Chapter 7
Plantation Culture

This chapter, following the chapter that deals with the generation of forest plantations, covers cultural practices designed to make and keep these plantations productive. Experience is called upon from both hemispheres of the Tropics—experience with many different sites and with many different species. Little is said about the economics of plantation culture, the details of which are influenced by local conditions. For this reason, a number of specific cases are presented in the appendices G through M.

Chapman and Allan (1978) offered the following list of necessary planning considerations for managing a timber plantation:

1. *Policy and Objectives*—Those instructions received by the project manager from higher authority as to what the project is to accomplish.

2. *Basic Information*—The project environment, history, land availability and suitability, facilities, institutional framework, and staff.

3. *Future Management*—Future operations to be carried out, working circles, plantation operations, equipment, financial resources, current budget, maintenance, administrative control, and records.

Evans (1992) outlined a sequence of decisions and operations for which planning must be done (table 7–1).

Table 7–1.—Sequence of industrial plantation decisions and operations

Usual silvicultural operation	Main decisions	Crop
Obtain seeds	Species?	Not applicable
Produce planting stock	Season? Containers? Size?	Seedlings Transplants
Prepare ground	Intensity?	Not applicable
Planting	Spacing? Fertilizer?	Young trees
Tending	Frequency? Methods?	Saplings
Low pruning	Need? Partial?	Small poles
Thinning	Timing? Intensity?	Large poles
High pruning	Need? Height?	Large poles
Harvesting	When?	Mature trees
Replant	Changes in species or culture?	Second crop

Source: Evans 1992.

The goal of plantation culture is to increase the volume or quality of the wood produced. The manager, therefore, needs a way to estimate the potential productivity and a means of assessing the effects of treatments on growth. The first may be obtained from volume tables and site-index curves if already published for the region. The second—assessing annual growth—can be difficult. Because growth in the moist Tropics is generally not distinctly seasonal, the growth of most tree species can be ascertained only by repeated measurements. Even with *Pinus caribaea hondurensis,* a species that in sharply seasonal climates forms annual growth rings in its wood, the growth of adjacent trees is highly variable (Slee 1972).

A compendium of the performance of 129 of the best timber plantations in Latin America, classified by approximate life zone, was published in 1960 (Wadsworth 1960). More recently, a summary of plantation performance through the 1980s was issued by the Food and Agriculture Organization (FAO) (Anon. 1985f) to serve as a guide for plantation practices throughout the region.

In summarizing the yields of plantations on grasslands or tropical, high-forest sites, Wood (1974) concluded that the greatest productivity is at medium altitudes; lowland, upper montane, and dry sites are less productive. The faster growing trees can sustain growth rates of 2 m in height per year and 1 cm in diameter at breast height. Production of 35 to 50 cubic meters (25 to 40 tonnes) per hectare per year is well documented. These high yields are limited largely to conifers or eucalypts.

Assessing plantation performance requires average tree sizes at different ages and volume tables or equations to convert these averages into quantities of usable products. An example of the former is a recently published set of site-classification curves for teak *(Tectona grandis)* (fig. 7–1) based on measurements in Colombia, Venezuela, Central America, and the Caribbean (Keogh 1982). Height here refers to "top height," or the height of the largest (in d.b.h.) 100 trees per hectare. Similar curves are also available for *P. caribaea* from Indonesia, Jamaica, and Suriname. Typical cellulose volume tables for *P. elliottii* and *P. taeda* have been produced for southern Brazil (tables 7–2, 7–3; Hosokawa and others 1979).

Site Quality

Plantation performance is a response not only to culture but also to site quality, a complex of climatic, edaphic, and biotic factors. Site quality may be influenced by cultural practices to some extent, but the manager must recognize the limitations. Identifying favorable and unfavorable sites for most tree species is no problem. At one extreme, the tree may not even survive—and at the other, the growth rate culminates (figs. 7–2, 7–3).

A clear site-to-growth relationship exists for teak, as shown in yield data from Java (table 7–4; Alphen de Veer 1958b). Trees on a site V were nearly twice as tall as those on a site II, and their productivity was nearly three times as great. The use of poor sites is costly to volume production. The effects of the site are cumulative, increasing with time.

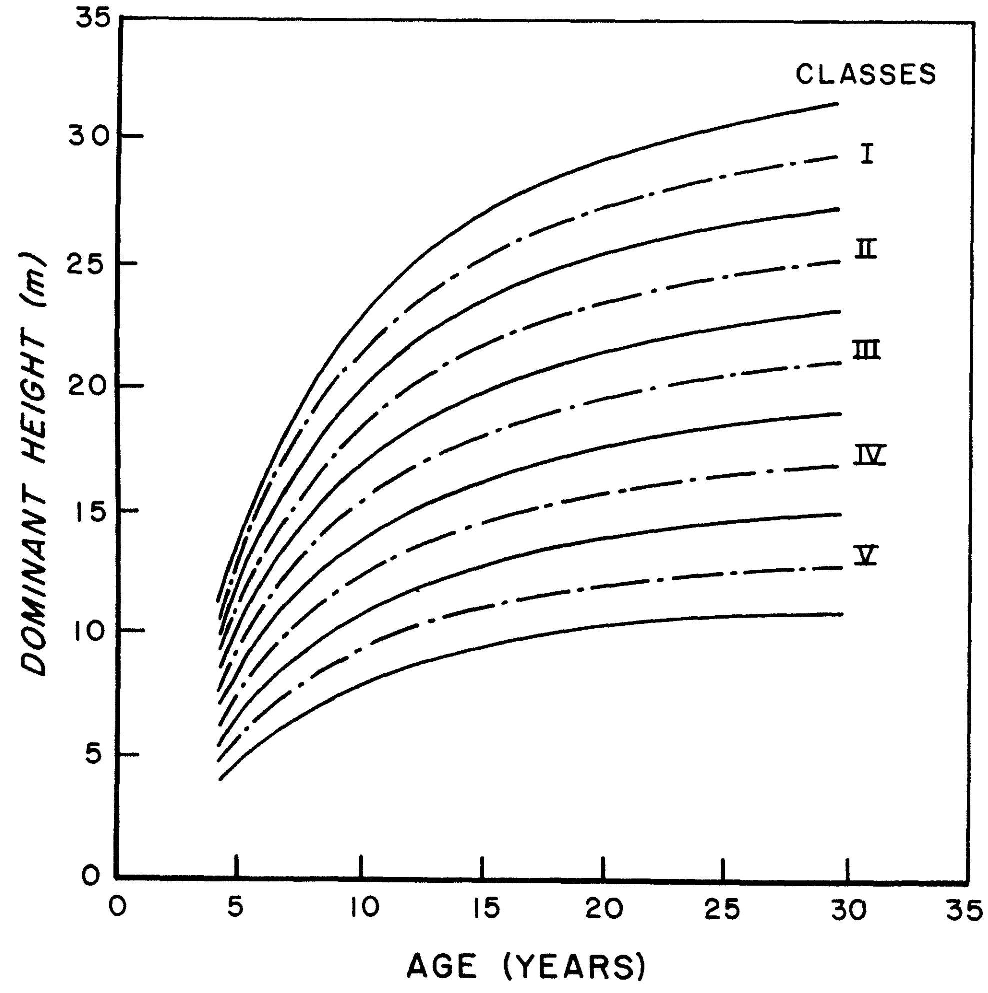

Figure 7–1.—*Site classes for teak in tropical America (Keogh 1982).*

Table 7–2.—Usable cellulose volume of *Pinus elliottii* in Parana, Brazil (m^3)

D.b.h. (cm)	Commercial height (m) 8	10	12	14	16	18	20
16	0.05	0.07	0.10	0.12	0.14		
20		0.12	0.16	0.19	0.23	0.26	
24			0.23	0.27	0.32	0.36	
28				0.37	0.42	0.47	0.52
32				0.47	0.53	0.58	0.64

Source: Hosokawa and others 1979.
Note: Volumes to 6 cm in diameter inside bark.
Regression equation: $V = 0.03096d + 0.0008d^2 - 0.02435h + 0.00291dh + 0.00004d^2h + 0.25225$, where V = volume, d = diameter in centimeters, and h = height in meters.

Wide variation in productivity of *Eucalyptus globulus* was found between sites classified in Madras, India (table 7–5; Krishnaswamy 1957b). *Eucalyptus globulus* in El Salvador is also very responsive to the site (Burgers 1960). Productivity is affected sharply, and the first coppice, which is at least as productive as the seedling crop on good sites, tends to fall behind on the poor site (table 7–6).

Pinus caribaea is very responsive to site quality in Suriname (Vincent 1970). Predicted yields at age 30, based on early growth, are shown in table 7–7. Suriname's site class I is mesic with sandy-loam soil on gradual, lower slopes, well drained but near streams. Site class III is midway between streams and uplands, with loamy-sand soil. Site class V is xeric upland savannas on coarse, white sands. The same species *(P. caribaea),* under premontane humid conditions in Costa Rica, with elevations between 600 and 1,100 m and annual rainfall of 220 cm, produced yields of wood inside bark averaging 45 m^3/ha/yr on 16 sites (Salazar 1976).

The much lower volumes produced in young plantations on relatively poor sites are illustrated in a *P. caribaea* plantation in southern Queensland, Australia (Anon. 1972b). At age 8, the volume of the site-90 plantation was only 22 percent of the volume on site 110 (table 7–8). At age 20, it was 62 percent. Current annual growth also culminates later on the poorer site.

Site-Quality Improvement in Plantations. Site quality and productivity can be improved in plantations. Such improvement is particularly marked on soils that have been degraded by cultivation, grazing, or fire. Litterfall

Table 7–3.—Usable cellulose volume of *Pinus taeda* in Parana, Brazil (m^3)

D.b.h. (cm)	Commercial height (m) 8	10	12	14	16	18	20
16	0.06	0.08	0.10	0.12	0.14		
20		0.14	0.17	0.20	0.23	0.26	
24			0.26	0.30	0.35	0.39	
28				0.39	0.45	0.50	0.56
32				0.51	0.58	0.64	0.70

Source: Hosokawa and others 1979.
Note: Volumes to 6 cm in diameter inside bark.
Regression equation: $V = -0.0140 + 0.0003d^2 - 0.0159h + 0.017dh - 0.000000009d^2h + 0.12766$, where V = volume, d = diameter in centimeters, and h = height in meters.

Figure 7–2.— *Disregard for site qualities such as soil depth or moisture level may lead to poor tree form, as illustrated by this* Gmelina arborea *in Peru.*

Table 7–4.—Teak *(Tectona grandis)* yields by site quality in Java

Site quality class[a]	Height of tallest 100 trees per hectare (m)		Mean annual increment including thinnings (m^3/ha/yr)	
	30 yr.	80 yr.	30 yr.	80 yr.
II	16	21	3.9	2.9
III	20	27	5.4	4.0
IV	25	33	7.6	5.8
V	29	39	10.5	8.1

Source: Alphen de Veer 1958b.
[a]Classes are defined locally on the basis of tree height at a selected age.

beneath a 10-year-old pure teak plantation in west Africa decomposed within 6 months during the dry season and within 1 month during the rainy season (Egunjobi 1974). Significant increases in organic matter on the soil surface were found in teak plantations in Thailand that were only 4 years old (Wasan and Bunwong 1975). By the 15th year, increases were also found in the pH, the cation exchange capacity, phosphorus (P), potassium (K), calcium (Ca), and magnesium (Mg), but these were not statistically significant, even though they increased site quality.

Figure 7–3.— *A good site produces trees of both good form and rapid growth, as illustrated by these 1-year sprouts of* Paulownia tomentosa *in the Philippines.*

Studies of 23 *P. ponderosa* sites in the United States have shown that tree height increases with soil nitrogen (N) (one component of organic matter) (Zinke 1960). In fact, it was concluded that tree height is an index of total soil N. Presumably, *available* N would show a still stronger relationship. It therefore follows that plantation development that increases soil N should improve the site.

Site-quality changes effected by plantations are not fully understood. The common phenomenon of a coppice stand outproducing the plantation that preceded it suggests that the site may be actually improving. In Kenya, for example, in a first coppice stand of *E. grandis* at rotation age, 20 percent of the stems were larger than 15 cm in d.b.h. compared with only 4 percent in the previous seedling stand (Howland and Freeman 1970). An unknown (but probably significant) proportion of this increase is due not to site improvement, but to the established root systems inherited by the coppice stand.

Site Deterioration in Plantations. Unless compensating measures are taken, site productivity will decline sooner or later where timber crops are being removed. Some indication of this drain is seen in the aboveground biomass of plantations of *P. radiata* in South Africa (table 7–9; van Laar 1982).

The problem of the pure teak plantation, debated in India from the 1930s to the 1950s, reflected preoccupation with the repeated extraction and removal of nutrients from sites that were marginal at the outset. Deterioration of "laterite" soils in India, caused by clear-felling teak and subsequent burning, reportedly could change sites

Table 7–5.—Site effects on productivity of *Eucalyptus globulus* in Madras, India

Age (yr)	Mean d.b.h. (cm)		Mean height (m)		Annual increment (m^3/ha/yr)	
	Site I[a]	Site III	Site I	Site III	Site I	Site III
5	21.0	12.1	21.9	11.3	10.6	5.0
10	31.5	21.0	31.4	15.8	11.3	5.2
15	39.6	25.9	37.8	24.4	10.4	5.0
20	46.1	29.9	41.8	28.0	9.9	4.6

Source: Krishnaswamy 1957b.
[a]Site classes are defined locally on the basis of tree height at a selected age.

from eminently suitable to absolutely unsuitable for teak (Davis 1940). Even the good teak sites that had supported tall trees were poorer for the next crop.

Site deterioration has been documented during the life of closely spaced teak plantations subject to repeated burning of the litter (Bell 1973). In Trinidad, an 11-year-old plantation spaced 2 by 2 m, repeatedly burned over and without undergrowth, was compared to a natural forest. The plantation yielded 25 percent more runoff per unit of rainfall than the forest and eight times as much soil loss per unit of land area (5.6 versus 0.7 t/ha). It was clear that the rate of erosion had to be reduced to the equivalent of the nutrient input rate to maintain site productivity.

Much concern has been expressed recently regarding a prospective decline in site productivity under pines, particularly pure plantations of *P. radiata* in Australia. An early review of possible causes by Florence (1967) deserves mention here. His study pointed out that under mixed species, the forest soil develops properties that vary according to the species of understory trees growing in it; there is wide variation in the chemical composition of the litter and the nature and rate of decomposition. Productivity may depend in part on the accumulation by a single species of a nutrient that might otherwise be limiting. The fact that soils under oaks (*Quercus* spp.) have much higher nutrient-supplying power than those under pines suggests that pine productivity might be increased by the presence of other species.

Florence (1967) further pointed out that soil N content under mixed pines and nonconiferous species is much greater than it is in pure stands of either group. He concludes that this excess N may be the result of a more suitable environment for microbial activity. He cited the work of Tarrant (1961) in *Pseudotsuga menziesii* plantations in the northwestern United States, where the interplanting of *Alnus rubra* greatly increased total N in the soil and in the foliage. Pine plantations in Nigeria reportedly have not changed the physical condition of the soil but have increased the organic matter at the surface and reduced it in the deeper soil layers (Iyamabo 1970). The N level in the soil beneath the pines averaged 24 percent less than on sites without the pines. Florence (1967) also

Table 7–6.—Site effects on productivity of 8-year-old *Eucalyptus globulus* in El Salvador

Site class[a]	Mean height (m)		Yield (m^3/ha/yr)	
	Seedling	Coppice	Seedling	Coppice
I	18	21	9.8	9.8
III	16	17	5.2	5.5
V	14	13	2.8	1.1

Source: Burgers 1960.
[a]Classes are defined locally on the basis of tree height at a selected age.

Table 7–7.—*Pinus caribaea* performance at age 30 in Suriname by site class

Site class[a]	Mean annual increment (m^3) Sawtimber	Pulpwood	Total
I	10.2	5.5	15.7
III	8.4	4.6	13.0
V	0.0	3.3	3.3

Source: Vincent 1970.

[a]Classes are defined locally on the basis of tree height at a selected age.

noted that a number of the introduced timber species that have been outstandingly successful have attributes that ameliorate site adversities.

