studied - plant height (H), clear bole length (CBL) and DBH - were indicative of plantation productivity. These parameters were highly variable and were reported to be under sufficient genetic control. The differences between plus trees and comparison trees are illustrated by the following examples (extremes for plus trees and comparison trees):

	H (m)	CBL (m)	DBH (cm)
plus tree	38.0	23.0	73.8
comparison tree	18.8	7.5	30.2

Predicted gain values were estimated for individual batches along with an overall estimate. Maximum predicted gain for height was observed to be 10.7 m, 5.59 m for CBL and 16.95 cm for DBH. The significantly different mean square values and high heritability, along with a 20 percent selection intensity, assures a shifting of the mean towards the direction of the selection. The batches with higher predicted gain values were indicated for use in the mass clonal multiplication programme and also for further breeding and improvement [Bagchi 1995].

Quality seed production is an indispensable part of successful plantation of any species. Kumar [1992] described methods and work on teak seed improvement done in Maharashtra Van Sanshodhan Sanstha, Chandrapur, India. Teak seed orchards to the extent of 166.5 ha have been raised after standardization of vegetative propagation. Further flowering and fruiting behaviour of some clones at different ages has been described. Characteristics of teak seeds of different origins have also been discussed. It has been observed that, generally, flowering and fruiting increases with age of a teak seed orchard. Seed from clonal seed orchards showed better germination rates than general seed.

Reproduction of tree species by vegetative means is an important aspect for genetic improvement and becomes necessary to develop quick and economic methods of producing plant material of desired traits. These methods are useful for multiplication of species and for producing clones. Considerable efforts have been made to propagate teak (*Tectona grandis)* by vegetative propagation. In teak macropropagation by cleft grafting, budding and branch cutting have been successfully employed for establishing clones of desired quality. Almost 80 to 100 percent success was obtained in the case of cleft grafting and bud grafting; however, maximum 60 percent success was recorded by rooting of branch cuttings. The other methods of propagation like air layering were not successful with teak [Nautiyal and Rawat 1994].

Relative resistance of certain clones of *Tectona grandis* to the teak leaf skeletonizer *Eutectona marchaeralis* has been studied in India. Teak leaf skeletonizer is a serious pest having a wide distribution throughout the teak areas in India, Myanmar, Sri Lanka, Indochina and from the Malayan region to Australia. It is capable of destroying up to 80 percent of the leaf surface, which of course retards teak's growth. Eleven selected clones of teak were evaluated for their natural variation in susceptibility to *Eutectona machaeralis.* APT-20, APT-8, and MHSCJ-2 were observed to be the most resistant clones as the leaf areas consumed by the larvae were 1.07, 2.13 and 3.94 cm^2. UPD-1 followed by TNT-11 were the most susceptible (leaf area consumed was 9.46 and 6.87 cm^2 respectively [Meshram *et al.* 1994]).

The teak improvement programme in Thailand was discussed by Kaosa-ard [1984]. Activities in the frame of this programme include: 1) Breeding Section: selection of plus trees, propagation of plus trees, multiplication garden, clonal tests, pollination of teak, progeny tests, provenance selection; 2)

Seed Production Section: seed orchard, seed production area, seed source area; 3) Gene Conservation Section; and 4) Seed Procurement Section.

5. PINE PLANTATIONS

Three factors that affect productively of tropical pine plantations are discussed below: species/provenances matching to site, tree improvement and fertilization. Again, provenance selection is considered separately in this review due to its obvious importance for success of any plantation. No unique (for pine plantations only) factors that affect plantation productivity were identified.

5.1 PLANTATION YIELD ESTIMATION

For estimation of pine stand volume on an area basis, the following regressions were developed [Wormald 1975]:

Malawi $V = - 4.835 + 0.3936\ GH_{dom}$
Kenya $V = 20.764 - 1.20.764 - 1.269G - 1.3601\ H_{dom} + .462275\ GH_{dom}$
(where V = total volume under bark in m^3/ha, G = basal area in m^2/ha, H_{dom} = dominant height in metres)

5.2 COMMON FACTORS

5.2.1 Species/provenances matching to site

5.2.1.1 Tropical Africa

A trial of 15 provenances of *Pinus oocarpa* Schiede and one provenance of *P. caribae* Morelet was assessed in 1980 at Nzoia, in northwestern Kenya as part of the CFI (Commonwealth Forestry Institute)-coordinated intensive assessments of the international provenance trials of *E. oocarpa* [Chagala and Gibson 1984]. For height a clear picture of superiority of the Nicaraguan provenances - Yucul, Camelias and Rafael - had emerged, closely followed by Mountain Pine Ridge, Belize. DBH and volume under bark (VUB) showed essentially the same results, with the Honduran and Guatemalan provenances being significantly less productive. The highest value for DBH - 17.7 mm - at the age of 8 years was for Yucul (Nicaragua) provenance compared to 14.0 mm for the Bucaral provenance (Guatemala). The most productive provenance (Yucul) was more than twice as productive as the poorest performer - Angeles (Honduras); VUB of these provenances was 175 and 70 dm^3 respectively.

A *Pinus elliottii* and *P. taeda* provenance trial was established in Malawi at five sites [Ingram 1984]. Seedlots of pines for the trial were obtained from within their natural ranges in USA, Zimbabwe and Malawi. The highest gain in basal area in *P. elliottii* trial was observed at Dedza site, where the fastest growing provenance - No. 21 from Florida - achieved 46.0 m^2/ha, while the slowest provenance (at this site, as well as overall in the trial) - No. 7 from South Carolina - had a basal area of only 16.8 m^2/ha. In *P. taeda* the highest gain was attained at Nthungwa site, where basal area of 29.2 m^2/ha was recorded for local provenance No. 31, while the poorest performer - seedlot No. 21 from Virginia - had basal area of only 6.1 m^2/ha. Correlation of mean height and basal area on latitude of origin for the American provenances of both pines were all significant. Variation between sites and between provenances within sites were much greater in *P. taeda*. This was probably associated with greater natural range of *P. taeda*. Overall the productivity of *P. taeda* was greater than that of *P. elliottii*. The performance of the African provenances of *P. elliottii* was good, but not as good as would be expected following selection for local conditions, and it would appear that yield of Malawian plantations could be improved by the importation of genetic stock from the southern end of the species' natural range. The results of African provenances of *P. taeda* were very encouraging, performing well at all sites.