Evidence of an apparent decline in productivity of *Pinus radiata* in South Australia has appeared as reduced basal area (Bednall 1968). Plantations repeated on the same site gave basal areas of 20 versus 29 m^2/ha at age 15. Bednall determined that none of the factors suggested was conclusively related to the decline. These factors included the soil-water regime, soil type, slash burning, the interval between felling and replanting, and site preparation. He suggested that the following factors deserve study as possible causes of decline: nutrient depletion, depletion of water supply, toxic residuals from the first crop, reduction in the genetic standard, and changes in establishment practices because of residual stumps.

Hatch and Mitchell (1972) suggested that N loss as a result of thinnings may have diminished the growth of subsequent crops of *P. radiata*. This study found that repeated thinnings alone could remove as much as 470 kg/ha of N during a typical pine rotation.

Decreased productivity of second-rotation *P. radiata* has also been reported from New Zealand (Whyte 1973). There, marked declines in height, basal area, and volume growth were apparent in a few areas, whereas in most other areas the declines were minor, and in still others, not apparent. A complication was that comparisons had to be made between plantations that were in close proximity but not in precisely the same location. Some of the declines appeared to be permanent, but most were transitory, limited to the first 5 to 8 years of the second crop.

Whyte (1973) concluded that the declines were enough to extend rotations by 2 years to attain the height of first-rotation crops, by 8 years for the same basal area, and by 5 years for the same total stem volume. He noted that reduced productivity was particularly noticeable on ridges and upper slopes, whereas on valley bottoms the second crop was often better than the first. He recommended shortening the regeneration period and preventing sheet erosion on ridges and slopes.

The complexities of proving a productivity decline were pointed out by Chaffey (1973), who called for long-term plots and detailed stem analyses. He assumed that almost certainly no single cause was at work. The abiotic factors, chemical and physical soil changes, may be

Table 7–8.—Site effects on *Pinus caribaea* in Queensland, Australia

Age (yr)	Standing volume (m^3/ha) Site 90[a]	Site 110	Current annual increment (m^3/ha/yr) Site 90	Site 110
8	17	76	—[b]	—[b]
10	40	117	11.8	20.7
12	75	172	17.5	27.3
14	123	234	23.9	30.9
16	175	293	25.9	29.8
18	214	343	19.3	24.8
20	241	386	13.7	21.4

Source: Anon. 1972a.

[a]Site quality measured by tree height at a locally selected age.

[b]Insignificant.

Table 7–9.—Aboveground biomass in a 40-year-old *Pinus radiata* plantation in South Africa

Tree d.b.h. (cm)	Oven-dry biomass per tree: Stemwood (kg)	Stemwood (%)	Bark (kg)	Bark (%)	Branchwood (kg)	Branchwood (%)	Needles (kg)	Needles (%)
30	344	87	36	9	7	2	7	2
60	1,499	81	168	9	138	8	35	2

Source: van Laar 1982.

cyclic. Climatic fluctuations are difficult to assess. The role of the living component of the soil in decomposition cannot be ignored in investigation. Mycorrhizal antagonisms could be responsible in some situations.

A study of logging residues in *P. radiata* plantations in southwest Victoria, Australia, suggests an important source of site deterioration (Flinn and others 1979). The residue on the surface after logging was 796 t/ha. When burning was done to prepare for replanting, 84 percent of the dry matter was lost. Other losses from the residues included 72 percent of the N, 27 percent of the P, 21 percent of the K, 31 percent of the Ca, 16 percent of the Mg, 40 percent of the sulfur (S), 30 percent of the iron (Fe), and 34 percent of the manganese (Mn). Under these circumstances, the recommendation was not to burn.

A review of second-rotation productivity declines in 53 pairs of plots matched on the same site in Swaziland was undertaken by Evans (1978). His results from 14-year-old plantations appear in table 7–10. Evans believed the climate to be the primary cause of the decline. Poorer weather prevailed during the second rotation, particularly shorter wet seasons during the last 3 years. He concluded that the climate obscured (and probably transcended) other site trends. Early volume growth in the second rotation was better than in the first at ages 5 to 6 by a margin of 10 to nearly 25 percent, but declined to 7 percent below the first rotation at age 14. Evans suggested that the constantly increasing constraint might not be climatic. He concluded that neither alarm nor complacency is warranted, but the need for more information is critical.

In a subsequent review, Evans (1980) concluded that evidence is still not adequate to prove a decline in monoculture yields in plantations. He pointed to the confounding factors of improved genetics and management with each rotation, coppices versus seedlings, and cumulative mortality with successive coppice crops. He considered results with *P. radiata* to be confounded by improvements in practice. He found no evidence of decline in *P. elliottii* yields in east Africa, where seeds were collected from the same parent trees. He concluded, however, that trends might still be found that

Table 7–10.—Comparative productivity of first and second rotations of 14-year-old *Pinus patula* in Swaziland

Item	Mean height (m)	Mean volume per tree (m^3)	Volume per hectare (m^3/ha/yr)	MAI[a]
Rotation				
First	18.1	0.243	299	21.4
Second	17.5	0.226	276	19.8
Percent decline	3.4	6.9	7.6	7.5

Source: Evans 1978.
Note: Significance level = 5 percent.
[a]Mean annual increment.

could relate to climatic variation, genetic improvement, direct plantation effects, or silvicultural practices such as thinning, skidding, debris disposal, burning, and fertilizing.

There remains cause for concern over productivity where crops are repeatedly harvested. A net loss of nutrients is inevitable, and sooner or later, compensation must be made if productivity is not to decline. Soil studies alone will not adequately account for the important trends because much of the nutrient supply is in the biomass (Fearnside and Rankin 1980).

The effect of harvested plantations on site quality is further illuminated by studies of the nutrient content in eight plots of *Gmelina arborea* and four of *P. caribaea* in plantations (Chijioke 1980). For both species (tables 7–11, 7–12), stemwood had the lowest percentage of nutrients, but when combined with the bark, it contained more than half the aboveground nutrients of the plantation. Whole-tree harvesting caused 25 percent more nutrient loss than leaving the slash on the site. Leaving the bark would have saved 5 to 10 percent more.

Chijioke's studies provided no evidence that monocultures per se deplete soil nutrient reserves faster than mixtures, *other things being equal.* Rapid nutrient depletion, however, is clearly associated with rapid growth, short rotations, and whole-crop harvesting.

Chijioke concluded that the nutrient immobilized most depends on the age at which the crop is harvested. For example, the quantity of nutrient elements immobilized in *G. arborea* trees 13 to 15 years old is only 6 to 9 percent greater than it is in 5- to 6-year-old trees, yet the biomass is 25 to 66 percent greater. Producing five 5- to 6-year-old crops of *G. arborea* during a 30-year period would be more than twice as demanding as producing two crops 13 to 15 years old during the same period.

According to Chijioke, any decline in tree growth in later rotations on the soils of the Tropics will most likely be the result of the soils' incapacity to convert nutrients from unavailable to available forms at the pace of tree demand, or slow mineralization. He did not foresee any decline as a result of the absence of essential nutrients. In pine plantations, he found no evidence to suggest decline in later rotations to be a result of soil-nutrient losses due to harvesting. He suspected that lowered soil moisture could be more of a limiting factor. He recommended (1) leaving slash, (2) doing no burning, (3) continuously monitoring soil nutrients, and (4) conducting fertilization tests of marginal soils.

Genetic Relationships

Plantation managers must recognize that their crop is highly variable, not only from site to site and species to species but also from tree to tree. Tree species vary in differentiation by provenances. Wide-ranging species are usually less uniform than those with a narrow native

Table 7–11.—Nutrient levels in 6-year-old *Gmelina* plantations in Nigeria and Brazil

	Major nutrients				
Index	N	P	K	Ca	Mg
	Kilograms per hectare				
Nutrient content					
Aboveground (live)	128–352	22–63	93–208	42–185	39–79
Stem and bark	90–182	14–38	71–136	34–108	31–51
	Percent				
Dry weight					
Aboveground	3.49	0.35	2.55	1.64	0.83
Stem and bark	0.71	0.08	0.96	0.86	0.25

Source: Chijioke 1980.
N = Nitrogen. K = Potassium. Mg = Manganese. P = Phosphorus. Ca = Calcium.

Table 7–12.—Nutrient levels in 6-year-old *Pinus caribaea* plantations in Suriname and Brazil

Index	Major nutrients				
	N	P	K	Ca	Mg
	Kilograms per hectare				
Nutrient content					
Aboveground (live)	197	33	46	78	25
Stem and bark	99	21	31	25	17
	Percent				
Dry weight					
Aboveground	1.93	0.13	0.60	1.05	0.28
Stem and bark	0.37	0.03	0.17	0.22	0.08

Source: Chijioke 1980.
N = Nitrogen. K = Potassium. Mg = Manganese. P = Phosphorus. Ca = Calcium.

range (Lines 1968). Exploiting this variation to improve future crops is a management responsibility.

Genetic manipulation, termed "tree improvement," has much to offer the plantation manager. The genetic potential of tree populations varies so widely that tree improvement can often produce trees with characteristics not found in nature (Zobel 1972). Tree improvement may lead not only to higher yields but also to greater tree adaptability to marginal sites and resistance to pests and diseases. Once the genetic makeup of the trees has been improved, genetic manipulation need not be repeated, but further manipulation may result in additional gains.

The Nature of Genetic Variation. Tree form is apparently more heritable than growth capability. Studies of *Cupressus lusitanica* in Kenya (Dyson 1966) indicated that tree size was a poor criterion for selection of crop trees. A study of 11 provenances of *Tectona grandis* in Tanzania showed that straightness and tree height at age 5 were related to source, whereas d.b.h. was not (Persson 1971). Had Trinidad's first teak seeds come from Travancore, India, instead of Tenassarim, in what is now Myanmar, the species might well have been judged a failure because of poor form, heavy branching, and slow height growth (Beard 1943). *Gmelina arborea* in west Africa (such as at Enugu, Nigeria) is reportedly much better formed than in other locations (Anon. 1959d). Tests of 22 provenances of *Swietenia macrophylla* and *S. humilis* in Puerto Rico showed interprovenance differences at age 4 (Geary 1969).

An ingenious study of teak in Nigeria further demonstrated the impropriety of selecting parent trees solely on the basis of their apparent vigor (Wyatt-Smith and Lowe 1972). Thirty-four pairs of dominant and subordinate teak trees were selected from a 14-year-old, unthinned plantation. The dominants had a mean d.b.h. of 23.8 cm; the subordinates, 13.6 cm. Each was budded on teak stocks, and height growth was compared after 1 year. After eliminating variation in the vigor of stocks and mortality, no significant differences in clone heights were found.

Wyatt-Smith and Lowe concluded that the heritability of vigor is low and that if it cannot be demonstrated in vegetative material, it is even less likely to show up in seedling progeny. They further concluded that apparent vigor is not an effective indicator of a superior genotype because inherited differences are almost entirely overwhelmed by environmental influences on vigor.

This low heritability of apparent vigor has important implications (Wyatt-Smith and Lowe 1972). If the environment is almost all important in determining the growth performance of a tree, silviculturists should be able to select and culture the trees they wish to become dominants without fear of dysgenic stand deterioration. A corollary is that harvesting what are apparently the "best" trees in a natural stand may not leave subordinate trees that are genetically inferior.

Evidence that tree characteristics other than apparent vigor may be heritable is seen in the early discovery in

India that the phenomenon of twists in teak stems is independent of any influences soil and treatment may exert (table 7–13; Champion 1930).

The occurrence of branchless leaders (foxtails) in pines in the Tropics is influenced by climate and other site conditions but is also due in part to genetic factors (Anon. 1960b). Under favorable conditions for *P. merkusii* in Indonesia, foxtailing ranged from 0 to 30 percent and was due to soil characteristics (Hamzah and Natawiria 1974). In Malaysia, Greathouse (1973) found foxtailing of *P. caribaea* to range from 30 percent on a good site to 47 percent on a poor one. Yet, the heritability of the foxtailing trait in *P. caribaea* is sufficient to preclude selecting it (Ledig and Whitmore 1981). Also, forking and branch diameter increase with foxtailing.

Foxtails are generally considered inferior trees and are thinned out. Their large, widely spaced branch whorls make them susceptible to wind damage. Nevertheless, in a study of *P. caribaea* in Malaysia, trees with a foxtail of 2.15 m or longer were larger at age 6 on good sites than normal trees (Greathouse 1973); the reverse was true on poor sites.

A common observation in provenance testing is variation in the time of foliage flushing, presumably reflecting climatic differences at the points of origin. A trial in Nigeria of *Cedrela* from Argentina, Belize, Brazil, Costa Rica, Cuba, Jamaica, Mexico, and Puerto Rico showed such variation and led to the hypothesis that it might affect growth rates because of the gains from correlating flushing with the rainy period in the area of introduction (Omogiola 1972).

Table 7–13.—Twisting in teak progeny as related to seed source in India

Seed source		Progeny twisted 7°+ in region of extreme twisting (%)
Parent tree	Surrounding trees	
Imported		
Straight	Straight	1
Local		
Straight	Straight	25
Straight	Twisted	36
Twisted	Straight	59
Twisted	Twisted	65

Source: Champion 1930.
Note: Natural regeneration of twisted trees in forest = 72.

Even the mass collection of seeds from successful local plantations may produce better results than the first generation of imported seeds. Identifying the best local seed sources should be a priority for the plantation manager. The possibility of different responses by individual eucalypts to fertilizer treatment has been suggested as a result of the large variability observed in Zambia (Hans and Burley 1972).

Hybrids of species brought together in plantations are not uncommon, particularly in *Eucalyptus*. Some show hybrid vigor superior to either parent, but variability in all characteristics is a frequent result that is accentuated in later generations (Hans 1974). Strongly inherited *Eucalyptus* characteristics include rate of growth (in contrast to findings with teak) (Wyatt-Smith and Lowe 1972), character of wood (Pryor 1956), and resistance to the large numbers of leaf-eating insects of their native land. In Australia, many species of *Eucalyptus* cover a wide range but occur as small isolated groups, probably crossing within (but possibly not between) groups. This suggests a source of diversity worth investigating (Pryor 1956).

Variation in wood properties among trees and the prospects for their genetic improvement are commonly taken for granted or are expected to result from improvements in other properties such as tree form. Although increased volume production is generally more important than improved wood quality, the two can be manipulated independently, so there is no reason not to improve them simultaneously (Zobel and Kelliston 1973). For example, specific gravity and cell-wall thickness of latewood tracheids (imperforate wood cells) are both important to wood yield and quality for pulp and paper manufacture, and both are heritable enough to permit economically important gains through their genetic manipulation. With *P. caribaea*, there is potential for an increase in specific gravity of from 50 to 80 kg/m^3 through manipulation (Zobel and Kelliston 1973).

When *S. macrophylla* and *S. mahogani* are grown together, as in Cuba and Puerto Rico, an intermediate form (or race) develops that is reportedly a hybrid; it in turn produces an F2 generation with segregated *S. mahagoni*, *S. macrophylla*, and the F1 hybrid (Marquetti and others 1975). The intermediate race is considered superior to the others on certain dry sites (Briscoe and Nobles 1966). Natural variation in the wood of *S. macrophylla* in Bolivia has led to recognition of four different races with a range of specific gravities from 0.55 to 0.71 (Irmay 1949).

Wide variability within the genus *Prosopis* is to be seen in the following examples, all from the closely related species *P. chilensis, P. chilensis glandulosa, P. glandulosa,* and *P. juliflora* (Magini and Tulstrup 1955). Of these, the species that are from arid areas are useful under very dry conditions; those from Mexico are frost hardy; those from Argentina produce the best fodder; those from Peru require good drainage; and those from Argentina are best for irrigated plantations.

Not only is the durability of teak wood variable, but the variability in trees tested from throughout its natural range suggests that genetic factors are largely responsible (Da Costa and others 1961).

Provenance trials of *P. caribaea* in Transvaal and Zululand, South Africa, at age 16 and 17 showed that trees from seeds originating at higher latitudes produced less wood volume but had superior form (Falkenhagen 1979).

Potential Genetic Gains. Attempts at tree improvement in tropical forest plantations have been localized and relatively recent, so the gains that can be achieved by genetic manipulation are yet to be realized. How great those gains might be is suggested by limited data.

Mass selection from 6- to 9-year-old plantations of *P. elliottii* in Queensland, Australia, led to clear improvements in the progeny, both in volume and straightness (Nikles 1966). Phenotypic selection of parent trees proved to be very reliable. Only rarely did mass-selected parents (the 400 most vigorous and well-formed trees per hectare) produce progeny without significant gains over the checks. And in no case have such progeny proven inferior to the checks. While useful gains were obtained from progeny of open-pollinated, selected parents, spectacular gains came from controlled pollination of the same trees.

Thirteen-year-old *P. elliottii* in Australia from closed-pollinated, selected trees showed a gain of 6 percent in total height, 21 percent in straightness, and 22 percent in volume per unit of area (Anon. 1972a).

A resume of genetic gains from tree breeding in the Tropics has been presented by Venkatesh (1976). He listed as types of gains clean cylindrical boles, stem straightness, timber and pulp quality, thinner branches, compact crowns, and less reaction wood. He pointed out that mass selection alone nearly doubled *Eucalyptus* yields in Brazil, from 60 to 112 m^3/ha/yr. Merely converting plus stands (of already selected stock) into seed-production areas by eliminating all undesirable trees can increase productivity 5 to 10 percent. Seed orchards established from outstanding plus trees may increase productivity 10 to 20 percent in the first rotation. Plus-tree seed orchards of *P. caribaea* have provided a gain of up to 50 percent in the proportion of straight stems.

The selection of 25 plus trees of 8 species in Tanzania led to seed crops that yielded 10 percent faster growth than did trees from unselected seeds (Vaclav and Skoupy 1973).

Venkatesh (1976) pointed out that seed orchards started with seedlings were much easier to establish but gave only half the gain of first-stage, clonal orchards. Orchards of progeny-tested trees are likely to gain an additional 35 to 45 percent. Crossing of two closely allied species is another approach to genetic gain. Hybrids of *E. camaldulensis* and *E. tereticornis* in India have shown 30 percent more height growth and 80 percent more d.b.h. growth than either species at 4 years. Hybridization also promises better adaptability to poor drainage, salinity, and drought as well as resistance to pests and diseases. A crossing of *P. caribaea* and *P. elliottii* in Australia produced an F1 hybrid better adapted to swamp sites than either parent (Slee 1969). Moreover, the cross retained the rapid growth rate of *P. caribaea*. Gains in 6-year volume growth due to hybrid vigor are reported from Australia (table 7–14; Anon. 1971–72). Interestingly, the greatest percentage hybrid gains are for unfertilized trees.

Selection of plus trees of *Cupressus lusitanica* in Kenya at the rate of 1 plus tree to 206,400 trees planted led to a 125-percent increase in stem growth and corresponding improvements in other tree characteristics (table 7–15; Dyson 1969).

Further gains are to be expected by crossbreeding superior stock. For example, *Cedrela* grafted onto *Toona* stock resists the shootborer *Hypsipyla grandella* (Grijpma

Table 7–14.—Hybrid vigor in *Pinus caribaea* and *P. elliottii* in Australia

Stock	Mean volume (m^3/hundred trees) No fertilizer	P	NP	NPK and Cu
P. elliottii and *P. caribaea*	3.8	38.9	34.0	38.4
Hybrid	9.6	60.0	59.5	43.6
P. elliottii and *P. hondurensis*	3.3	43.5	39.2	30.9
Hybrid	14.7	75.6	68.0	53.2
P. caribaea and *P. hondurensis*	1.7	33.4	25.6	20.2
Hybrid	6.5	52.7	38.8	34.0
Mean gain, *percent*	250.0	63.0	68.0	46.0

Source: Anon. 1972b.
Note: NPK and Cu = Nitrogen, phosphorus, potassium, and copper.
P. caribaea = P. caribaea caribaea. P. hondurensis = P. caribaea hondurensis.

1976). Because the larvae of the insect die when boring into the tissue of *Toona,* a toxicant is postulated as the source of resistance.

However, genetic gains, if accompanied by a narrowing of the diversity of germplasm, may increase the risk of pest and disease problems (Gibson and Jones 1977).

Economic Considerations in Genetic Tree Improvement. The key controllable plantation expenditures are establishment costs, crop security, and time. Genetic tree improvement could benefit all three. If a tree species is sufficiently variable to respond to selection and is widely used, tree-improvement costs may be greatly exceeded by even minimal benefits (Carlisle and Teich 1975).

From the viewpoint of wood utilization, a good case can be made for investing in tree improvement. For kraft pulp and paper manufacture in the Southern United States, specific gravity is the most important wood property (van Buijtenen and others 1975). With short rotations, tree breeding for high specific gravity is desirable. Modifying paper properties by refining or using additives is generally more expensive than achieving the same result by using genetics or silviculture.

An important economic aspect of tree improvement is the early ability to predict later tree performance. In provenance trials with *P. caribaea* in Transvaal and Zululand, later genetic traits were strongly correlated with those traits visible at age 8 (Falkenhagen 1979). Therefore, it may prove justifiable to wait for the results of progeny tests before embarking on large planting programs (Champion 1943).

Tree Improvement as an Aspect of Management. Tree improvement must be considered to be as integral a part of forest management as is silviculture. Breadth of the genetic base is as important as phenotype performance. Silvicultural practices focusing primarily on rapid growth could compromise productivity in the long run by excessive production of wood with juvenile characteristics and unfavorable earlywood-to-latewood ratios (Bevege 1976).

Pinus caribaea trees in plantations in Australia develop little latewood compared with naturally occurring trees and are, therefore, often of much lower density (Hughes

Table 7–15.—Selection gains with *Cupressus lusitanica* in Kenya

Character	Gain (%)
Stem volume	125
Stem straightness	30
Reduction of canker and fluting	85
Reduction of branches per stem	13
Improvement in branch angle	42
Knot index	45

Source: Dyson 1969.

1968a). This may reduce their value for heavy construction, but it makes them more suitable for joinery. Pulpwood from fast-growing *P. caribaea* plantations is markedly superior to pulpwood from natural forests. The wide natural variability exhibited by this species is partly genetic. It is the task of management to sort out and control these genetic properties for improved utilization (Hughes 1968a).

Plantations will become more important sources of genetic material as dependence on planted trees for future timber increases. As collections of genetic material become more complete, the best sources of genes will be the resultant plantations. "Storage" of different sources in 10-ha plots has been suggested as integral to management (Willan 1973). Because of the value of this material for future production, it probably will be safer in the care of plantation managers than in the wild. Although an attempt to save everything will fail, more than only the best trees must be conserved (Zobel 1978a). The *characteristics* of each provenance as a unit should be preserved through the conservation of many representative trees.

Undertaking Tree Improvement. Before tree breeding proves practical, silvicultural practice must apply interspecific selection to eliminate undesirable parental stock at the species level. Then, within species, genotype and phenotype characteristics may be related and thus reward the selection for good visible traits.

Tree improvement can best be undertaken in a sequence of progressively more intensive steps, including some or all of the following (Cooling 1967; Jones, N. 1967):

- Identify seed origin of established trees.
- Secure from a range of provenances a genetic base adequate for sound selection.
- Compare performance of trees from different provenances.
- Select superior stands.
- Use rogued superior stands as interim seed-source areas.
- Select superior phenotypes.
- Use controlled-pollination seedlings from numerous superior phenotypes to establish interim seed orchards.
- Screen controlled-pollination seedlings or vegetatively propagated progeny (including tissue culture) of superior phenotypes; preserve the best in a clonal collection.
- Use either seedling or vegetative propagation to develop (from progeny screening) clonal seed orchards that are adequate for large-scale planting.
- Continue to search for outstanding phenotypes for future improvement and inclusion of new and better genes in the clonal collection and seed orchards.
- Test crosses to determine the potential of hybrids.

An early and important stage in the development of superior trees calls for the interim seed-source areas mentioned above (Kelliston 1969), which serve until seed orchards attain commercial production. These are plus stands from which undesirable phenotypes have been removed and around which isolation barriers against foreign pollen have been established. The progeny from such areas usually have not been tested, so proof of superiority is lacking. However, experience has shown that trees from seeds collected in such areas are superior to those from commercial lots in uniformity, form, and pest resistance (Kelliston 1969).

Wherever there is a prospective plantation of 75,000 ha or more, seed orchards designed to maximize matings among trees selected for desirable characteristics should be established to supply planting material. In a seed orchard, at least 25 clones are required, and 50 to 100 are preferable. They should be planted at twice the density that is ultimately desired and in a random arrangement to ensure separation of the ramets of each clone. Fertilization can promote flowering, and irrigation is also stimulating.

All traits are not 100 percent inherited, as the example of vigor in *Tectona grandis* indicates (Wyatt-Smith and Lowe 1972). Therefore, if optimum results are to be achieved, the degree of heritability of different traits must be determined as early as possible in the selection process because selection for some characteristics may unfavorably affect others.

In east Africa, the selection process began with pine plantations that were at least 10 years old and 10 or more meters tall (Dyson and Paterson 1966). Field personnel made the first selection, based on straightness and circularity of bole, narrowness of crown, freedom from disease, fertility, and size relative to five free, neighboring trees. Other characteristics considered valuable were persistence of the leader, symmetry of the crown, smallness of the branches, flatness of the branch angle, good natural pruning, slight taper, freedom from epicormic branches, and minimal buttressing (Jones, N. 1967). Cores may also be checked from randomly selected trees for ring width, percentage of latewood, fiber length, density, and grain angle. Wood quality is as important a selection criterion as are form and branching habit (Hughes 1973).

Selection criteria for *P. caribaea* in Suriname (Teunissen and Voorhoeve 1973) have included the following:

- Habit, straightness, lack of forks, full crown, diameter, and height above the average of nearby trees
- Branches with an angle of about 90° to the bole
- Nodes not excessively protruding
- Full flowering later than average and of medium abundance
- Few whorls per meter of bole
- Few branches per whorl
- Low ratio of branch diameter to stem diameter
- High ratio of girth at midlength to girth at one-tenth of length.

In Australia, selection criteria have included acceptable wood properties, including minimal spiral grain, moderate basic density, and long fibers (Anon. 1968b).

In Ghana, the search for plus trees of export quality among indigenous genera, such as *Afrormosia, Entandrophragma, Khaya, Tarrietia, Terminalia,* and *Triplochiton,* has been guided by the following criteria (Britwum 1970): (1) bole with minor buttresses and free of fluting, sweep, and other irregularities; (2) bole clear for 30 m or more; (3) no sign of spiral grain; (4) branches small with good natural pruning; and (5) freedom from disease or injuries. From the trees so selected, seed orchards based on grafting were proposed.

Tree-improvement efforts with *E. deglupta* began with seed collection from all apparent variants (throughout the natural range) (Davidson 1973b). When provenance trials reached 11 to 20 years old, superior trees were selected on the basis of vigor, form, and wood density. Seed orchards were then established from seeds from the selected phenotypes, after heavy culling in the nursery. The orchard spacing was wide to foster seed production. Clonal orchards using cuttings and grafting from outstanding phenotypes were also set up.

Experience with *E. deglupta* led Davidson (1973b) to several conclusions that may prove generally useful. Because the growth potential of the species seemed already adequate, the goal was uniformity. Because low cellulose yields had been reported, there seemed a logical opportunity to increase the cellulose percentage in the wood. Wood density varied widely, presenting another opportunity for genetic improvement. However, because wood density is affected by growth rate, the primary goal would be uniformity. Fiber length was found insufficiently variable to warrant much attention.

The timing of flowering and other factors favors self-pollination of eucalypts (Eldridge 1976). Almost all species tested are self-fertile to some degree. Until eucalypt breeding systems and selection consequences are better known, breeders should assume that a lot of nonrandom mating and low heritabilities occurs, and consequently, breeding programs should emphasize family selection rather than selection of individual phenotypes (Eldridge 1976).

The intensity of mass selection should vary with the size and quality of the seed source and the purpose of the collection. From small plantation areas (or within those already improved and made more uniform genetically), as many as one fifth of the trees may be selected (Nikles 1973). On the other hand, selection from unimproved plantations to establish untested clonal seed orchards may require only 1 in 24,000. Such selections for clone banks and open-pollinated progeny tests with *Cupressus lusitanica* and *P. patula* in Colombia have been as selective as 1 in 82,000 (Gutierrez and Ladrach 1978).

Tree spacing in seed-production areas is critical to yields. In 13- to 16-year-old *P. taeda* plantations in Australia, pollen production was greatest at 262 trees per hectare and lowest at 608 trees per hectare (table 7–16; Florence and McWilliam 1956).

Cone production reflects not only pollen availability but also successful pollination. Florence and McWilliam (1956) found that cone production in *P. taeda* in Australia responded significantly to site quality. The effects of spacing on cone production in 13- to 16-year old plantations of *P. elliottii* and *Araucaria cunninghamii* in Australia are shown in table 7–17. The number of *P. elliottii* seeds per cone varied with pollen availability, decreasing in dense stands where little pollen was available. At densities of 140 to 450 trees per hectare, the number of seeds per cone averaged about 100. In contrast, at a density of 790 trees per hectare, there were only 86 seeds per cone (Florence and McWilliam 1956). These studies led to a recommended spacing in thinned, seed-production areas or seed orchards of 7.3 by 7.3 m, or 187 trees per hectare. At age 20, plus stands thinned to this spacing should yield 62 *P. elliottii* cones per tree and 28 kg of viable seeds per hectare, and 70 *A. cunninghamii* cones per tree and 1,120 kg of viable seeds per hectare (Florence and McWilliam 1956).

Orchards may be planted densely with a plan to rogue out some of the genotypes (Shelbourne 1973). Once progeny tests have been completed, a new orchard may be established with those trees of best potential for the combined traits under selection.

Table 7–16.—*Pinus taeda* pollen production as related to tree spacing in 13- to 16-year-old seed orchards in Australia

	Male amenta[a]	
No. of trees per hectare	Per tree (thousands)	Per hectare (hundred thousands)
128	60	78
163	57	93
262	50	132
403	24	95
608	3	19
1,902	2	42

Source: Florence and McWilliam 1956.
[a]Amenta are spikes of unisexual unpetaled flowers.

Tropical America is deeply involved in screening tree provenances. By 1962, air layering of *P. caribaea* was in progress in Trinidad as a beginning of clonal trials (Chalmers 1962). By 1976, Brazil was testing the 3 varieties of *P. caribaea,* as well as *P. elliottii densa, P. kesiya, P. oocarpa,* and *P. pseudostrobus,* some 31 provenances at 13 locations within 3 states. Tests are also in progress in many other countries of the region; Mexico has a program that apparently is comparable to Brazil's (Patino 1976).

Rotation

Selecting a rotation is basic to plantation planning and management. It reflects the tree size needed for the ultimate yield and the expected growth period required to achieve that size. Nevertheless, in the Tropics, plantings have seldom been established fast enough to meet future requirements; therefore, planting has proceeded at a feasible rate, leaving ultimate tree size and rotation tentative because of unforeseeable market changes, economic fluctuations, and unproved growth rates. This uncertainty does not argue against rational planning but merely confirms that a first crop on any site may not grow at the rate predicted by the best informed sources. Added to this uncertainty is the ever widening range of tree diameters as the plantation grows, suggesting different growth periods for different stand components. Market limitations for small trees, long an obstacle to intensive silviculture throughout the Tropics, have been reduced to a point where some rotations have been shortened drastically.

Several types of rotations are recognized (Fenton 1968). A physical rotation is intended to fill any real or anticipated need. A silvicultural rotation optimizes natural regeneration. A technical rotation serves the requirements of given products. A maximum-production rotation provides the greatest mean annual yield of marketable volume. A financial rotation produces the greatest return from a forest area.

The financial rotation tends to be longer than the maximum-production rotation for fuelwood because large trees are cheaper to harvest than small trees. But it tends to be shorter than the rotation of maximum production of large trees because of the cost of carrying investments. The financial rotation length may be extended by a sharp increase in the value of large-diameter trees.