The performance of five *Pinus merkusii* Jungh. and de Vriese provenances was evaluated in Tanzania, at Buhindi, Mwanza [Madoffe *et al.* 1984]. At 10 years the trial was assessed for various parameters. The provenance from Pekalongan, Java (Indonesia), was outstanding for most parameters. It had a survival rate of 75 percent, mean height of 14.6 m, DBH of 19.8 cm, and a mean basal area of 57.5 m^2/ha. In comparison, for the poorest performer - Phayao provenance from Thailand - these parameters were 72 percent, 6.3 m, 10.3 cm, and 18.4 m^2/ha respectively.

Provenances of *P. kesiya* from Philippines, Viet Nam, India, Myanmar, Zimbabwe and Thailand were tested in Zimbabwe. This trial indicated that Vietnamese material has considerable merit for breeding, and the major occurrence of this species in Viet Nam should be thoroughly sampled for use in international provenance research. By extension, the landrace that was established in Madagascar 70-80 years ago, almost certainly from Vietnamese provenances, must also be regarded as a valuable source of material for provenance research and breeding. DBH of the fastest Dalat provenance (Viet Nam) was 17.24 cm compared to 13.50 cm of Assam provenance (India) [Mullin *et al.* 1984].

A 12-year-old provenance trial of *Pinus caribaea* was assessed for height and DBH at three test locations in Nigeria [Otegbeye and Shado 1984]. There was a substantial amount of variation in DBH among the five provenances at all sites. Miango was found to be the location best suited to the growth of the species. *P. caribaea var. hondurensis* excelled at all the three sites, the best seed source being a provenance from Belize. The biggest difference in DBH within a site was achieved at Nimbia site, with Belize provenance having DBH of 54.2 cm and Bahamas provenance being 39.6 cm at age 12 years.

An international provenance study of *Pinus caribaea* (vars. *hondurensis, bahamensis, caribaea)* demonstrated the possibility of a 35 percent gain in DBH growth and 178 percent VUB in Côte d'Ivoire (San Pedro), 35 percent and 191 percent respectively in Congo (Loudima), and 22 percent and 79 percent respectively in Zambia (Chati). Corresponding figures for *P. oocarpa/P. patula* ssp. *tecunumanii* were 25 percent for DBH and 75 percent for VUB in Côte d'Ivoire (San Pedro) [Birks and Barnes 1990].

5.2.1.2 Tropical Asia and Pacific

Results of germination, survival, height, diameter and form measurements were presented for a *Pinus kesiya* provenance trial at Koraput, Orissa (India), aged 11 years. A total of 12 provenances, seven from the Philippines, two from Thailand, and one each from Viet Nam, Zambia, and Assam, were included in this trial. After 9 years in the field the mean survival rate was only 47 percent. Mean height and DBH were 10 m and 16 cm respectively. The differences between provenances were insignificant. However, provenances from the Philippines and Zambia seemed to grow slightly better than those from Assam, Viet Nam, and Thailand. Both Thai provenances exhibited the best form traits [Das and Stephan 1984a].

Results of a provenance trial established in 1974 at Koraput (India), with eight provenances of *Pinus caribaea var. hondurensis* and one provenance of *P. caribaea var. bahamensis,* were presented and compared with results of earlier trials of tropical pines [Das and Stephan 1984b]. The mean height and DBH differed considerably between the nine *P. caribaea* provenances at age 7 years. The difference between fastest- (Limones, Honduras) and slowest- (Poptun, Guatemala) growing *P. caribaea* provenances in relation to height and DBH was 46 percent and 53 percent respectively. The *P. caribaea var. hondurensis* were generally better in growth than the *P. caribaea var. bahamensis* or *P. caribaea var. caribaea*. The fastest growing provenance of *P. caribaea var. hondurensis* was almost twice as fast (in terms of DBH growth) as the slowest in this trial, *P. pseudostrobus.* Only *P. kesiya* from Philippines and Assam showed considerably better height and diameter growth. *P. pseudostrobus* and *P. taeda* exhibited poor growth. That result was not unexpected, because both are pine species from habitats with different ecological conditions. The best performer - *P. kesiya* from Philippines - at age 8 years had DBH of 14.6 cm, while the slowest - *P. taeda* - had DBH of 5.3 cm. In general, *P. caribaea* and *P. kesyia* were considered the most promising species on the tested sites.

Eighteen sources representing four major regions of the natural distribution of *P. kesiya* in Thailand, the Philippines, Viet Nam and Assam were tested in the northern highlands of Thailand, at Huey Bong [Granhof 1984]. After 9 years of growth, there were significant differences in yield, stem form, insect resistance, branching, flowering and wood density. Results point to three local sources from the Chiang Mai province - Doi Inthanon, Mae Rid and Doi Suthep - as the most suitable for reforestation in this region. In terms of yield, Doi Inthanon was the best source and produced an MAI of 4.6 m^3/ha/yr compared to 1.2 m^3/ha/yr by the Kabayan provenance.

Five provenances of *P. kesiya* (Thailand, Philippines, Viet Nam) were included in a series of species/provenance trials in the Bai Bang area in northern Viet Nam. Overall survival of *P. kesiya* compared well with that of *P. caribaea* and *P. oocarpa* but its height growth 18 months after planting was less than half that of the other two species. The indigenous provenance from Huang Su Phi showed the best performance for *P. kesiya* on all sites [Burley and Armitage 1980].

An international provenance study of *Pinus caribaea* (vars. *hondurensis, bahamensis, caribaea)* demonstrated the possibility of a 45 percent gain in DBH growth and 228 percent in VUB in Thailand (Chumporn), and 25 percent and 75 percent respectively in Malaysia (Bukit Tapah). Corresponding figures for *P. oocarpa/P. patula* ssp. *tecunumanii* were 34 percent (DBH gain) and 225 percent (VUB gain) in Thailand (Huey Bong) [Birks and Barnes 1990].

5.2.1.3 Tropical Latin America and the Caribbean

Pinus caribaea (vars. *hondurensis, bahamensis, caribaea)* demonstrated the possibility of a 31 percent gain in DBH growth and 124 percent in VUB in Brazil (Jari), and 56 percent and 305 percent respectively in Puerto Rico (Anasco) [Birks and Barnes 1990]. Corresponding figures for *P. oocarpa/P. patula* ssp. *tecunumanii* were 23 percent (DBH gain) and 116 percent (VUB gain) in Brazil (Agudos), 21 percent and 145 percent respectively in Ecuador (Conocoto), and 64 percent and 400 percent respectively for Puerto Rico (Anasco).

An international study of provenance variation in *Pinus caribaea*, *P. oocarpa,* and *P. patual ssp. tecunumanii* was undertaken in a set of 29 trials in numerous locations representing the following countries: Australia, Côte d'Ivoire, Congo, Tanzania, Zambia, Kenya, Thailand, Fiji, Malaysia, Brazil, Puerto Rico, and Ecuador [Birks and Barnes 1990]. There were highly significant differences in height, DBH and VUB in *P. caribaea.* All provenances of vars. *hondurensis* outperformed those of the vars. *bahamensis* and *caribaea*. The best performer across sites among the var. *hondurensis* provenances was Byfield seed orchard (Queensland, Australia) which itself was based on a population of Mountain Pine Ridge (Belize) origin. This latter provenance was not, however, the best performer among the natural sources. First in this respect was the coastal provenance, Laguna del Pinar from Nicaragua, represented in only two trials. The best performer across a large number of sites was Guanaja (Honduras), the only island source of var. *hondurensis*. Santos (Belize) was the poorest.

Overall, across 16 sites in the *P. caribaea* study, the best performer in mean height growth gained 31 percent compared to the poorest one, 28 percent in mean DBH and 127 percent in mean VUB. Guanaja had the thickest bark and also the highest proportion of bark when taken as a percentage of total tree volume. In contrast, the coastal sources had low values for both bark traits. The best inland sources for wood production generally had the highest bark volumes with the exception of Limones (Honduras) which had low wood production but relatively thick bark. Some genotype x environment interactions were registered in the productivity trials, e.g. Mountain Pine Ridge provenance was top in the South African site but ranked near the bottom in Côte d'Ivoire. Some caution is also advised in interpreting the early performance of var. *caribaea.* When planted in its optimum environment, it can start to outperform var. *hondurensis* after 15-20 years which may be too late in a pulpwood rotation but would be significant in a sawlog rotation. In making decisions, therefore, as to which provenances might perform best under particular conditions, one should temper the general conclusions given here with an interpretation of provenance performance in the individual trials that have environmental conditions closest to one's own.

In a *Pinus oocarpa* and *P. patula* ssp. *tecunumanii* provenance study, significant differences were recorded between provenances for height, DBH and VUB [Birks and Barnes 1990]. The four sources of *P. patula* ssp. *tecunumanii* (from Nicaragua and Belize) were outstandingly the best provenances in most localities. The best overall performers among *P. oocarpa* provenances were Pueblo Caido and Lima (Guatemala), Bonete (Nicaragua), and Agua Fria (Honduras). It is possible to conclude that provenances around Coban in Guatemala are likely to be good whereas those in the eastern-most part of Guatemala are likely to be among the poorest. The overall best performer in height gained 26 percent compared to the poorest one across 13 sites in the *Pinus oocarpa* and *P. patula* ssp. *tecunumanii* provenance study, 31 percent in DBH, and 148 percent in VUB.

5.2.2 Tree improvement

Foster *et al.* [1995], in a recent paper on economics of tree improvement in the tropics, presented an overview of the major steps in a tree improvement programme. They are selection, mobilization, orchard establishment, and genetic testing. a) Selection refers to the process of choosing a subset of the population that will be allowed to contribute to future reforestation. Identification of the superior seed sources for a particular region and site is crucial. b) Selection of the superior individual trees (phenotypes) for inclusion in the breeding and production populations is the next step - mobilization phase. c) The orchard phase is marked by the establishment of a genetic archive (frequently called a gene bank) or a production seed orchard or cutting orchard. A seed orchard provides seed for seedlings and a cutting orchard provides cuttings for rooted cutting production. Two purposes are generally served in this part of the programme: collecting exact genetic copies of each select tree (via grafting, rooted cuttings, or tissue culture plantlets) for preservation and future breeding; and establishing a mechanism for producing adequate numbers of their genetically improved seeds or vegetative propagules (usually rooted cuttings) for reforestation. These enhance forest productivity and hence increase financial returns. d) Genetic testing refers to the methods whereby apparently superior trees are systematically tested for two reasons: polygenic inheritance of economically important traits; and genotype x environment interactions that can mask true genetic value of an individual. Genotypes with proven superiority can be selected either to enter the next generation of the programme or to remain in a seed or cutting orchard after the proven inferior genotypes have been removed (rogued).

Some published rates of volume gain from tree improvement programmes were presented by Foster *et al.* [1995]. A sample of the data related to genetic improvement of pines is shown in Table 8.

Table 8: Volume gains from tree improvement

Species	Volume gain (%)	Situation	Reference
Loblolly pine	10.7-13.0	Plus tree selection	Carlisle and Teich 1975
	32.5	Progeny test-save	Carlisle and Teich 1975
	17.0-25.1	Roguing/selection	Porterfield 1974
	10.0-20.0	First generation seed orchard	Porterfield 1974
	8.0-15.0	Single cycle	Hollowell and Porterfield 1986
	6.4	Unrogued seed orchard	Talbert 1985
	12.7	Rogued seed orchard	Talbert 1985
	15.0-20.0	Selection	Weir 1981
	23.0-25.0	Heavy roguing	Weir 1981
Radiata pine	19.0-23.0	Open pollinated (o/p)	Arnold 1990
	27.0-32.0	Control pollinated (c/p)	Arnold 1990
	45.0	C/p crosses (1978)	Shelbourne 1989
	12.0-13.0	O/p 1979	Shelbourne 1989
	26.0	C/p 1979	Shelbourne 1989
	46.0	C/p crosses best families	Shelbourne 1989
	9.0-22.0	Seed orchard	Wright and Eldridge 1985
Caribbean pine	10.4-14.7	Seed orchard	Shelbourne 1989
Maritime pine	15.0	Seed orchard	Wright and Eldridge 1985
Pinus pinaster	30.0	Propagation top families	Wright and Eldridge 1985
Pine (var.)	5.0-15.0	South Africa	Arnold 1990

Source: Foster *et al.* 1995.

Improvements in productivity by forest tree breeding in Korea have been estimated by Ryu and Shim [1988]. Progenies of 17 plus trees of red pine (*Pinus densiflora*) outgrew by 57 percent the progenies of unselected trees at age 15. If the best three families are selected among the 17, more than double the volume growth of the remaining 14 is expected. The hybrid *Pinus rigida x P. taeda* showed more than double the volume growth compared to *P. rigida* at a southern plantation at age 15. However, the superiority of the hybrid decreased in northern plantations, mainly because of low cold hardiness of the hybrid. At a northern plantation, the hybrid grew less than the *P. rigida* on a flat area. Introduction of *P. rigida* also showed increased volume growth. Volume increase by selection of the best five provenances among 45 at age 12 was estimated as 53 percent more than that of progenies of plus trees in Korea. An additional 14 percent volume increase was expected by selection of the best families within the best provenances.