Table 7–17.—The effect of tree spacing on cone production of *Pinus elliottii* and *Araucaria cunninghamii* in Australia

No. of trees per hectare	No. of cones per tree	Cones per hectare (thousands)
P. elliottii		
148	40–120	5.5–16.5
198	32–85	6.4–17.6
445	8–45	3.6–20.8
790	2–14	1.6–16.2
A. cunninghamii		
247	54–85	13.2–21.1
445	32–65	12.1–28.9
692	11–44	6.8–30.1
939	11–18	9.4–17.2
1,423	5–8	5.3–10.8

Source: Florence and McWilliam 1956.

Selecting a rotation is desirable at the outset, but at that time it may be an arbitrary decision because few studies document the costs of and responses to various practices such as thinning and the effects of tree-size distribution and tree age on product quality and value (Fenton 1968).

The variety of markets has led to widespread differences in rotation length. Where fuelwood is the product, rotations not much longer than the time needed to reach the culmination of mean annual increment may be used. The chief constraints here are the high proportion of bark and the cost of handling small trees. For *Leucaena leucocephala,* rotations as short as 2 to 3 years were recommended long ago (Matthews 1914), with the mean d.b.h. as small as 5 cm and the height only about 3 m. More recent studies of the giant varieties of *Leucaena* show a threefold increase per tree in biomass from the 3rd to the 4th year (1.7 to 5.5 kg), suggesting later harvesting if the growth per unit of area is sustained (Pathak and others 1981).

Casuarina equisetifolia, commonly used as fuelwood in the eastern Tropics, has been managed on a rotation of 6 to 10 years (Raghavan 1947). At the other extreme was the rotation set for teak in what is now Myanmar during the 1950s, 150 years for trees 70 cm in d.b.h. on moist sites and 60 cm in d.b.h. on dry sites (Aung Din 1957). Two factors have tended to reduce long rotations. The growing scarcity of large timber in natural forests has adjusted the market to smaller trees. Also, increasing populations and local demand for less specialized wood products have permitted intermediate cuttings that make up more of the yield and thus decrease the average rotation length.

The African species *Aucoumea klaineana,* a source of prized veneer wood, has been planted widely in Gabon (Catinot 1962). Thinnings led to strong sprouting and to studies of the wood for pulp. In plantations of 750 trees per hectare, the wood volume doubled from the 7th to the 10th year and again from the 10th to the 18th (Leroy-Deval 1975). However, because current growth began dropping after the 11th year, it was concluded that the best pulpwood rotation was 11 to 12 years.

Wood Quality. As the rotation increases, there is a decrease in the percentage of the low-quality corewood and the percentage of wood with sloping grain, particularly in pines (Fielding 1967). Increases occur in the average cell length, the average specific gravity (although this may decrease in certain broadleaf species), and the percentage of heartwood. These trends all favor longer rotations for wood quality.

For paper production, there are some drawbacks to short-rotation wood from broadleaf trees. Juvenile wood has more reaction wood, although in rotations of at least 8 years, the specific gravities and pulp yields may equal those of mature wood (Einspahr 1976). Beating-energy requirements and cooking times are less for the short-rotation wood, but for conifers, chemical requirements may be higher. However, the presence of more bark can reduce paper yield and tearing strength.

Rotations used in South Africa with *Eucalyptus* (mostly *E. grandis*) have been 6 to 10 years for posts, pulpwood, and mine timbers; 10 to 14 years for utility poles; and 14 to 30 years for saw and veneer logs (Poynton 1981).

Tree and stand growth provide guidance for determining the optimum rotation. They vary according to site, stand condition, species, and measurement method. Some universal sources of variation, following, have been listed by Assman (1970):

- The age of trees determines not only the growth rates and yields for limited growth periods but also the average yield for the mean tree age.
- Age for age, there are more trees on poor sites.
- For any given mean height, there are fewer stems per unit of area on poor sites.
- At the same crop height, light-demanding species have fewer trees per unit of area than do shade-tolerant species.
- Mean tree diameter is really the quadratic mean, corresponding to the tree's mean basal area. (This mean is also approximately that of a stem with the mean volume.)
- Top height, a useful measure for volume estimates, is the average of the 100 largest trees in d.b.h. on a hectare.
- Basal area growth may culminate and decline before yield becomes important.
- Height growth decreases regularly with age. Site quality should be determined by tree height rather than by crop yield.
- Form factor, a value that converts the product of d.b.h. and total height into tree volume, increases with age as a stand mean.
- Volume growth results from the combined effects of basal area and height growth in addition to changes in the form factor.
- Mean annual volume increment (MAI) of the stand begins to decline well before the MAI of the individual trees.

Usually, the interaction of several parameters that change with the plantation's age determines the rotation. Height, diameter, basal area, and volume all increase, and each culminates later in the life of a plantation than its predecessor. Means culminate still later.

Rotation is often based on the age at which current growth falls to a point equal to the MAI, obviously the culmination of the latter. However, two economic parameters may influence the rotation decision. For most uses, the larger the tree, the more valuable the wood per unit of volume, meaning that the current and mean increases in value culminate later than the increase in volume. On the other hand, carrying charges rise ever more rapidly with cumulative interest, tending to shorten rotations for maximum returns. To these factors must be added local influences, such as risk of blowdown, price fluctuations, yield versus frequency of regeneration costs, and special needs of the owner.

A study in Nigeria with the principal broadleaf species showed that current basal-area growth culminates long before merchantable timber sizes for quality woods are attained (Lowe 1970). For *Tectona grandis, Terminalia ivorensis,* and *Triplochiton scleroxylon,* stem basal-area growth per tree culminates at 7 to 8 years. For *Nauclea diderrichii,* the culmination was between 10 and 12 years.

A number of examples of dates from plantations significant to selection of a rotation are presented in appendix I.

Growth Prediction. As noted before, theories of energy fixation suggest that the maximum potential synthesis of dry wood might reach 60 t/ha/yr (Dawkins 1964b). In actual practice, however, the maximum aboveground production of dry wood, including branches, appears to be 20 to 40 t/ha/yr for *E. grandis, E. regnans, E. saligna, P. merkusii,* and *P. radiata* at high elevations with favorable rainfall and soils (Dawkins 1964b). Comparable limits were 20 t/ha/yr for *Agathis* and *Swietenia* and 10 to 15 t/ha/yr for *Simarouba* and *Tectona*. Generally tropical angiosperms, such as *Aucoumea, Maesopsis, Schefflera,* and *Triplochiton* are not expected to yield more than 5 to 10 t/ha/yr of dry wood. Dawkins (1964a) concluded that for these genera, 11 t/ha/yr was never exceeded, and the usual maximum, with 90-percent crown cover (the greatest practical crown freedom), was less than 8 t/ha/yr. Such yields reflect the effects of using the best available genotypes and microsites, better than management could ever hope for within the existing range of genotypes. Intolerant and light-wooded species showed the lowest yields (Dawkins 1964b).

Many of the data presented in this section are taken from yield tables. Their derivation and use deserve some description. The discussion that follows is adapted from Vuokila (1965). Yield tables deal with attainable yield, not necessarily harvestable yield. They are models and do not necessarily fit any specific stand. They show the progressive development of stands at periodic intervals covering the greater part of their useful life on a specific site. They generally show the number of trees, d.b.h., tree height, basal area, and yields, including thinnings.

Normal yield tables deal with fully stocked natural stands that have never been cut. These tables are useful as a basis for comparison. Empirical yield tables concern average actual stand conditions; some provide yields from residual stands after harvesting. Preliminary or provisional yield tables present single sets of figures for each site under average treatment. Multiple yield tables indicate how stands develop under various degrees of intermediate cutting, usually specifying light, heavy, or low thinnings. These may need revision as practices change.

Variable-density yield tables or functions are more versatile, because they enable the forester to predict the results of any intermediate treatment. They are based on studies of trees rather than stands, where data are required on tree growth under a great variety of conditions. The development of the stand is then derived from that of the trees in it. When properly prepared, these yield tables can be adapted to any stand and any thinning regime.

In the Temperate Zone, the following criteria have been established for predicting volume and growth (Assman 1970):

1. Tree volume, from d.b.h. and total height (R, the coefficient of determination or the correlation coefficient squared = 0.99, meaning that 99 percent of the variation is explained)

2. Stand volume, from stand basal area and height of the 100 largest trees per hectare ($R = 0.99$)

3. Diameter growth, from stand age, height of dominants, d.b.h. of trees, mean d.b.h. of stand, thinning interval, and percentage of basal area removed in thinning ($R = 0.93$)

4. Height growth, from initial mean stand d.b.h., initial tree height, initial age, and initial tree d.b.h. ($R = 0.94$)

5. Basal-area growth, from initial stand age, height of 100 largest trees per hectare, initial basal area per hectare, percentage of basal area removed in thinning, thinning interval, and initial mean d.b.h. of the stand ($R = 0.96$)

6. Volume growth, from MAI in tree d.b.h. between thinnings, initial tree age, initial tree d.b.h., initial height, and mean height of 100 largest (in d.b.h.) trees per hectare ($R = 0.93$).

When comparing volume in the field, workers commonly assume a single form factor for all trees. In East Africa, the same form factor was found applicable to *Cupressus lusitanica, E. saligna,* and *P. patula* (Osmaston 1961). Thus, a "silve" was developed in Uganda for rapid volume comparisons. It was equal to d.b.h.^{2} (in inches) times total height (in feet) divided by 500 (Osmaston 1961). This equation gives a range from 0.96 for a tree 4 inches in d.b.h. and 30 feet tall to 138.24 for a tree 24 inches in d.b.h. and 120 feet tall. In the metric system, the corresponding silve is d.b.h.^{2} (in centimeters) times total height (in meters) divided by 1,000, or 1.0 for a tree 10 cm in d.b.h. and 10 m tall, and 144 for a tree 60 cm in d.b.h. and 40 m tall.

Plantation Treatment

Planting is merely a prelude to plantation establishment. Only in exceptional areas does planting alone ensure survival and development of a satisfactory plantation.

Protection. The first requisite for plantation success is protection from hazards, such as fire, grazing or other animal damage, and human trespass. Local inhabitants can play a key role in preventing, reporting, and controlling problems of this sort. Involving them in the planning and in the employment opportunities offered by plantations is one way to encourage their support. If fire is a serious problem, residents may need to be educated or convinced as to its consequences and trained and equipped to fight fires on a volunteer basis.

Vegetation Control. Worldwide experience has shown that there is a need to control growth of unwanted vegetation (weed growth) on most forest sites. Recently planted trees have small root systems and have just suffered planting shock. In wet climates, herbaceous growth and vines tend to smother even fast-growing trees planted on well-prepared sites. In dry climates, such plants compete with the planted trees for scarce water. Some vegetation control is vital to the success of most plantations. Under adverse conditions, entire plantations may be destroyed by uncontrolled growth.

Weeds in the moist Tropics are so serious a problem that one of the foremost requirements for tree species to be planted in the region is rapid early height growth. First-year height growth of as much as 1.5 m has been specified as a minimum in some places (Lamb 1969b).

The invasion of young plantations by fast-growing, pioneer vegetation may be either harmful or beneficial. The entry of *Musanga cecropioides* into *Aucoumea* plantations in Gabon has been considered harmful and its elimination has been recommended (Deval 1967). In contrast, however, the invasion of *Cecropia* and *Simarouba* into plantations of *Swietenia macrophylla* in Martinique practically eliminated attacks by the mahogany shootborer, evidently because of the added shade provided by these species (Marie 1949).

The optimum weeding intensity must be determined locally. Excessive weed growth in a teak coppice reduced productivity (Laurie 1934a). But keeping rubber plantations continuously weed free resulted in soil erosion and reduced productivity (Haines 1934). On the other hand, clean weeding of *G. arborea* planted at 1.2 by 1.8 m in what is now Malaysia permitted development of a closed canopy within 18 months (Anon. 1948c).

Weeding-intensity requirements vary with the site. On wet sites, competition may be for nutrients or light, so illumination from above must be ensured. Weed growth is rapid and must be set back enough to free the trees for 4 to 6 months or longer. Aboveground growth (and preferably roots) of weeds and vines should be set back or destroyed for a radius of at least 1 m around each tree. At some spacings, this is almost equivalent to complete weeding. This intensity of weeding should no longer be necessary when the trees reach 2 m in height.

On dry sites, competition is chiefly for moisture, so weeds must be removed for a distance beyond that of aboveground contact with the seedling, to a radius of 1.5 m or more, meaning complete weeding. Weed roots should be grubbed out (Dawkins 1955b, Laurie 1941a). In Zambia, spot weeding around each *P. kesiya* on miombo dry forest sites did not stimulate early growth (Endean and Jones 1972). On the other hand, teak in Tanzania showed a 57-percent increase in height during the first year after clean weeding (Bryant 1968).

The intensity of the weeding that is required also depends on the tree and weed species present. For example, *P. caribaea* in Puerto Rico came up through matojo grass *(Andropogon licormis)* after only an initial weeding around each tree, but with grasses such as *Panicum maximum* and *Pennisetum purpureum,* as many as six weedings during the first 17 months were required (Geary and Zambrana 1972). Clearly, the ease of weed control is an important criterion for classifying planting sites.

An early experiment in what is now Sri Lanka shed light on how much weeding was needed for *Eucalyptus* and other broadleaf species (Holmes 1941). Three patterns of weeding were compared: clean weeding, covering the entire area; strip weeding, limited to the planting lines; and patch weeding, only surrounding each tree. The *Eucalyptus* species were considered established at a height of 2 m and the other species at 3 m.

Clean weeding showed a slight advantage over the other methods at the outset, but by the end of the first year, the strip-weeded trees had caught up. During the second year, patch-weeded trees caught up as well. The best combination of methods was clean weeding the first year followed by strip weeding the second. The trees so treated usually became established in 2 years but always by the third year.

The need for weeding does not cease so promptly everywhere. A 3-year-old plantation of *Cupressus lusitanica* in Colombia had attained an average d.b.h. of 2.8 cm and had long overtopped the herbaceous vegetation, but it lacked vigor and appeared chlorotic. When a dense stand of *Melinus minutifolia* grass was eliminated, the trees so treated increased 50 percent in diameter growth over the untreated trees.

To determine the need for replanting, initial plantation-survival data are needed promptly as well as subsequently, because progressive mortality may result from weed competition. Too often, assessment is done in a slipshod fashion, yielding no reliable information about either the percentage of trees that survived or when or why mortality occurred. Permanent sample rows with a fixed number of trees in each should be selected at random in sufficient numbers to ensure coverage of the range of site conditions. Observations should note possible causes of mortality as well as numbers of living and dead trees. The frequency of survival assessment can best be decided locally. The first assessment should precede the end of the planting season to afford an opportunity to fill gaps. Extra checks might be needed to detect effects of abnormal weather.

Some tree loss at the time of planting or immediately thereafter is to be expected, so provision for replanting should be included in initial project budgets. Trees may be lost through exposure at the time of planting, treatment during planting, or adverse weather shortly afterwards. Because far more trees are planted than may eventually be harvested, such losses are tolerable to some degree. In Mexico, evenly distributed losses as high as 75 percent have been accepted (Martinez McNaught 1978). However, failed patches large enough to allow serious weed invasion usually merit replanting. This should be done during the first year to avoid a permanent age disadvantage for the replanted trees. Replanting represents added investment, generally costs more per tree than initial planting, and may lead to higher weeding costs. Therefore, the causes of mortality in the initial planting bear investigation, and their elimination, where possible, is usually justified economically.

Experience in southern Brazil has shown that eucalypts commonly require weeding for 2 to 3 years (Simoes and others 1976). On the other hand, where their growth is rapid (up to 4.5 m in height at the end of 12 months), no further weeding may be needed. Slow-growing pines are better able to compete with weeds in southern Brazil, so weeding may not be as necessary. Eucalypts are weeded twice per year; pines, four or five times in all.

At Jari, along the Amazon in Brazil, the most serious weeds in plantations are the trees of *Cecropia* spp., which have been poisoned or harvested for cellulose (Woessner 1980a, 1980b). In Trinidad, *P. caribaea* plantings have undergone weeding and vine cutting for 3 years (Lackhan 1976). The need for weeding persists longer on moist sites. Weeding for up to 7 years is required in pine plantations in the wet mountains of Costa Rica (Salazar 1978).

On the grasslands of Papua New Guinea, pine plantations require three weedings the first year, two during the second, and one during each of the third and fifth years (Lamb 1974). In India, plantations of *E. tereticornis* are commonly weeded two to three times per year for 3 years (Lohani 1978). In Fiji, weeding and vine cutting in plantations of *S. macrophylla* are necessary for up to 5 years (Busby 1967).

Natural forest is sometimes retained between rows of underplanted trees to reduce the problem of weed control. But it is a common mistake to assume that underplanted trees will generally come through without weeding. If the planted trees are to grow, they require direct sunlight, which can be rapidly obscured by weeds.

In fact, weeding planted trees within a natural forest is a task almost equivalent to weeding plantations in the open. Openings above the planted trees that are adequate to stimulate their growth will also stimulate herbaceous vine growth. Although the weeds may not be as exuberant in a natural forest as in the open, tending (particularly vine cutting) may be required for 5 years or more. Overhanging crowns must also be cut back.

In Uganda, the limitations of clearing in corridors above underplanted trees were shown in a study by Dawkins (1956). Clearing the entire understory of trees up to 10 m tall was twice as costly as clearing only corridors. However, the corridors closed over in 18 months, almost completely suppressing the planted trees. Removing all of these overlapping branches would almost require clear felling.

Weeding may be done by hand, by machine, or with herbicides. Evans (1992) found that manual methods require the least skill and supervision, and chemical methods, the most. Where dense grass must be completely removed, the labor cost (or employment value!) was 25 worker-days per hectare for manual weeding, 6 to 15 for mechanical, and 1 or 2 for chemical.

Traditionally, plantations that are small or on rough topography are weeded by hand, with machetes and hoes. The machete, probably the most common tool in the region, is skillfully used by most workers. Nevertheless, it is dangerous and is frequently the cause of injuries, both to planted trees and to workers. Training workers in the use of such a tool may seem redundant, but even experienced machete handlers benefit by learning safety techniques. One technique is to hold down vegetation with a forked stick while chopping. Another is constant vigilance for obstructions and other workers while chopping. Safety shoes and shinguards are rarely used and may appear impractical, but they prevent injuries. Crews should be trained and equipped to apply first aid.

In southern Brazil, mechanized weeding using disks and rototillers has been common (Simoes and others 1976). Spacing between the rows must be wide enough to admit the machinery. However, even where mechanical equipment may prove suitable, cleanings between machine-weeded strips may have to be done manually.

Herbicides are frequently more effective than mechanical weeding. A drawback of some herbicides may be the difficulty of transporting the solvent (oil or water) to the site. Nevertheless, herbicides require less human effort and provide longer weed-free periods. Herbicides can kill both excess trees over underplantings and vines and weeds at ground level. Their effectiveness is proved, and when publicly sanctioned chemicals are used as instructed and the process is properly monitored, there should be little cause for environmental concern. The decision to use herbicides hinges largely on a complex of political, economic, and social factors. A rational decision requires a full appraisal of all risks involved, an estimate of the cost of other weeding treatments (Newton 1975), and public sanction.

Herbicides are most commonly applied with hand-operated, knapsack sprayers. Great care must be taken in spraying around recently planted trees, because they, too, are susceptible to some herbicides. Workers must be trained to prevent herbicides from being inhaled or contacting their bodies. The most hazardous stage of the spraying operation in new plantations can be eliminated by placing a conical or cylindrical shield over each tree as nearby weeds are sprayed.

The cost of weeding, which may exceed that of land preparation and planting several times, is a major deterrent to reforestation (Gutierrez 1970, Salazar 1978). On lowland rain forest sites, even *Eucalyptus* may require 17 to 49 days of weeding labor per hectare (Lamb and Bruce 1974). This requirement argues for selecting tree species for planting that are capable of rapid early height growth. Production of trees that are so slow growing that semiannual weedings are required over a period of several years may never be profitable.

Project budgets must provide for weeding; otherwise, funds for new plantings may be reduced by the cost of weeding recent plantations (Iyamabo and Ojo 1972). Any project should also compare the cost-effectiveness of different weeding techniques and intensities. Total weed control may look good but it is not generally necessary. Therefore, significant cost savings may be possible through less frequent or less complete weedings.

Weeding of *Eucalyptus* can be avoided on some sites in South America if the land is completely cultivated and fertilized at the outset (Donald 1971). Fertilizing is not yet common in tropical forests, but agricultural experience suggests that tests are worthwhile.

Cover Crops. Cover crops have been planted under a variety of tropical tree plantations. Indigenous groundcover species have commonly been used in rubber plantations in what is now Malaysia (Haines 1934). They reduce erosion and runoff by increasing percolation of rainwater into the soil, lower soil temperature and thus reduce evaporation, and add organic matter to the soil surface (Haines 1934). Nevertheless, cover crops make demands on the soil. Early experience with leguminous cover crops showed that their greatest benefits came only after they were worked into the soil (Becking 1951).

An exhaustive report (Watson 1973) presents more evidence regarding leguminous groundcovers in rubber plantations. If the cover crop is planted at the same time the rubber is planted, the groundcover may develop rapidly for 3 years and then drop off as the canopy closes. Pot trials indicated that legumes may fix as much as 235 kg/ha of excess N during 5 months. However, legumes may cause a heavy drain on P, requiring the equivalent of 280 kg/ha of rock phosphate in the first

12 months and 110 kg/ha annually thereafter. Nevertheless, legumes grow vigorously and provide a rapid buildup of organic matter on the soil surface (Watson 1973).

Studies in Oubangui-Chari, Central African Republic, indicated that for soil and water conservation, the best cover beneath young coffee plantations was mulch, but this alternative was considered too costly (Forester 1959). Clean-weeding led to excessive soil erosion. Covers of *Paspalum* grass, sweet potatoes, and *Leucaena* were not compatible. *Pueraria* (kudzu), if controlled, was found low in nutrient drain and had about the same beneficial effect on the coffee as clean-weeding.

In tests in southern Queensland, Australia, a perennial leguminous groundcover under *P. caribaea* and *P. elliottii* began to deteriorate after 3 years (Richards 1967). Such covers depressed the yields of exotic pines but stimulated those of native conifers (*Agathis robusta* and *Araucaria cunninghamii*), while increasing the N content of the native conifers and having no effect on the N content of the pines. Nevertheless, the pines still outgrew the natives.

In summary, there has been little conclusive experience concerning good groundcovers under timber plantations. In Puerto Rico, soil and water conservation seems assured if thinning is sufficient to keep the canopy open between the tree crowns. Native herbaceous vegetation provides at the surface a continuous cover that is sufficient to control erosion.

Interplanting. Multiple cropping with timber trees and the use of the taungya system are treated in detail in the next chapter. This section is primarily concerned with interplanting to benefit established timber crops.

Early studies of teak in India showed that the species tolerated *Leucaena* and *Syzygium jambolanum* beneath it (Laurie 1934b). In fact, underplanting bamboo was recommended because where bamboo grows with teak, there is no epicormic branching of the teak.

The role of *Leucaena* in teak plantations was ascertained early in Java, well before the present century (Becking 1951). Teak grew slowly on poor sites and failed to get away. *Leucaena* was found to be an excellent understory. It covers the ground quickly and completely, remaining green during the dry season and thus preventing weeds. It is easy to sow, tolerates teak shade, and can be planted sufficiently close to the teak to favor good trunk formation. *Leucaena* may increase teak productivity 50 percent by increasing soil porosity, humus content, and nutrient levels. It sprouts after fires, prevents erosion, and produces excellent firewood and charcoal. On poor soils, *Leucaena* will outgrow teak and so must be pruned back. Maximum benefits accrue if pruned foliage is placed about the teak trees. Cattle eat the foliage, so other species (such as *Acacia villosa*) have been substituted in some locations.

In India, underplanting teak with trees or shrubs to maintain or improve soil or prevent otherwise inevitable weed growth has reduced basal-area growth of the teak by as much as 33 percent (Venkataramany 1956). This loss must be offset by compensating products from the interplanted crop. Valuable woods, or specialty trees like *Rauwolfia* and *Cinnamomum,* have been recommended for such situations.

Leucaena has been interplanted with *P. merkusii* in Java (Alphen de Veer 1954). While the pines are young, the *Leucaena* must be pruned down, but it dies as soon as the pines close.

Soil Cultivation. The soil under plantations is seldom cultivated after planting except where other crops are interplanted. An experiment with *E. alba* in Brazil showed that annual soil cultivation for 1 to 3 years after planting had no effect on tree development (Guimaraes and others 1959).

Cultivating other crops within tree plantations, however, has been done with some success for over a century. The practice arose in response to two problems: (1) the high cost of tending young plantations limited plantation establishment, and (2) land suitable for agricultural crops was in short supply. The practice, called "taungya," a joint effort by tropical forest landowners and farmers, originated in what is now Myanmar in 1866 (Blanford 1925). Taungya is defined as the establishment by a farmer of a forest crop by planting trees within an agricultural crop and weeding the trees for the duration of the agricultural crop (Dawkins 1958c).

Baur (1964b) pointed out that because taungya is normally associated with a low standard of living, it is sometimes criticized. Yet, in a world facing a population explosion, it may ultimately prove to be the only way for much of the world's population to have any living whatsoever.

The practice has been applied mostly in seasonal forests. It began in India by 1914 and has spread throughout the Tropics since. By 1961, there were 78,000 ha of taungya plantations in Ghana (Danso 1966). There, the timber was first felled by the government; then the villagers cleared, burned, and prepared the area for planting. The government may plant the trees, and afterwards, the farmer intercrops the area for 1 to 3 years.

The discovery in the State of Bombay, India, that natural regeneration of teak was not satisfactory led to the use of taungya there (Kaikini 1960). Also, in the dry forests of Madras, cashew *(Anacardium occidentale),* which commonly turned yellow and grew slowly, shot forth and grew rapidly when intercultivated with *E. tereticornis* (Rajasingh 1968). One or two food crops have been interplanted with *Eucalyptus* in some parts of India (Lohani 1978).

In what is now Myanmar, taungya proved useful with natural regeneration (Kermode 1952, 1955). When there was more regeneration of valuable tree species in dry and semi-evergreen secondary forests than had been expected, taungya planters were allowed to cultivate between the young trees. Enough teak survived for an average tree spacing of less than 1.8 by 1.8 m. Only one farm crop was generally harvested before the teak took over.

In Malaysia, taungya was tested with *P. caribaea* and apparently was successful (Ramli Mansor and Ong 1972). Results with dipterocarps were reported to be "variable." Experience there emphasizes a need for developing clear working plans before introducing taungya to protect conservation areas and to define agreement terms and the level of tending to be done (Fielding 1972).

At Mayumbe, in what was formerly Zaire, a taungya practice developed with *Terminalia superba* and banana culture (Dawkins 1955b). In this taungya practice, known as "uniformisation par le bas," the farmer, who pays rent for the use of the land, plants bananas a year after forest harvesting; the next year, he or she plants trees supplied by the government. By the end of the fourth or fifth year, the trees are established. Taungya was reportedly successful in Uganda with *Terminalia, Triplochiton,* and several Meliaceae (Lawton 1976).

Taungya was introduced into tropical America in Trinidad for teak planting (Cater 1941). Two agricultural crops were produced before the teak was growing freely. Crops that outgrew the teak were prohibited, including cassava, pigeon peas, okra, and taniers. In Suriname, the system has been used to establish *Cordia alliodora* (Vega 1978). Corn, rice, bananas, and cassava are used with certain restrictions. Cultivation lasts 2 years on sandy soils and 3 years on clay. The farmer continues to care for the trees until the fourth year, at which time they may be 8 m tall. In Puerto Rico, under the name of the "parcelero system," thousands of hectares of worn-out land were reforested successfully with mahogany (*Swietenia* spp.), *Eucalyptus* spp., and other species from 1935 to 1945.

Experience in India has led to several conclusions about the advantages and limitations of taungya (Kadambi 1957). The system may permit cheap plantation establishment and gainful employment (fig. 7–4). Properly managed, the system can also meet at least part of the demand for tillable land. On the other hand, taungya works only in areas where there is a demand for agricultural crops. It also requires sufficient land to ensure continuous rotational cropping for the planters. On the marginal land that is usually available, it exposes the soil and robs it of some fertility. Moreover, taungya does

Figure 7–4.—*Early vegetation control using taungya in Java, interplanting* Leucaena leucocephala, Tectona grandis, *corn, and rice.*

not necessarily substitute for all tending because further care is usually needed after the farmers leave (Danso 1966). An early but profound observation about taungya was that success depends on making it attractive to the farmers and showing them that it is in their best interests (Kennedy 1930).

Irrigation. Irrigating timber trees may seem a questionable investment. Yet because trees are desperately needed in tropical dry regions, many irrigated plantations have been established in the Eastern Hemisphere.

Some of the earliest and most successful irrigated plantations are in Punjab, India (Kitchingman 1944), where desert receiving 20 to 50 cm of rainfall annually was converted to forest yielding 2.2 to 3.4 t/ha/yr of firewood. The species planted is chiefly *Dalbergia sissoo,* spaced at 1.8 by 3.0 m. At age 6, tree diameters range from 5 to 10 cm and heights to 10 m. At that time, a thinning yields 28 to 35 steres of stacked fuelwood per hectare. At 12 years, a second thinning takes an equal volume, and the final felling is in the 20th year. The four major irrigated plantations in the region in 1944 are described in table 7–18 (Kitchingman 1944).

A more recent trial of irrigated plantings for wood was started in the Sudan (Booth 1965). Early results were promising with *Acacia farnesiana, Albizia lebbek, Casuarina cunninghamiana, Conocarpus latifolius, D. sissoo, Eucalyptus* spp., *G. arborea, L. leucocephala, Melia azedarach, Prosopis juliflora,* and the bamboo, *Dendrocalamus strictus.*

The water requirements for irrigated plantations are indicated by a test in Pakistan (Sheikh and Masrur 1972). These requirements were summed for a 7-month growing season by three irrigation techniques: drip, trench, and flood. Amounts needed proved to be 2.2 m^3 per tree for drip, 9.9 m^3 for trench, and 14.9 m^3 for flood. Corresponding mean seasonal height growths were 61 cm, 66 cm, and 81 cm, respectively. Height growth per cubic meter of water by the three techniques was 28 cm, 7 cm, and 5 cm, respectively, indicating that drip irrigation was the most efficient.

Burning. Burning litter beneath established plantations releases N and may add ammonium nitrogen to the underlying humus and mineral soil layers (Wollum and Davey 1975). Subsequent nitrification may result from increased availability of substrate ammonium and essential elements.

A long-term test of annual burning in wattle plantations (*Acacia* spp.) in Natal, South Africa, showed no adverse effect on the quality or yield of this legume (Beard and Darby 1951). Nor was there any measurable decrease in the humus content of the soil, its water-holding capacity, or stored moisture. The pH increased slightly, but no adverse effects were apparent. Ten years later it was concluded that burning adversely affected crop performance only when the ash was lost by water or wind erosion (Beard 1961).

It is common for coniferous plantations to be burned inadvertently. They tend to be well adapted to fire and thus resist fairly well. In fact, controlled burning in pine stands, a common practice in the Temperate Zone, has been recommended in Brazilian plantations of *P. elliottii* and *P. taeda* to reduce the fire hazard from a fuel buildup (Soares 1975).

Fertilizers. Tree plantations capture, conserve, and recycle large volumes of nutrients; so fertilizer needs, if any, are much less than for agricultural crops. The nutrient return through litter from a *Eucalyptus* hybrid plantation in India illustrates this point (table 7–19; George

Table 7–18.—Area and growth of irrigated plantations in India in 1944

Plantation	Year begun	1944 area (ha)	Mean annual increment (m^3/ha/yr)
Changa Manga	1866	4,200	20
Chichawathi	1913	3,620	10
Khanewal	1915	6,300	6
Daphar	1919	2,670	8

Source: Kitchingman 1944.