Basal area and projected volume growth were compared for trees from routine genetically unimproved seedlots and a first generation seed orchard (Green Hills) seedlot of radiata pine, planted in progeny tests on two sites in New South Wales, Australia. At the two test sites, the Green Hills Seed Orchard (GHSO) stock achieved gains over the routines for mean BA of 7 percent and 15 percent at age 12 years, increasing to 14 percent and 20 percent, respectively, at 15 years. Gains over the routines for mean volume at 15 years were 15 percent and 40 percent, respectively. The advantage of the GHSO stock over the mean of the routines, in predicted total BA production over a whole rotation, was 21-22 percent, based on data from two test sites. The orchard stock was also predicted to yield about 20-25 percent more total sawlog volume over a rotation than the mean of the routines, while corresponding gains in MAI were 17-18 percent. Discounted cash flow analyses were carried out, incorporating royalties from projected volume yields from the different seedlots, and full plantation establishment and marketing costs over a rotation on two planting site types. Almost all Net Present Values (NPVs) were positive, with substantial gains per hectare, of the order of US$ 300, estimated from the use of stock with growth rates equivalent to the GHSO stock rather than stock equivalent to the means of the routines. Internal Rate of Return (IRR) for most seedlots exceeded 4 percent, with IRR for the GHSO stock about 0.9 percent points higher than that for the mean of the routine stock. These results indicate that production and use of seed orchard stock equivalent to the GHSO stock, rather than routine stock, would significantly improve the return on investment in plantation projects [Johnson *et al.* 1992].

Eldridge [1982] provided ample evidence for the gains obtainable from improved harvesting efficiency and from increased stemwood yield in *Pinus radiata*. A plantation derived from Tallaganda Seed Orchard seed was compared to a plantation derived from seed collected from 200 seed-bearing trees chosen at random in a 7-year-old plantation near Canberra, Australia. The plantation derived from seed orchard seed yielded significantly higher proportions of straight trees free from stem defects, with a favourable crown configuration, which would lead eventually to improved harvest efficiency. The plantation derived from the seed orchard also grew faster, to yield a greater volume of stemwood per hectare. Volume gain achieved at the seed-orchard plantation was 9-29 percent at different sites, basal area gain was 11-22 percent, while gain in terms of the proportion of trees with form and vigour above average was 57-129 percent. Eldridge [1982] concluded that given two to three more generations of selection, whole forests of trees to at least the standard of the best of today's "plus" or breeding trees could be obtained. He also noted that the quickest change could be made with the help of vegetative propagation.

Successful examples of vegetative propagation of *Pinus kesiya* were reported by Guldager *et al.* [1980]. The trees were propagated by grafting with 70 percent success in Madagascar, Malawi, Thailand and Zambia; by air layering in Philippines, Madagascar, Zimbabwe and Rhodesia with 40-85 percent success; and by rooting of stem cuttings with up to 20 percent success.

Fowler [1978] provided some examples of genetic gain obtained in pine improvement programmes. A rogued first-generation orchard of *Pinus taeda* and *P. elliottii* produced stock which, in open pollinated plantings, is 10 to 20 percent greater in volume than the commercial check's volume. Improved stock from first-generation orchards from five improvement programmes in Australia and New Zealand is 10 to 53 percent greater in volume than commercial checks. Polycross progenies of *P. patula* in Rhodesia produced volume increases of 17 percent at 5 years and 37 percent at 8 years over commercial checks and comparable gains were obtained from *P. elliottii* and *P. taeda* in South Africa. Of interest is that all the above programmes were based on multi-trait selection schemes and that comparable gains in other traits, except for disease resistance, were also attained.

In a review on *Pinus patula* compiled by Wormald [1975], genetic gain from plus tree selection was estimated by comparing 26 plus trees and 130 neighbours in East Africa. The value of genetic gain was 11 percent for volume over bark, 5 percent for DBH, and 2 percent for height. However, it was calculated that as a result of first-generation selection, the gain in volumes per unit area might be as high as 60 percent and in value as much as 90 percent. It was considered that if 'super class' plus trees were used and silvicultural regimes were adapted to make the most of their potential, the gain might be as much as 100 percent in volume, and 150 percent in value. These calculations need to be tested in progeny trials and with only ten super trees there may be problems with the combining ability of the parents.

5.2.3 Fertilization

Phosphorous appeared to be the most limiting major nutrient in pine plantations in Kalimantan, Indonesia. First-year height growth was increased 25-100 percent with application of triple-superphosphate soon after planting. Delaying application by 6 to 8 months resulted in little response, presumably due to rapid nutrient uptake by grass and brush species [Long and Johnson 1981].

Returns from fertilizer application can be properly evaluated only when experimental evidence can be translated into future yields. Results of three of four fertilizer experiments in *Pinus radiata* plantations in Australia and New Zealand confirmed that response to dosages of fertilizer applied at mid-rotation ages can be sustained and enhanced over time [Woollons *et al.* 1988]. In the first trial, fertilizer responses in basal area of 4.1 and 2.0 m^2/ha were obtained in unthinned (1425 stems/ha) and thinned (639 stems/ha) experimental stands over 14 years. In the second trial, highly significant responses to fertilizer application were present: 6.2 and 3.9 m^2/ha (571 and 357 stems/ha respectively). Results of the third trial were similar. Nevertheless, the same result was not achieved in the fourth trial; after a highly significant response of 4.5 m^2/ha in stand basal area 4 years after fertilizer application, the response eroded to 2.0 m^2/ha after a further 6 years of growth. Sites with marginal or marginally induced nitrogen deficiency seem likely to exhibit sustained responses but grossly deficient sites may not necessarily behave similarly. Hunter *et al.* [1986] reported results from a nitrogen fertilizer trial on sand-dunes in the Manawatu, New Zealand, where a response of 5.3 m^2/ha 5 years after topdressing had eroded to 3.7 m^2/ha after a further 5 years. Lack of tree height response to fertilizer was reported.

The effect of fertilizer (nitrogen and phosphorous) was assessed for a radiata pine plantation in Nelson Region, New Zealand 4 years following fertilizer application [Lowell 1987]. Stand volume was increased as a result of fertilizer application by 19 percent. Fertilizer increased the sawlog volume (25 cm top diameter) most, with minimal effect on chipwood (25 cm to 15 cm top diameter). The volume change resulting from the fertilizer-induced change in tree shape was modelled using a flexible polynomial taper equation within a distribution-based stand volume system.

Results from experiments with *Pinus radiata* at several locations raise serious doubts about the benefits of current nitrogen fertilization practices on sandy soils in South Australia and western Victoria. The growth response to nitrogen application was more readily detected in diameter growth than in tree height. The response in diameter was 4-10 percent at age 3 years. The substantial growth response, commonly observed in the early stages of intensive silviculture, is likely to be a combined effect of good site preparation, weed control and perhaps general nutrition [Nambiar and Cellier 1985].

Heavy applications of superphosphate (112 kg P/ha at planting and 75 kg P/ha at age 7 years) improved growth rates of *P. radiata* on weathered soils of the Moutere gravels in the Nelson region of New Zealand during the 11-year study period by two or three times over the untreated plots [Mead 1990]. However, even these rates were unable to maintain phosphorous concentrations at non-limiting levels for more than a few years after application. Boron fertilizer prevented dieback, although there was no response in tree volume. Individual-tree doses of nitrogen fertilizer (17 g/tree), applied along with phosphorous and boron in the first two growing seasons, resulted by age 5 years in a 0.6 m height growth increase over plots treated with phosphorous and boron alone. However, a volume response was not detectable at age 7 years. Application of 150 kg N/ha with phosphorous and boron after thinning at age 7 years led to a 12 percent volume response over the phosphorous + boron treatment by age 11 years, 244 percent volume gain over the boron treatment, and 288 percent volume gain over the control. However, this response was only short-lived. There was no response to nitrogen in the absence of phosphorous and boron.

The 12 percent response to N + P + B over P alone was smaller than expected. Foliar analysis suggested that the limited response resulted from inadequate phosphorous availability. This conclusion was also supported by the responses obtained in a nitrogen x phosphorous factorial experiment in a 14-year-old stand at Harakeke, New Zealand [Mead and Gadgil 1978]. In that trial, where the phosphate fertilizer maintained foliar phosphorous levels above 0.16 percent for at least 3 years, there was a 46 percent volume increase (73 m^3/ha) to 208 kg N/ha. Mead [1990] concluded that if nitrogen fertilizer is to be used by forest managers, it is extremely important to ensure that other deficiencies are eliminated. It was also noted that adding nitrogen fertilizer on low-phosphorous sites can be detrimental.

Highly significant responses in height growth were recorded for *Pinus caribaea* and *Pinus kesiya* at age four years following application of fertilizer (500 kg/ha of NPK - 17:5:22) at Kunjingini, PNG. Fertilized trees gained 452 percent (*Pinus caribaea*) and 820 percent (*Pinus kesiya*) in height [Evans 1992].

Fertilizers have been applied in *P. kesiya* plantations, particularly in Madagascar and South East Asia, to correct nutrient deficiencies in *P. kesiya* on degraded soils or to increase production. In the former country there have been marked responses to P and K together (in the stands treated at the time of planting with P + K, mean height at age five years was 6.4 m compared with 3.5 m for the untreated areas), none to P alone, or to Ca and Mg. However, N has sometimes stimulated growth and sometimes not. In the Philippines N and P have stimulated growth on degraded soils while in Zambia any responses by *P. kesiya* to N, P, and/or K have been too small to be worthwhile. Boron deficiencies have been corrected by applying this element in Brazil and South East Asia. The only general guideline that can be given therefore is that fertilizer regimes, if warranted, must be worked out in relation to the conditions in a particular locality [Armitage and Wood 1980].

In Swaziland a trial has indicated the advantage of both cultivating and fertilizing young *P. patula*. It appeared that the effect of fertilizer (NPK) was longer lasting than that of cultivation. It is also of interest that the second rotation crops appeared to have better growth than the first rotation crops and that removal of the needle mat had a deleterious effect. The highest gain in height growth as a result of fertilizer application (29 percent) was achieved at first rotation establishment trial at Usutu at the age of 18 months with no cultivation, and at the age of 30 months with no cultivation, but with all ground cover cleared. An experiment in Madagascar indicated that application of nitrogen at planting increased mortality and depressed growth of *P. patula.* Application of phosphate increased growth and decreased variability; potassium had little effect [Wormald 1975].

In planting *Pinus elliottii* plantations in China, the leaves of *Acacia auriculiformis* were used as a basic manure, and resulted in 30 percent greater tree height than control one year after planting [Haishui and Zengjiang 1993].

6. CONCLUSIONS

6.1 GENERAL

This paper is not a complete survey of all studies published on factors affecting productivity of tropical forest plantations. It is rather a beginning of what would be a long and complicated process of database construction on the subject. In general, it can be concluded that gains from a good tree improvement programme (starting with species/provenance matching to site) can usually result in considerable gain in wood yields from tropical forest plantations. Optimal nursery and silvicultural practices (including those discussed in this study: seed pre-treatment, application of nitrogen-fixing soil micro-organisms, optimal spacing for defined end use, selection of adequate site, fertilization, and irrigation) can considerably increase such gains further.

Quantification of possible increases in plantation yield for a particular site, species or provenance is difficult. The numbers presented in this study have to be treated very carefully. Gains reported cannot be expected to be reproduced within the same range at a different geographic location and under different climatic and edaphic conditions. Moreover, it is nearly impossible to predict interrelations of different factors involved that can affect plantation productivity. Percentage gains as a result of silviculture and tree improvement operations, as reviewed in this study, are widely variable (Table 9). Incorporating the wide range of such data into a model for prediction of future gains is a challenging task.

Major statements on factors affecting productivity of tropical forest plantations, as reviewed in this paper, are outlined below for each of four genera under consideration.