Table 7–19.—Nutrient return through litter in a *Eucalyptus* hybrid plantation in India

Plantation age (yr)	Annual return of nutrients from litter (kg/ha)				
	N	P	K	Ca	Mg
5	29.8	1.6	15.0	40.2	5.0
10	59.2	3.9	30.6	73.2	9.3

Source: George 1982.
N = Nitrogen. K = Potassium. Mg = Manganese.
P = Phosphorus. Ca = Calcium.

1982). The plantation, located in a climate with 200 cm of annual rainfall, averaged 11.1 cm in d.b.h. and 14.6 m in height at age 5, and at age 10, it averaged 14.4 cm in d.b.h. and 19.0 m in height.

Wild plants devote about 2.5 percent of their photosynthetic energy to fixing atmospheric N and another 5 percent to reducing recycled nitrate previously fixed through decay (Gutschick 1978). Sooner or later, the exhaustion of fossil fuels will require reliance on photosynthesis for the world's energy requirements. However, because even legumes do not fix all the N they need and N fertilizer may increase crop yields fivefold, greater fertilizer use in agriculture is an attractive, near-term alternative to destroying more forests for intermittent cropping.

There are at least three major reasons, which follow, for using fertilizers in the Tropics:

- Increased food production, which is currently attainable chiefly through the use of fertilizers, is the best hope for soon reducing the pressure to lay waste to the rest of the forests of the Tropics.
- Neither N fixation nor decay can be increased sufficiently, and soon enough, to provide nutrients for the foreseeable food needs of tropical peoples.
- Production and use of fertilizers to produce more food for the Tropics in the near term may well be the highest use of fossil resources.

Gutschick (1978) pointed out that crop rotation with legumes cannot provide even half the yield that current fertilizer use does. The return of all sewage N to fields would offset only about 10 percent of current fertilizer use, and the cost of transportation would negate all but a small fraction of this amount. Moreover, the hydrogen (H) for the ammonia in fertilizers can be generated by the use of abundant coal as well as by limited petroleum.

The need for fertilizers in tropical forest plantations is described well by Lundgren (1978); his arguments are summarized in the paragraphs below. His conclusions, based on experience in Tanzania, appear to be generally applicable to the inherently infertile soils of the humid and subhumid Tropics, regardless of the species planted.

Conversion of natural vegetation to man-made forests using today's management techniques will inevitably deteriorate the soil by decreasing organic matter and nutrient levels, damaging topsoil structure, and reducing porosity. The magnitude and speed of this deterioration will depend on the climate, soil conditions, management practices, and species used.

Any soil deterioration will retard the growth of the trees. It may appear quickly, as a result of soil compaction or erosion, or more slowly, as a result of decreased water-retention capacity. The decline may not be significant during the first two or three tree-crop rotations on favorable sites. It may also be temporarily offset by improved seeds and silvicultural methods; but, because these will increase the demand on soil fertility, the benefit will probably not last beyond one or two rotations. On poor sites, growth may decline late in the first or second rotation.

These concerns, however, are no argument against intensive forest production. Forestry may still be a more ecologically sustainable form of land use than farming. At least some types of site deterioration can be controlled once they are identified.

The fact that site deterioration is likely is less a source of anxiety than is the failure of forest managers to recognize that such a prospect exists. Soil-management research is considered much more important by tropical agriculturists than by foresters. Without much larger investments in site maintenance, long-term forest-yield forecasts could prove illusory.

Most foresters question the urgency of applying soil amendments. Reasons include the fact that trees can utilize existing site resources better than other crops, the belief that sustained productivity can be met through genetics, and the lack of local evidence that forest crops respond to fertilizers (Nwoboshi 1968). As a consequence, investment in fertilizers is not seen as justifiable.

Although the cost of fertilizers is expected to rise, their use in forestry will doubtlessly increase. For one thing, the competition for land may force the need for the higher yields produced by fertilizers (Swan 1965). Moreover, wood scarcities should increase the value of increased yields attributable to fertilizer use. Potential productivity gains from fertilizing appear greater and more immediate than can be expected from other silvicultural practices. Jari now fertilizes 3 times per 5–7 year rotation.

Each of the primary nutrients has a distinct effect on plant development (May 1954). Nitrogen contributes chiefly to vegetative growth, the formation of stems and leaves. Phosphorus encourages root development and hastens seed ripening. Potassium is necessary for assimilation and increases disease resistance. Of these three primary nutrients, none is effective in the absence of the other two.

A worldwide study of 13,000 fertilizer trials was conducted by the Food and Agriculture Organization (FAO) from 1961 to 1964 (Phillips 1972). In tropical America, the tests showed an average growth increase of 95 percent. The value of the added growth in comparison to its costs also generally increased more with time. The study showed that in humid and subhumid areas, the main increase in yield is produced by added N, but this effect may be increased more economically by the addition of P. The addition of K to N and P increased yields in most of the trials. For each of the three nutrients, the largest growth increase is brought about by the first 20 kg/ha. Gains generally culminate at 60 kg/ha, and such applications might be economically sound with genetically improved trees.

Fertilizer application has proved necessary for the survival of many tropical plantations (Ojo and Jackson 1973). Pines in one area of Nigeria grow poorly unless given superphosphate. Eucalypts in parts of Africa suffer severe dieback unless borate fertilizers are applied. Phosphorus is the element that most often generates responses in field trials. In fact, N without P often produces no reaction at all, and N alone can injure pines. Favorable responses to K alone are few.

Nitrogen fertilizers affect both tree form and uniformity (Schultz 1976). Fertilizers increase tree d.b.h. more than height and thus increase taper, reducing the form factor. They also reduce the variability of tree d.b.h. within the plantation (Schultz 1976).

The effects of fertilizers on wood properties not only vary from species to species but also appear to vary from tree to tree (Zobel and others 1961). The treatment of a 16-year-old *P. taeda* plantation in the United States with 180 kg/ha of N, 90 kg/ha of superphosphate and 90 kg/ha of potash for 3 consecutive years produced wood during the subsequent 7 years that was significantly lower in specific gravity (up to 16 percent) than was the wood 7 years before treatment (Zobel and others 1961). Other studies suggest that *P. palustris* and *P. taeda* wood may increase in specific gravity following fertilizer use and that there is no decrease in the quality of the juvenile heart wood or the summerwood percentage (Schmidtling 1973). Any reduction in specific gravity is more than compensated for by the increase in volume production resulting from fertilization and improved culture. Another benefit can be less heartwood at the pulpwood stage.

The common sources of nutrient elements contain about the following percentages of N, P, and K (May 1954):

Nutrient	Percent
Nitrogen	
Sodium nitrate	15
Ammonium sulphate	20
Farmyard manure	0.4–0.7
Phosphorus (P_2O_5)	
Superphosphate	20
Double or triple superphosphate	40
Farmyard manure	0.2–0.4
Potassium	
Potassium sulphate	50
Muriate of potash	48
Wood ash	5–15
Farmyard manure	0.1–0.7

Fertilizer application must be viewed in the context of nutrient balance. The outgo through leaching, erosion, or harvesting must be at least compensated for by additions. A historic example of the consequences of ignoring this need is to be seen in the case of litter removal for fuel from a forest in Germany over a 25-year period

Table 7–20.—Nutrient flux in a *Pinus radiata* plantation on a 35-year rotation in New Zealand

Index	Nutrients (kg/ha/yr)			
	N	P	K	Ca
Input				
(rainfall)	—[a]	1.1	21.8	3.9
Removal				
(two thinnings)	6.6	0.9	8.1	5.4
Net balance	—[a]	+0.2	+13.7	–1.5

Source: Will 1968, cited by Schultz 1976.
[a]Data not available.
N = Nitrogen. K = Potassium.
P = Phosphorus. Ca = Calcium.

(Bray and Gorham 1964). This drain reduced the basal-area growth of the forest about two-thirds, and after the practice was discontinued, the forest took 30 years to recover.

The significance of the N balance to wood production is evident in a closely monitored forest in central Europe (Wehrmann 1961). Nitrogen input from precipitation was between 3 and 7 kg/ha/yr, and absorption of ammonia from the air added another 4 to 7 kg/ha/yr. Leaching losses were 2 to 4 kg/ha/yr. Harvesting of "derbholz" (the usable trees, without bark, in excess of 7 cm in diameter) removed N at the rate of 10 kg/ha/yr. Also, harvesting branches, bark, and roots increased N removal to about 20 kg/ha/yr. It was concluded that no form of economic wood production would yield sufficient N to balance these removals even though the use of N-fixing species would be beneficial. Adding needed N by fertilizing would not only eliminate the deficiency but reduce the susceptibility of the forest to fungi and pests (Wehrmann 1961).

Table 7–21.—Net nutrient demands of *Pinus radiata* in New Zealand

Period	Nutrients demand (kg/ha)			
	N	P	K	Ca
First 10 years	493	41	308	201
Next 25 years	0	12	84	90
10 years, second rotation	246	20	199	99

Source: Will 1968, cited by Schultz 1976.
N = Nitrogen. K = Potassium.
P = Phosphorus. Ca = Calcium.

The natural replacement of soil nutrients has not been measured widely in the Tropics. Evidence from Puerto Rico, however, suggests that the K-supplying power of certain common soils may be adequate to sustain forest crops indefinitely. Tests of sandy Ultisols, using 4 years of intensive grass cropping to reduce the K to the replacement level, showed a natural input of about 35 kg/ha/yr of K (Abruna and others 1976). In the uplands, the mean for 17 soils was 90 kg/ha/yr. For six Oxisols, it was about 50 kg/ha/yr. And for seven Inceptisols, ranging from loams over tuffaceous shale to loams derived from coarse diorite, K input averaged 106 kg/ha/yr.

A much larger than average increase in the N content of young planted pines in the United States and Europe, on the order of 50 kg/ha/yr (Richards and Voigt 1965), is not readily explained by the contribution from precipitation (10 to 12 kg/ha/yr). Free-living, N-fixing bacteria contribute less than 10 kg/ha/yr. Experiments using the isotope N^{15} suggest that the soil is the site for fixation of the rest (Richards and Voigt 1965).

Plantations naturally tend to conserve and recycle nutrients, possibly resulting in a larger residual supply for subsequent rotations. About half of the N, P, and K in the needles of *P. taeda* is translocated to other organs immediately before abscission (Schultz 1976). The less mobile elements, Ca and Mg, remain in the needles when they fall. The net demands of *P. radiata* in New Zealand are shown in table 7–20 (Will 1968, cited by Schultz 1976). Table 7–21 suggests that subsequent crops may demand much less from the soil than did the first crop.

This average nutrient balance does not reflect conditions during the early age of the plantation when uptake greatly exceeds return through litterfall. It is at that time that fertilizer may do the most good. The fertilizer need varies with the nutrient requirements of each species. For example, in Australia in a 2-year-old plantation, nutrient uptake by *E. grandis* exceeded that of *P. elliottii* by these percentages: N, 86 percent; P, 197 percent; K, 366 percent; Ca, 1,243 percent; and Mg, 347 percent.

The return of nutrients through litterfall from plantations is a significant source of further growth (table 7–22; Egunjobi 1974).

The amounts of nutrients removed through timber harvesting and the amounts left behind were determined for *Eucalyptus* in the Mediterranean region (Philippis 1966, cited by Singh 1967). There, the average annual rate of removal of P_2O_5 was 8.6 to 10.8 kg/ha, whereas 6.4 to 16.6 kg/ha were left. For K_2, the amounts were 34.5 to 289.3 kg/ha removed and 78.8 to 296.1 kg/ha left. For calcium oxide, they were 70.2 to 136.5 kg/ha removed and 277.7 to 478.1 kg/ha left. The residues left are generally more than the removals.

The significance of new, more intensive timber-harvesting methods on nutrient levels has been studied in the Temperate Zone. In Finland, whole-tree skidding removed half the slash that would have been left by traditional methods and thus removed almost twice as much N and P (Malkonen 1972). Whole-tree chipping in the forest removes 50 percent more N and P. Moreover, loss through logging is not limited to direct removal because leaching is also increased. The prospect of nutrient deficiency becomes greater as forest plantations are relegated to poorer soils so that agriculture can be expanded on the better areas.

Nutrients lost through harvesting will probably eventually have to be replaced by fertilizers, and amounts will have to exceed losses because much of the applied fertilizer leaches.

Studies in Casamance, Senegal, showed that teak litter decomposes rapidly, organic carbon (C) mineralization is active, and N mineralization is restrained (Maheut and Dommergues 1960). Mineral fertilizers will eventually be needed to sustain productivity. It was suggested that this prospect could be ameliorated by mixing species. Species that mineralize C slowly, such as *K. grandifoliola,* might reduce the rate of drain of organic matter. Species that produce organic matter capable of increasing mineralizable N might also improve the nutrient balance.

The nutrient content of five *E. globulus* trees in Italy shows tree-harvesting effects that are relevant to tropical forests (table 7–23; Lubrano 1968). These trees averaged 24 cm in d.b.h. and 21.6 m in height. The percentages in table 7–23 show that removal of the stem and bark in tree harvesting takes more than half the nutrients bound up in the aboveground biomass. In plantations yielding 15 m^3/ha/yr, this would mean an average annual removal of 8.2 kg/ha/yr of N, 2.9 kg of P, 9.9 kg of K, 50.4 kg of Ca, and 4.0 kg of Mg.

Where adding N to a site at the time of planting does not greatly stimulate growth, it may be that competing vegetation is better prepared than freshly planted trees to take advantage of the added N (Wollum and Davey

Table 7–22.—Return of nutrients through litterfall from a 10-year-old teak *(Tectona grandis)* plantation and from natural forests in west Africa

	3-year average annual return (kg/ha)				
Source	N	P	K	Ca	Mg
Teak plantation, Nigeria					
Leaves	82.0	8.4	63.5	179.0	20.0
Seeds, floral parts	6.5	.7	5.6	3.8	.9
Twigs	2.0	.4	2.6	3.5	.6
Total	**90.5**	**9.5**	**71.7**	**186.3**	**21.5**
Moist evergreen forest, Burkina Faso	164.0	11.0	54.0	73.0	—[a]
Moist deciduous forest, Ghana	199.0	7.0	68.0	206.0	—[a]

Source: Egunjobi 1974.
[a]Information for these items not available.
N = Nitrogen. K = Potassium. Mg = Manganese. P = Phosphorus. Ca = Calcium.

Table 7-23.—Nutrient content of five *Eucalyptus globulus* trees grown in Italy

Element	Dry biomass (g/tree)	Aboveground biomass (%) Stem and bark	Branches	Leaves
Nitrogen	672	59	13	28
Phosphorus	57	71	14	15
Potassium	306	60	14	26
Calcium	1,808	68	24	8
Magnesium	301	82	13	5

Source: Lubrano 1968.

1975). Even where competition is controlled, the response to large doses of N is short lived. It is not possible to build long-lasting reserves of N in the soil, as can be done with P and K. Therefore, the amount of N fertilizer needed depends heavily on the plant's *current* requirements (Wollum and Davey 1975). Also, eliminating vegetation that apparently is competing with very young forest trees may not always be beneficial. Some types of vegetation may sufficiently improve the N economy that they more than compensate for any detrimental effects they might otherwise have.

Variable results are surely confounded by the natural supply of nutrients, many applications possibly being made where the nutrient supply was adequate or excessive. Also, in unthinned, established plantations, the trees may be too crowded to react (Schultz 1976).

The long-term benefits of P application are to be seen in a study with *P. radiata* in Australia (Turner 1982). The plantation was treated at age 4. At age 16, the plantation that had been treated with 100 kg/ha of P had 3.2 times the basal area and 4.5 times the volume of the untreated control. After 30 years, the respective mean d.b.h. of the two plantations had reached 38.8 cm and 26.5 cm, and the net returns from the crop were A$8,600 per hectare and A$3,195 per hectare. All treatments except the lowest (25 kg/ha) were profitable.

Still another source of inconsistency in the results of fertilizer tests is the interaction of multiple nutrient deficiencies. Positive results using N and P together, where N alone is either ineffective or detrimental, are common. Such results have been reported with neem (*Azadirachta indica*), eucalypts, pines, and *Gmelina* (Jackson 1973). Such confusion can be eliminated by including in every test one or more treatments in which all nutrients other than the one being tested are present in available form in abundance.