Table 9: Percentage gain from tree improvement and silvicultural treatments

Genus	Country			Gain (%)				References
Treatment		**DBH**	**MAI**	**BA**	**V**	**H**	**Y**	
Acacia								
Spp./Prov. Matching	China	8-728			107-129			Minquan et al. 1989; Chuanbi 1989; Haishui and Zengjiang 1993
	Thailand	229-1107						Pinyopusarerk 1989
	Fiji	157						Awang and Bhuimibhamon 1993
	Indonesia		59-242					Suhaendi 1993
	Pakistan	41-257						Ansari et al. 1993
	Sri Lanka	56-247						Vivekanandan 1993
Spacing	Malaysia		222					National Research Council 1983
	Thailand		11-52					Kietvuttinon 1985
Symbiotic Associations	Senegal					8-50		Cornet and Diem 1982
	Philippines	192				70-210		dela Cruz and Yantaseth 1993; dela Cruz et al. 1992; Lorilla et al. 1992
Eucalyptus								
Spp./Prov. Matching	China	212						Wenlong and Jiayu 1989
	Thailand	41-63						Pinyopusarerk 1989
	Sri Lanka	147						Weerewardane 1989
	Israel		700					Jacobs 1979
	Nigeria		239					Jackson and Ojo 1973
	Australia/Tasm.	8-517						Turnbull et al. 1993; Moran et al., 1990; Borough et al. 1984
	Brazil		82					Evans 1992
Spacing	PNG			41				Evans 1992
	India	89	17-1445					Lohani 1980; Bhatia 1980
	Australia	59-82					133	Opie et al. 1984; Borough et al. 1984
	Thailand				729			Vacharangkura 1988
	Ethiopia		34					Poschen-Eiche 1989
Genetic Improvement	Brazil		78		25-178			Zobel and Ikemori 1983; Campinhos and Claudio-da-Silva 1990; Lal 1994
	South Africa				8-60			Foster et al. 1995; Van Wyk 1977
	India		400		463			Arya and Sharma 1990; Lal 1994
Teak								
Spp./Prov. Matching	India	32				15-33		Kadambi 1972
Genetic Improvement	India	144				102		Bagchi 1995
Fertilization/Irrigation	PNG					1138		Evans 1992
	Puerto Rico						60	Briscoe and Ybarra Coronado 1971
	India	93-176	57-121			13-4348		Gogate et al. 1995a; 1995b
Site Quality	El Salvador et al.		1600					Keogh 1979
	Liberia					260-350		Drechsel et al. 1990/91; Zech and Drechsel 1991
	Benin					161		Drechsel et al. 1990/91
	Bangladesh	45-54						Haque and Osman 1993
	Thailand				502			Sahunalu 1985
	India					150		Alexander et al. 1987
Pinus								
Spp./Prov. Matching	Kenya	26			150			Chagala and Gibson 1984
	India	0-175						Das and Stephan 1984a; 1984b
	Thailand		283					Granhof 1984
	Malawi			174-379				Ingram 1984
	Tanzania	92						Madoffe et al. 1984
	Zimbabwe	28						Mullin et al. 1984
	Nigeria	37						Otegbeye and Shado 1984
	Korea				53-67			Ryu and Shim 1988
	New Zealand				20-30			Foster et al. 1995
	various tropical	21-64			75-400	26-31		Birks and Barnes 1990
Genetic Improvement	various				5-46			Foster et al. 1995
	Korea				57-100			Ryu and Shim 1988
	Australia		17-18	11-22	9-53			Johnson et al. 1992; Fowler 1978; Eldridge 1982
	Rhodesia				17-37			Fowler 1978
	var. East Africa				11			Wormald 1975
Fertilization	Indonesia					25-100		Long and Johnson 1981
	New Zealand				19			Lowell 1987
	Australia	4-10						Nambiar and Cellier 1985.
	PNG					452-820		Evans 1992
	China					30		Haishui and Zengjiang1993
	New Zealand				46-288			Mead 1990; Mead and Gadgil 1978
	Madagascar					83		Armitage and Wood 1980
	Swaziland					29		Wormald 1975
Note: Spp./Prov. matching means matching species/provenances to site. See also note on next page.								

Note: The percentage of volume (V) (or VUB (volume under bark), or VOB (volume over bark)), MAI (mean annual increment), DBH (diameter at breast height), BA (basal area), H (height) or yield (Y) gain is calculated from the additional volume of wood (or other parameter) resulting from the genetic or silvicultural improvement (e.g. fertilization, provenance selection, site selection, spacing selection) and a base value. For example, an additional 1 m^3/ha of wood under a tree improvement programme as compared to a volume yield of 10 m^3/ha from an unimproved source would be a 10 percent gain. The basis for comparison can be either an unimproved situation (e.g. unfertilized plantation, local seed source), or the poorest performer in the study.

6.2 ACACIA

6.2.1 Common factors

6.2.1.1 Species/provenance matching to site

The success of plantation establishment and productivity is determined largely by the grower's choice of species and seed source [Callaham 1964]. *Acacia mangium* is a major fast-growing tree species in forestry plantation programmes in Asia and the Pacific. This acacia is playing an expanding role due to its versatility and ability to tolerate harsh sites (e.g. sites with infertile soils, degraded grasslands) better than any other species of acacia [e.g. Tan 1987]. For *A. mangium*, trials established in almost all countries where it has been introduced are still in the rangewide screening stage [Awang and Bhuimibhamon 1993]. Multi-site trials of *Acacia mangium* revealed a significant genotype x environment interaction effect on total wood production [Awang and Bhuimibhamon 1993]. The existence of provenance x environment interactions can be exploited for higher genetic gain. This results in a choice related to site adaptability: one can select either a single provenance that is broadly adaptable over a range of sites, or the most productive provenance at each site. The choice depends on the relative costs and benefits, and the availability of resources [Nickles 1991]. Numerous provenance trials of *Acacia mangium* conducted in tropical Asia-Pacific indicated the superiority of seed sources of PNG origin [e.g. Awang and Bhuimibhamon 1993].

Trials of other tropical *Acacia* species also showed PNG provenances to be superior. Among them are *A. auriculiformis* [Evans 1992], *A. crassicarpa* [Minquan *et al.* 1989], and *A. aulacocarpa* [Minquan *et al.* 1989].

The objectives of the species/provenance trials in the tropical Asia-Pacific region include:

- selection for fast growth and improved productivity (e.g. Australian provenance of *Acacia mangium* Claudie River in Indonesia [Suhaendi 1993]; PNG provenance of *A. mangium* in Malaysia [Nickles 1991]);
- selection for high-altitude tolerance (Kuranda provenance of *A. mangium* in Viet Nam [Kha and Nghia 1991]);
- selection for high survival rate (PNG provenance of *A. auriculiformis* in China [Monquan *et al.* 1989]);
- selection for saline-soils tolerance (*A. ampliceps* in Pakistan [Ansari *et al.* 1993]);
- selection for best performance in a dry zone (*A. mangium* in Sri Lanka [Vivekanandan 1993]).

Acacias in tropical Africa have made great strides during the last 20 years. The most encouraging results in dry tropical Africa were obtained in Senegal for several Australian acacias: *Acacia coriacea*, *A. sclerosperma*, and *A. bivenosa*. Due to their drought resistance these three species are most interesting in the prevention and control of erosion [Cossalter 1987]. *A. mearnsii* was the most successful among Australian acacias introduced to a cool moist climate (Tanzania) [Kessy 1987]. In semi-humid to semi-arid areas of Kenya, *A. crassicarpa* was the best *Acacia* species in terms of growth and survival [Milimo 1989].

6.2.1.2 Spacing

The choice of initial spacing is determined mainly by the end use of the plantation material, and to some extent by tree form. Various initial spacings have been reported for the same species at different locations even within the same country. This indicates a lack of information on optimum spacing for different objectives [Srivastava 1993]. Initial spacings reported for tropical acacia plantations include 3 x 3 m, 2.4 x 2.4 m, 4 x 2 m, 2.5 x 2.5 m, 2 x 2 m, 3 x 3.7 m, 4 x 6 m, 1 x 2 m, 1 x 3 m, 1 x 4 m, and 4 x 4 m. Lower densities are considered desirable for longer rotations, under which conditions the stand needs lower investment and produces greater log volume and economic returns. In contrast, higher densities are more suitable for short-term management, but incur higher establishment costs, produce lower log volume and poorer economic returns, although maturing early.

6.2.2 Factors unique for Acacia plantations

6.2.2.1 Symbiotic associations

Of all genera discussed in this review, *Acacia* is by far the most effective in symbiotic associations with *Rhizobium* bacteria and mycorrhizae, and the most effective in atmospheric nitrogen fixation. Data on plantation yield increases as a result of symbiotic associations of acacias with some micro-organisms were not available to the author when this review was compiled. Nevertheless, it is clear from the publications consulted that, used together, effective *Rhizobium* strains and effective VAM fungi can increase early seedling growth in areas of marginal fertility, and can economically substitute for large portions of early chemical fertilizer requirements in such areas. This eventually will lead to enhanced productivity and sustainability of acacia plantations.

6.2.2.2 Seed pre-treatment

Seeds of *Acacia* species are known to have hard seed coats that completely prevent the inhibition of water and exchange of gas, thus preventing initiation of the germination process [Khasa 1993b]. The experiments reviewed reported mainly the effect of acacia seed pre-treatment on germination rate in laboratories and nurseries. However, it is very important to emphasize the potential value of this factor in plantation productivity gains. There are two objectives of acacia seed treatment for potential success of the plantations: increase in seed germination rate; and seedling uniformity within the nursery.

6.3 EUCALYPT

6.3.1 Species/provenance matching to site

The evolution of the eucalypts has produced species and provenances fitted to an enormous range of environmental conditions within the natural range of the genus. On the other hand, eucalypts are very variable genetically and adaptable to changing environmental conditions [Jacobs 1979].

The objectives of eucalypt species/provenance trials in the tropics as discussed in this study include:

- selection for fast growth (e.g. Australian provenances of *E. camaldulensis* and *E. tereticornis* in China [Wenlong and Jiayu 1989]);
- selection for improved productivity (e.g. Australian provenance Petford, *E. camaldulensis* in Nigeria [Jackson and Ojo 1973]);
- selection for disease resistance (e.g. Australian provenance 11681 of *E. grandis* in India [Tewari 1992]);

- selection for drought tolerance (*E. urophylla* in China [Wenlong and Jiayu 1989]);
- selection for tolerance of high elevations (*E. obliqua* and *E. laevopinea* in Australia [Borough 1984]);
- selection for insect resistance (Australian provenances Lake Frome and Lake Bolac of *E. camaldulensis* in Australia [Floyd *et al.* 1994]).

Analysis of information on provenance x environment interactions in some tropical eucalypt plantations suggests that there are significant changes in rank among different environments [Matheson and Raymond 1984]. However, most research reports that for each species there are some provenances which seem to grow better than the others almost everywhere. For example, Lake Albacutya provenance of *E. camaldulensis* has consistently good growth and form characteristics in several areas of Australia and Africa [Jackson and Ojo 1973].

6.3.1.1 Spacing

Widely spaced plantations of eucalypts are cheaper to grow [Evans 1992] than narrow-spaced ones. At the closer spacings, costs are higher due to both greater planting and weeding costs because of less opportunities for mechanized weed control.

A wide range of initial spacing has been tried in countries where eucalypts are planted (1 x 1 m, 2 x 2 m, 2 x 2.5 m, 2.5 x 2.5 m, 3 x 2 m, 3 x 2.5 m, 3 x 3 m, 3.33 x 2.25 m, 4 x 4 m, 4.5 x 4.5 m). The more stems per hectare the greater is the total volume yield in the early stages, and the greater the cost of planting stock and planting. Owners must decide on a spacing which suits their management objectives and site fertility. In general, poor sites should have wider spacings and good sites a closer spacing but one which permits the rapid development of high-quality pulpwood. Another important factor that should influence the decision on spacing is the likely use of mechanical equipment for cultivation and harvesting [Jacobs 1979].

Various studies on initial spacings conducted in PNG [Evans 1992], India [Tewari 1992; Bhatia 1980], Thailand [Sahunalu 1984], and Australia [Opie *et al.* 1984] indicated similar trends. A reduction in spacing (i.e. higher initial density) usually reduces mean height (but not necessarily mean dominant height), mean diameter, branch size, and taper, but increases basal area and total stemwood volume (but not necessarily merchantable volume).

6.3.1.2 Tree improvement

Davidson [1975-76] listed five tropical countries in which national eucalypt-breeding programmes were being vigorously pursued. These were South Africa (*E. grandis)*, Brazil (*E. grandis* and *E. urophylla)*, Zambia (*E. grandis* and *E. tereticornis*), Philippines (*E. deglupta)*, and PNG *(E. deglupta).* In addition to these, Congo has developed an advanced breeding strategy, based mainly on species hybrids; hybrids are also considered for large-scale planting in India [Jacobs 1979].

Jacobs [1979] listed several major steps of *Eucalyptus* tree improvement strategies:

Step 1	Species and provenances selection
Step 2	Selection and management of seed stands
Step 3	Individual selection
Step 4a	Progeny and clonal testing
Step 4b	Seed orchards
Step 5a	Controlled crossing
Step 5b	Massed production of improved material by vegetative propagation

Information on realized gains from eucalypt improvement programmes is still scarce. According to Foster *et al.* [1995], yield increases averaged 20-25 percent for tropical eucalypts. Four important methods of tree improvement in tropical eucalypts are reviewed in this study: vegetative propagation; hybridization; diallel progeny tests; and clonal selection.