Even though many tests of fertilizing *Eucalyptus* have produced inconsistent results, there is evidence that optimum nutrient conditions can be achieved and apparently are worth the effort (Cromer and Hausen 1972). In Victoria, Australia, the application of 101 kg/ha of N in the form of ammonium sulphate and ammonium nitrite and 45 kg/ha of P proved optimum, doubling height growth in the subsequent 2 years and increasing wood production tenfold, without any major adverse effects on wood density, extractives, lignin, or pentosan values.

Results of selected fertilizer tests around the world suggest treatments both worthy and unworthy of trial elsewhere. Numerous tests have been made with *P. caribaea*. An early test in what is now Belize compared the effects of applying 14 g, 28 g, and 56 g of triple superphosphate per tree (Anon. 1959g). The smallest amount had a marked effect on height growth, and the larger amounts were only slightly better.

Fertilizer treatments applied to *P. taeda* in south Queensland, Australia, at age 3 showed that the response to P depended on the N status (Richards and Bevege 1967a). To guarantee an immediate response to P, N must be added as well. The benefit-to-cost ratio with fertilizer was 1.33 versus 1.03 without fertilizer. Part of the benefit is that with added nutrients, 2,220 stems per hectare can be sustained until a pulpwood thinning at age 7; without fertilizer, only about 1,000 stems per hectare can be carried.

In Brazil, complete fertilizer applications to *P. caribaea bahamensis* at the time of planting increased first-year height growth by 67 percent, but in the second year the effects of N were no longer significant (Simoes and others 1970). In contrast, applications of P, K, and Ca continued to be beneficial.

In Australia, P applied to 8-year-old *P. taeda* produced remarkable results 4 years later (Anon. 1952a). The volume underbark to a minimum diameter of 7.6 cm at age 12 was 88 m^3/ha or 11 per year, compared to only 7 m^3/ha/yr without fertilizer. With 213 kg/ha of superphosphate broadcast at age 8, the 12-year volume increased 49 m^3/ha, or 12 m^3/ha/yr. With 430 kg/ha of superphosphate, the increase was 84 m^3/ha, or 21 m^3/ha/yr. With 918 kg/ha of superphosphate, the increase was 155 m^3/ha, or 39 m^3/ha/yr. The application of 1,774 kg/ha of superphosphate increased yield 157 m^3/ha, about the same as the next lighter application. These highest yields, five times those without fertilizer, probably cannot be maintained, but they do indicate a strong P deficiency.

Application of fertilizer to *E. saligna* on red-yellow Latosols in Sao Paulo, Brazil, produced spectacular growth increases over 5 years (Mello and others 1970). The application was 53 kg/ha of N, 172 kg/ha of P_2O_5, and 25 kg/ha of K_2O. The yield of the fertilized plantation at 5 years was 50 steres/ha/yr compared with 30 steres/ha/yr for the unfertilized plantation.

In Darwin, Australia, irrigating *Anthocephalus chinensis* with sewage effluent led to growth up to 10.6 cm in d.b.h. and 8.2 m in height in 18 months (Cracium 1978).

These examples of responses to fertilizer have not been presented in complete detail because their significance is qualitative rather than quantitative. Furthermore, for many of these studies, the initial availability of nutrients was unknown as was the amount of the fertilizer actually consumed by the plants. One is left with the clear impression that whatever the local fertilizer use for agricultural crops, the extent of nutrient deficiencies and the response of trees to supplementary nutrients merit study, in nurseries and in young and established plantations, particularly where growth problems exist.

Thinning

Wood products such as lumber and plywood can be made only from trees of certain minimum dimensions. As trees grow above these dimensions, their output and value rise, and the proportion of usable material declines. Even for pulpwood, tree size is important because industrial wood processing is linear; costs are affected more by the number of units handled than by their size. Some 15 to 20 trees 10 cm in d.b.h. must be felled and handled to provide the volume of a single tree 30 cm in d.b.h. Large trees are also more valuable because of the superior quality of their wood for most products. Therefore, forest-production goals, rotation lengths, and silvicultural practices all focus on tree diameter. Diameter growth is generally favored over wood volume or biomass growth as an index of timber-quality production. In most timber plantations, trees are planted too close for all to grow to a large diameter concurrently. These excess trees cost money and they compete for light, nutrients, and moisture. However, their presence accelerates the rate at which the canopy closes and suppresses weed growth. They may also encourage vertical, straight, tree stems and shade out lower branches. They also provide a selection of trees for the final crop.

Effects of Spacing. Under most conditions, initial spacing influences final yield more than does thinning. For example, an unthinned *P. taeda* plantation in the Southern United States spaced at 2.4 by 2.4 m yielded 256 m^3/ha at 34 years compared with 306 m^3/ha from a comparable plantation spaced at 1.5 by 1.5 m (Wakeley 1969). However, thinnings, which took 30 percent of all trees at 15 to 19 years, had no significant effect on 30-year yields at either of these spacings. The wider spacing is considered preferable because of its lower initial cost.

Early observations on spacing effects in the eastern Tropics led to the following conclusions (O'Conner 1935):

- The size attained by a tree at a given age must be related to the growing space previously at its disposal; all other factors influencing its size are fixed by the locality.
- Planted trees, until they start to compete with each other, will exhibit the absolute or normal growth standard for the species and locality.
- Planted trees left to grow unthinned will exhibit the absolute or normal growth standard for the species, locality, and stocking density.

The space required for each tree increases with tree size. For example, *Shorea robusta* trees 10 cm in d.b.h. need only a 2-m triangular spacing to ensure free growth (Suri

1970b). Their needs, as they grow, and those of *A. chinensis* and *Tectona grandis* (Fox 1968b), an extreme light demander, appear in table 7–24.

The effect of initial spacing on the quality of yields is demonstrated by two plantings of *E. camaldulensis* in Israel (Karschon 1960). The stand with the wider spacing showed a marked superiority in quality of yield even at a younger age (table 7–25).

Where biomass rather than tree size or form is the main objective, the highest yields will coincide with the culmination of basal-area growth. In pine plots in Queensland, Australia, spaced to allow free growth, the annual basal-area growth in plantations with 1,360 trees per hectare culminated between 11 and 13 years (Trist 1956). With 620 trees per hectare, basal-area growth culminated in the 13th to 16th year. With 320 trees per hectare, it culminated at 16 to 19 years.

The ratio of actual crown diameter to d.b.h. affects tree growth, and the ratio is partly defined by tree spacing. For example, spacing of *P. elliottii* has been positively shown to be related to the crown diameter-to-d.b.h. ratio (Harns and Collins 1965). Eucalypts do not tolerate interlocking crowns, and therefore, their required crown diameter-to-d.b.h. ratio is an indicator of the needed spacing (Lane-Poole 1936). A ratio of 18 was derived for many *Eucalyptus* species, suggesting that full stocking corresponds to that shown in table 7–26.

Studies in the Temperate Zone with *P. banksiana* and *Populus tremuloides* verify that crown overlap affects growth (Bella 1969). By using the crown-diameter-to-d.b.h. ratios of open-grown trees as a control and measuring the influence of competition on close-grown trees (the summed zone of overlap for competing trees), Bella determined that crown overlap is responsible for 70 percent of the variation in basal-area growth per tree.

Table 7–24.—Spacing requirements in meters for free growth of three tropical tree species by d.b.h.

D.b.h. (cm)	*Anthocephalus chinensis*	*Shorea robusta*	*Tectona grandis*
10	2.0	3.5	9.4
20	4.1	5.1	11.0
30	5.7	6.7	12.3
40	6.5	7.6	13.8
50	—[a]	8.9	15.4
60	—[a]	—[a]	17.0

Source: Fox 1968b, Suri 1970b.
[a]Information for these items not available.

Table 7–25.—Spacing of *Eucalyptus camaldulensis* and resultant tree quality in Israel

Spacing (m)	Age (yr)	Wood suitability (%) Poles	Posts and pulpwood	Chipwood
2 by 2	8	2	57	41
3 by 3	6	6	80	14

Source: Karshon 1960.

Studies have indicated the natural range of crown diameter-to-d.b.h. ratios for many species (Sandrasegaran 1966a): *E. robusta,* 17 to 19; *E. grandis,* 17 to 26 (the low end of the range for large trees 60 cm in d.b.h.); *E. saligna,* 18 to 26; *Swietenia macrophylla,* 18 to 21; *G. arborea,* 18 to 32; *T. grandis,* 22 to 30; and *Maesopsis eminii* (an extreme light demander), 36 to 39.

As an even-aged plantation grows, competition affects trees in several ways (Catinot 1969a). Average tree growth decreases. Three "stories" of trees generally form: dominant, dominated, and overtopped. This stratification results from a differential decrease in the water at the disposal of each tree, correspondingly lower transpiration, a decrease in photosynthesis (because the stomata are less open), and less H, decreasing cambial activity.

Table 7–26.—*Eucalyptus* stocking limit derived from crown-diameter-to-d.b.h. ratio

D.b.h. (cm)	No. of trees per hectare	Basal area (m^2/ha)
10	1,950	16
20	600	19
30	290	21
40	170	22
50	110	22
60	80	22

Source: Lane-Poole 1936.

The minerals available must be allotted more stringently to the ever larger biomass, and fewer constituents are available for new wood. These limitations are seen in the development of four, unthinned, 12-year-old plantations of *P. caribaea* in Puerto Rico (table 7–27; Whitmore and Liegel 1980).

Even where plantation spacing is uniform, local soil variations affect the extent and health of the tree root systems. These influences during establishment and shortly thereafter, before competition among trees sets in, significantly affect the initial and later growth rates of individual trees (Day 1966). The continuing effect of early advantage has been demonstrated in several studies. For example, in a *Triplochiton scleroxylon* plantation in Nigeria, 70 percent of the variation in basal-area growth per tree was related to the basal area of the tree at the beginning of the period (its former relative advantage), and only 11 percent was due to the current proximity of neighboring trees (Lowe 1967b). In a comparable study of *Shorea robusta,* 77.5 percent of the diameter variation was explained by initial size (Suri 1970a).

Tree height at a given age, a standard measure of site quality, is presumed to be essentially unaffected by tree spacing. This assumption is generally true in widely spaced plantations but not in closely spaced ones. A study of *P. elliottii* in the United States showed that in an unthinned plantation, tree height after the 11th year increased with spacing (Harns and Collins 1965). At age 14, the height of the dominant and codominant trees averaged 12.2 m with 2,470 trees per hectare and 9.8 m with 14,820 trees per hectare (Collins 1967).

Table 7–27.—Effects of spacing on unthinned, 12-year-old *Pinus caribaea* in Puerto Rico

Mean triangular spacing (m)	No. of trees per hectare	Mean d.b.h. (cm)	No. of stems per cubic meter
1.6	4,090	15.0	6.3
2.7	1,370	24.1	2.6
3.5	840	27.8	1.6
4.3	550	29.3	1.5

Source: Whitmore and Liegel 1980.

Reasons for Thinning. Thinning may be done to achieve the following (Fraser 1965):

- Accelerate diameter growth (shorten the rotation)
- Increase the percentage of trees reaching maturity
- Improve wood quality (fig. 7–5)
- Provide intermediate yields
- Increase light penetration to develop larger crowns
- Raise the temperature at the forest floor to accelerate decomposition
- Increase internal air currents
- Reduce humidity
- Encourage root development
- Maintain ground cover for erosion control (fig. 7–6).

There is ample evidence that thinning accelerates diameter growth. For example, *E. deglupta* that was thinned 60 percent at 3.5 years of age averaged 18 percent larger in diameter than unthinned trees within a year afterward (Ugalde Arias 1980). But thinnings usually reduce subsequent volume growth; therefore, where usable biomass is the desired product (as is characteristic

Figure 7–5.—*Thinning of* Araucaria angustifolia *in northern Argentina leaves the best trees for the later harvest.*

Figure 7–6.—*Early thinning of pine plantations for posts and poles allows enough light through the canopy to maintain a protective vegetative cover on the ground beneath the trees.*

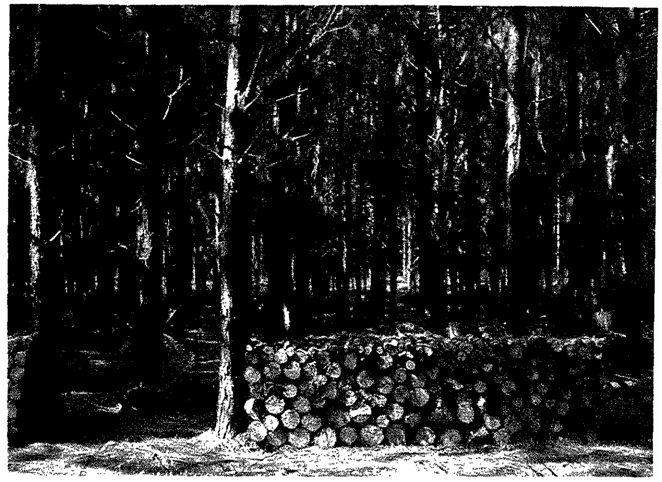

Figure 7–7.—*Thinnings for pulpwood provide early partial retirement of investments in plantations.*

of most *Eucalyptus* plantations), thinning may be counterproductive. Spacing of plantations for biomass is commonly wide enough to permit trees to attain harvestable size without thinning. Spacing may be 2.5 to 3.0 meters, and the trees are harvested at 5 to 12 years for the first crop and every 6 to 8 years thereafter. Genetically improved trees may attain pulpwood size earlier.

In addition to accelerating diameter growth, thinning may offer economic benefits. The early yields generated by thinnings, if marketable, may significantly offset carrying charges of plantations (fig. 7–7). The more rapid growth resulting from thinning should reduce rotation periods. The quality and sale value of the final crop should be near the maximum.

Experience with thinnings under local conditions should reveal the costs and benefits of alternative practices. When these are known, the plantation manager can plan a balanced culture, selecting an optimum combination of spacing, weeding, pruning, thinning, rotation, and yield.

The final product desired profoundly affects thinning practice, as seen from studies of *P. resinosa* in the United States (Lundgren 1981). The optimum residual basal area, regardless of product, proved to be 28 to 32 m^2/ha. For maximum usable biomass, the optimum number of trees was 3,950 per hectare. For usable roundwood volume, it was 1,970 to 2,470 trees per hectare. For sawtimber, it was 500 trees per hectare.

Thinning principles developed many decades ago in India are generally applicable (Singh 1955). These principles call for focusing on the number of trees left, not on the number of trees removed, the freedom of the crowns of the remaining trees, or the size of gaps created.

South African thinning experience led to the development of two coefficients as a basis for thinning regimes (O'Conner 1935). The coefficient of suppression is the quotient of the volume of any tree divided by the volume of a tree of the same age that has been free growing on the same site. The coefficient of response is the quotient of tree growth after thinning divided by that of a comparable unthinned tree. With these coefficients for different tree ages and growing conditions, it is possible to derive the following:

- The best spacing for growth of trees of any size
- The best spacing and rotation for maximum volume production regardless of tree size
- The relative effects of different thinning intensities on tree and stand growth
- A thinning regime for the production of trees of any mature size.

To sustain rapid diameter growth and yet fully use the site for optimum production, three basic thinning decisions must be made: when to thin, how many trees to leave, and which trees to leave.

When to Thin. Thinning should not be done so early in a plantation's life that it favors weed growth or branchiness. On the other hand, once crowding has already reduced diameter growth, thinning will not recover the loss. As trees grow and require more space, thinning should be repeated, leaving progressively fewer trees.

A general case can be made for thinning early in the life of the plantation. If done before competition is severe, thinning can prevent a lasting imbalance between the root systems and crowns of the trees (Day 1966). The idea is reflected in the recommendation for thinning southern pines in the United States while the crowns of the dominant and codominant trees are still 35 to 40 percent of their total heights (Wakeley 1954). Fast-growing, light-demanding *E. deglupta* has been thinned as early as the second year, the thinning yielding 22 m^3/ha, of which 6 m^3 was in poles (Rappard 1951).

Early thinning leads to an early peak in the growth rate as well as an early growth decline (Assman 1970). Stands thinned early may eventually be surpassed in growth by stands subjected to later, lighter thinnings that produce a lower peak but a longer period of growth acceleration.