6.4 TEAK

6.4.1 Species/provenances matching to site

In tropical America, Trinidad is recommended as an area of superior seed source [Keogh 1979]. In tropical Asia and Pacific, the choice between indigenous and exotic species is hotly debated. Although there are limitations in comparing the productivity data of different tree species in different plantations, it is apparent that exotic tree species may not always be superior to indigenous ones in terms of biomass production. It is the short-rotation management invariably associated with these exotics, as opposed to longer rotation management of indigenous species, which increases of utilizable biomass from the exotic species. Biomass available from multiple harvest through short-rotation plantation forestry of eucalypts over a period of 40 years is lower than the biomass available from a single harvest of indigenous species like teak under rotation of 40 years [Rao and Saxena 1991].

6.4.1.1 Site quality

The importance of site quality for high yields from teak plantations cannot be overestimated. Keogh [1979] suggested that individual countries must examine their situations (in terms of adequate site availability) before commencing or continuing planting programmes with teak. Those with lower population densities and low land pressures have the greatest opportunities and may be able to establish small teak plantations. Those with higher population densities and greater land pressures will find it more difficult. Results will be patchy and teak will be forced onto the poorer sites. However, if the better sites cannot be given to this species, it is advisable to consider alternatives.

A site classification chart for *Tectona grandis* constructed by Keogh [1979] may be used as a practical guide to the classification and prediction of teak growth throughout Tropical America and the Caribbean. Three criteria of a ‘good’ site for teak plantations are:

- good soil (deep, well drained, flat or slightly sloping alluvial soils with homogeneous profile);
- a 3-6 month dry season; and
- annual precipitation of over 1500 mm [Keogh 1979].

Mixed plantations should be preferred to pure teak plantations due to erosion hazards and better growth of teak. Reduced growth in the second rotation of pure teak plantations has been reported in India, Indonesia, and Senegal and led to research into what was termed “the pure teak problem”. Excessive soil erosion was found to be the main reason for the reduction in growth [Evans 1992].

6.4.1.2 Irrigation and fertilization

Irrigated teak plantations performed much better than rainfed plantations according to several studies. Use of sewage water (rich in N, P, K and S) in this context will not only decrease plantation cost by saving manuring expenditures, but will reduce pollution as well [Gogate *et al.* 1995b]. Introduction of teak as an exotic species was successful only on fertilized plantations [Evans 1992].

6.4.1.3 Tree improvement

Plus-tree selection is discussed as the basis of a teak improvement programme in India [Bagchi 1995]. Other aspects of teak tree improvement reviewed in this study include:

- seed orchards [Kumar 1992];
- vegetative propagation: cleft grafting, budding, branch cutting [Nautiyal and Rawat 1994];
- clonal selection (e.g. selection for clones resistant to teak leaf skeletonizer - a serious pest having wide distribution throughout the teak areas in tropical Asia-Pacific [Meshram *et al.* 1994]).

6.5 PINE

6.5.1 Species/provenance matching to site

Variation between sites and between provenances within sites were much greater in pine species with large natural ranges. For example, for this reason variation was greater in *Pinus taeda* compared to a *P. elliottii* provenance in Malawi, thus providing greater productivity of *P. taeda* [Ingram 1984]. Among other species and provenances tested in tropical Africa with considerable merit for breeding are the following: Nicaraguan provenances of *P. oocarpa* [Chagala and Gibson 1984]; African provenances of *P. taeda* [Ingram 1984]; Indonesian provenances of *P. merkusii* [Madoffe e*t al*. 1984]*;* Vietnamese provenances of *P. kesiya* [Mullin *et al.* 1984]; and Belize provenances of *P. caribaea var. hondurensis* [Otegbeye and Shado 1984].

In tropical Asia and Pacific region, the most promising pine species were *P. caribaea* and *P. kesyia.* All provenances of *P. caribaea var. hondurensis* outperformed those of the *vars. bahamensis* and *caribaea* in the international provenance study [Birks and Barnes 1990].

6.5.1.1 Fertilization

Fertilizers have been applied in tropical plantations to correct nutrient deficiencies in pines on degraded soils or to increase production. Response in pines to various nutrients have been tested: P, N, K, Ca, Mg, B. Phosphorous appeared to be the most limiting major nutrient in pine plantations in the tropics. Pine stand volume was shown to be higher as a result of phosphorous fertilizer application [e.g. Lowell 1987].

Results from some experimental trials with pines at several locations raise serious doubts about the benefits of current nitrogen fertilization practices [Nambiar and Cellier 1985; Wormald 1975]. Adding nitrogen fertilizer on low phosphorous sites can be detrimental. If nitrogen fertilizer is to be used by forest managers, it is extremely important to ensure that other deficiencies are eliminated [Mead 1990]. Another important conclusion is that fertilizer regimes, if warranted, must be worked out in relation to the conditions in a particular locality [Armitage and Wood 1980].

6.5.1.2 Tree improvement

Substantial increases in pine plantation productivity were achieved through:

- plus tree selection [Wormald 1975; Ryu and Shim 1988];
- hybridization [Ryu and Shim 1988];
- seed orchard establishment [Eldridge 1982]; and
- vegetative propagation [Guldager *et al.* 1980].

All pine improvement programmes reviewed in this study were based on multi-trait selection schemes. Substantial gains were attained in several traits except for disease resistance [Fowler 1978].

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The Global Fibre Supply Study (GFSS) of the FAO Forestry Department operates under the guidance of an Advisory Committee on Paper and Wood Products. The GFSS has produced the above-mentioned publications. To obtain a copy free of charge, please contact:

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Gains from a good tree improvement program (starting with species/provenance matching to site) can usually result in considerable gain in wood yields from tropical forest plantations. Optimal nursery and silvicultural practices (including seed pre-treatment, application of nitrogen-fixing soil micro-organisms, optimal spacing for defined end use, selection of adequate site, fertilization, and irrigation) can considerably increase such gains further. This report summarizes literature on gains that might be expected by implementing tree improvements and optimal silvicultural practices for acacias, eucalypts, teak and pines in tropical areas. Results are presented for each genus in turn, first examining factors common to all the genera, and then focusing on unique factors.

The data on tree-growth gains are extremely variable from study to study. They range from virtually no favourable response to tree improvement and optimal silviculture, to gains of many hundreds of percent over controls. This of course complicates the matter of using such data in global fibre supply modelling.