Early thinning is particularly important with very rapidly growing species such as *Ochroma lagopus.* When *O. lagopus* was planted at 4.3 by 4.3 m in Malaysia, without thinning, only 45 percent of the trees met the prescribed diameter growth rate of 9.7 cm/yr the first year, 13 percent in the second, and none in the third (Wycherly and Mitchell 1962).

Studies of thinning *P. caribaea hondurensis* in Queensland, Australia, showed that as standing basal area increased (up to 60 m^2/ha) basal-area growth also increased, indicating that thinnings confer no benefit to total volume production (Anderson and others 1981). Nevertheless, it was suggested that a single, precommercial thinning at about age 5 to 750 stems per hectare could have other values: eliminating the worst trees, increasing windfirmness, and accelerating the growth rate, yet reducing final yield only about 10 percent. Little mortality is expected before stands reach 70 m^2/ha at rotation age.

How Many Trees to Leave. Desirable plantation spacing may be derived from the unrestrained crown diameters characteristic of different bole diameters. Crown diameters of such trees, a crude index of photosynthesis potential, relate closely to d.b.h. Conifers and eucalypts need crown diameters about 14 times their d.b.h. Most other tropical species need crown diameters about 18 times their d.b.h. These relations suggest maximum basal areas of about 40 and 24 m^2/ha for conifers and eucalypts versus others, respectively, with square spacing. Thinning intensities for plantations of various stem diameters that would leave adequate crown space between each 15-year thinning are given in table 7–28.

Basal area has been used in Trinidad as a guide for thinning *P. caribaea* (Lackhan 1976). In the absence of markets for products of early thinnings, only 1,330 trees are planted per hectare. When the stands reach a basal area of about 25 m^2/ha, at age 10 to 15, about 7 m^2 are removed. When the remaining basal area reaches 26 m^2/ha, another 5 m^2 are removed.

Guiding thinning intensity by crown diameters in reality addresses crown areas, assuming that a crown area adequate to support acceptable diameter-growth rates must be accommodated. Theoretically, the tree crowns could develop so that they complement each other perfectly and utilize the entire area. This would mean that the maximum number of trees per hectare to be accommodated (just before thinning), using triangular spacing, might be 10,000 divided by 0.866 multiplied by the crown area per tree in square meters.

Which Trees to Leave. The third basic decision, which trees to leave, focuses on the final product. Because thinning is usually practiced only where large, well-formed, clean stems are the goal, the trees left to grow must include those that potentially meet these standards. Ideally, the largest and straightest, equally spaced trees should be left. Such thinnings are termed "from below," because it is chiefly the small trees that are removed. In Trinidad, for example, thinnings of *P. caribaea* plantations have concentrated on dying, diseased, and suppressed trees; whips (slender-crowned trees damaged by neighboring tree crowns); wolf trees (broad-crowned trees of poor form); badly compressed subdominants; and codominants that interfere with good dominants (Lackhan 1976).

A technique widely used in young plantations because of the ease of supervision is mechanical or row thinning, that is, removing alternate rows. Among young trees, row thinning does not remove so many potentially good

Table 7–28.—Fifteen-year thinning regimes for tropical tree species based on the relations between crown diameter and d.b.h.

D.b.h. (cm)	No. of trees per hectare[a]		No. of removals per hectare	
	Conifers and eucalypts	Others	Conifers and eucalypts	Others
15	1,300	1,100	740	760
30	560	340	310	190
45	250	150	250	70
60	0	80	0	80

Note: For triangular spacing, divide the number of trees per hectare by 0.866 and increase removals accordingly.
[a]Desirable plantation spacings: conifers and eucalypts, 14 × d.b.h.; others, 18 × d.b.h.

trees as to preclude later selection of a quality crop. Where removal of alternate rows is inadequate for the first thinning, additional trees within the remaining rows may be removed from below. Another approach is to set a minimum crop-tree diameter and remove trees of lower diameters. A marked tape or fixed caliper can facilitate their identification.

A study of 6-year-old *P. patula* in Colombia (Ladrach 1979) showed that after mechanical (row) thinning, 50 percent of the trees immediately increased their mean d.b.h. from 10.4 to 10.9 cm. Thinning by individual tree selection from below raised the mean d.b.h. from 10.9 to 12.7 cm. Four years later, a difference of 1.5 cm in diameter growth favored thinning from below.

Thinning from below automatically boosts mean tree diameter because the smallest trees are removed. This increase, of course, is not a reflection of growth. A spectacular illustration of the instantaneous gains available from thinning is apparent in data for *Anthocephalus chinensis* from Sabah (Fox 1968b) summarized in table 7–29. These data show that selecting the larger trees for the crop can increase the mean diameter by 50 percent or more. Studies of growth stimulation should relate to mean diameters after (rather than before) thinning. This relation to growth rate is apparent in data from 30-year-old plantations of *Swietenia macrophylla* and *Tarrietia utilis* in Ivory Coast (Martinot-Lagarde 1961), as summarized in table 7–30.

The importance of distinguishing spacing effects on the size of final crop trees (most of which are dominants) from the effects on the average tree is illustrated by studies of *Cupressus lusitanica* in Kenya (Pudden 1959). Regression analysis of data from thousands of hectares of plantations showed stand density to have a negligible effect on either the diameter or height of the final crop trees. This raises a basic question as to some of the purported benefits of thinning.

Recommendations from Uganda on thinning (Lamb 1968e) focus on the quality of the trees to be left rather than on the deficiencies of those to be removed. The form and height of residual trees have been considered more important than stem diameter. Selecting the best trees requires the weighing of other characteristics, such as: the absence of crook or sweep; the lack of bole fluting; the size, angle, and persistence of branches; their apparent immunity to fungi and insect attacks; and their height and d.b.h. excess over their nearest five neighbors. Isolated plantations thinned once or twice using these criteria are potentially superior seed sources. Especially outstanding trees could serve for vegetative propagation of selected clones.

Generally, trees are selected for removal as much to upgrade the remaining crop as to obtain an intermediate yield. For this reason, the best trees are left and the worst removed. Dead and dying (or totally oppressed) trees are removed if marketable, but otherwise their removal is of little or no significance to future productivity. Trees with form too poor to yield primary products, regardless of their vigor, are generally next in priority for removal. And finally, the remaining trees may be thinned to release those most promising. The degree of intervention should seek the most favorable relation between cost and reduction of competition (Schulz and Rodriguez 1966).

If thinning is to maximize acceleration of the more desirable trees left, thinning from below is not sharply focused on this objective because some of the less

Table 7–29.—Size differentiation for unthinned *Anthocephalus chinensis* in Sabah (d.b.h. in cm)

Age (yr)	Spacing: 3.6- by 3.6-m, Mean	Spacing: 3.6- by 3.6-m, Best 50 trees per hectare	Spacing: 6.1- by 6.1-m, Mean	Spacing: 6.1- by 6.1-m, Best 50 trees per hectare
4.0	—[a]	—[a]	12.8	19.9
6.0	—[a]	—[a]	19.0	26.5
8.0	14.0	25.5	—[a]	—[a]
11.8	18.0	29.7	—[a]	—[a]

Source: Fox 1968b.
[a]Information for these items not available.

desirable large trees may be competing with the best. An approach being tried with *P. caribaea* in Puerto Rico is to identify and paintmark a generous number of trees for the sawtimber crop (about 300 per hectare). Then, at age 7 to 9, thinning removes as posts only the trees that are adjacent to those that are as tall as or taller than the sawtimber trees yet are not crop trees (those considered to be the only competitors). It is assumed that no further release of the crop trees will be needed but that remaining noncompetitors (those not expected to compete in the future) may be removed for posts before the canopy closes above them, as needed for intermediate products, with little significance to the progress of the crop.

Economic Considerations. To a large extent, practical considerations dictate thinning practice. Thinnings cost money and initially may yield small material for which there may be no market. Plantations where spacing is wide enough to obviate the need for precommercial thinnings may require a longer weeding period and special attention to pruning. Frequent, light thinnings appear to be ideal from the standpoint of sustained, rapid diameter growth but may yield so little usable material that they are impractical. Yet, less frequent thinnings must either be heavier (leaving the forest open and less productive during the period immediately following) or will allow the forest to become too dense for rapid diameter growth before the next thinning.

In Australia, harvesting costs for *P. caribaea* are about double production costs, so substantial savings can be expected from fewer and heavier thinnings (Hanson 1966). For economic reasons, thinning *P. taeda* in the United States for pulpwood is thought to offer no advantages in pulpwood production, and thinnings for sawtimber are considered beneficial chiefly to shorten the rotation (Goebel and others 1974).

Thinning in tropical America is not yet widely justified on economic grounds (Wadsworth 1978) and may not become commonplace until more demand appears for the products of small trees. Production is currently highly oriented toward fiber (Bryant and Williston 1978). Both social and economic goals might be better served by considering lumber and plywood as primary (high-value) products, and pulp, composition boards, and fuelwood as secondary products, however great the proportion of the wood volume entering into the latter.

Table 7–30.—Diameter growth relative to tree size for *Swietenia macrophylla* and *Tarrietia utilis* in Ivory Coast

Portion of stand	Mean annual diameter growth (cm): *S. macrophylla*	Mean annual diameter growth (cm): *T. utilis*
All trees	0.68	0.63
Largest 300 trees per hectare	1.02	0.80
Largest 150 trees per hectare	1.20	0.96
Largest 50 trees per hectare	1.39	1.14

Source: Martinot-Lagarde 1961.

Effects of Thinning on Wood. To understand how thinning affects wood properties, it is necessary to know how these properties are related to tree age, growth rate, and position of the wood within the stem. For example, it was concluded many years ago that teak timber with fewer than 1.6 rings per centimeter is weak; the strongest wood has 2.0 to 2.4 rings per centimeter (Limaye 1942).

Studies of softwoods grown in the United Kingdom have shown that wood density varies with tree age (Rendle and Phillips 1957). Wide-ring wood formed in middle life is denser than wood of similar ring width laid down in early life. The higher density of later wood does not depend, as has been assumed, on the usual decline in diameter growth. After a certain age, even rapidly growing trees can produce wood of reasonably high density. It would be misleading, however, to assert that wood density depends almost entirely on the age of the tree when the wood is laid down.

Boyd (1968) reported that with age, *P. caribaea* in South Africa rapidly increases in wood density and strength up to about 22 years. The strength of *P. radiata* wood formed during the first 5 years may be less than half the strength of wood formed after 15 to 20 years. The large core of juvenile wood in rapidly grown conifers generally has a low percentage of latewood, low specific gravity, short tracheids, high longitudinal shrinkage, and often spiral grain and compression wood. Nevertheless, conifers (as well as *Eucalyptus*) may at an early age produce wood that is better for papermaking in terms of yield, bursting strength, sheet density, and tearing strength than at a later age. Heavy thinning of pines leads to lower wood density and shorter tracheids. Uneven spacing that may result from thinning can cause asymmetrical stem growth.

Boyd points out that the effects of thinning on angiosperms tend to be more varied. With some species, slow growth leads to lower specific gravity, but the opposite may be true for others. Rapid wood production tends to adversely affect uniformity, texture, dimensional stability, machinability, and wear characteristics. The properties of eucalypt woods tend to vary in proportion to density. Wood from fast-growing plantations is slightly lower in density than the corresponding wood from native forests. Wood from fast-growing eucalypts in Australia is subject to severe manufacturing problems because of growth stresses, but its low density leads to easy seasoning and good machining properties.

Experience with *P. patula* in South Africa has shown a number of defects in wide-ringed timber (Villiers and others 1961). Included are excessive longitudinal shrinkage, uneven texture, knottiness, compression wood, and spiral grain. The first few inner rings invariably contain wood of this type, and the opportunity for restricting the diameter of this core is limited. A spacing of 2.4 by 2.4 m resulted in cores that were only about 2.5 cm smaller than those in trees grown at a spacing of 3.5 by 3.5 m. Close spacings are said to increase the contrast between the corewood and the later wood.

Although rapidly grown conifers tend to have longer tracheids than slowly grown trees, thinning may cause sudden growth rate increases that reduce tracheid length in the new wide rings (Fielding 1967). Silvicultural practices that promote dense, deep crowns on conifers tend to increase production of earlywood and thus reduce specific gravity of the wood near the crown. However, differences in growth rates generally have little if any effect on the specific gravity of the corewood.

Heavy thinning of *P. taeda* in the Southern United States at age 9 increased ring width nearly threefold during the ensuing 4 years, from 0.26 to 0.71 cm (Smith 1968). The percentage of latewood declined from 36 to 28, and specific gravity dropped from 0.45 to 0.42; both decreases were statistically significant.

Effects of Thinning on Yields. Deciding whether or how much to thin has important yield implications. The manager needs to know in advance the magnitude and timing of the potential benefits. Some of the pertinent ways thinning can affect yields—and thus the return on investment—are discussed in more detail in appendix J.

The reduced number of stems limits tree selection for the final crop and the quantity and quality of the product at various stages, including log size, taper, ring width, wood density, fiber length, and the characteristics and distribution of knots (Wardle 1968).

Thinning is based on the premise that beyond a certain limit, increased stand density diminishes usable volume production per unit of forest area. Average stem diameters, branch sizes, and taper all increase with spacing. Susceptibility to fire and to disease and insect attacks may also be reduced by thinning.

Thinning affects not only the remaining trees but also the site. The contribution of litterfall to soil nutrients is closely related to the basal area of the forest and, therefore, is reduced in proportion to the thinning intensity (Bray and Gorham 1964). The residue from thinnings may add a large volume of C to the site, increasing the C-to-N ratio (Wollum and Davey 1975). Exhaustion of N by decomposing organisms might be expected but has not been reported.

Thinning Systems. Thinning systems involve intensity, tree selection, and assessment. The intensity of thinning has often been expressed in terms of the number or percentage of trees removed; the emphasis was thus on intermediate yields. A standard classification of thinnings applied widely by the British throughout the Tropics (Champion and Seth 1968) was as follows:

Thinning class	Trees removed
A. Light	Moribund, diseased, and suppressed
B. Moderate	Class A trees plus defective subdominants, whips, and branchy advance growth
C. Heavy	Class B trees plus all subdominants and defective codominants that can be removed without leaving a permanent gap in the canopy
D. Very heavy	Class C trees plus any dominants and codominants that can be removed, yet also retaining a well-spaced, evenly distributed stand of trees with good boles and crowns.

A measure that reflects both the trees and basal area removed is the Queensland thinning ratio (Bevege 1972):

$$\text{Ratio} = \frac{\text{(basal area removed divided by initial basal area)}}{\text{(stocking removed divided by initial stocking).}}$$

This ratio is sensitive to the size of the trees removed. Removing numerous small trees (a high percentage of stocking) produces a high denominator relative to the numerator and thus a low ratio. Under Queensland conditions, cleanings of the understory yield ratios of less than 0.43. Conventional low thinnings range in ratio from 0.43 to 0.56. Severe low thinnings to light crown thinnings range from 0.57 to 0.81. Severe crown thinnings yield ratios of more than 0.81.

Basal area, because it reflects tree size as well as number, is a better measure of the intensity of tree competition than is the number of trees. It is also simple to derive from tree-diameter measurements. As a measure of stand volume growth, however, basal area is insensitive to tree height. Use of basal area to compare volume in early and late thinnings may be biased if the trees removed early are shorter than those removed later (Assman 1970). However, merchantable height of tropical broadleaf trees for timber tends to be fixed early in the life of the tree by branching, making basal area and volume thereafter directly related.

However, if the main benefits from thinnings are to be increased quantity and quality production for the residual stand, it seems more logical to classify thinnings by the number or percentage of trees retained rather than removed. Thus, one early thinning classification proposed for India was as follows (Sagreiya 1944):

Type of thinning	Percentage of stems retained
Very light	50 to 75
Light	33 to 67
Moderate	25 to 50
Heavy	11 to 33
Very heavy	6 to 25

Thinnings have also been classified according to crown freedom (Singh 1947, 1960). Classes may be based on the percentage of the trees remaining that have free crowns.

Thinning intensity is in part dictated by the frequency of thinnings. The longer the interval, the more space should be left for each tree. To determine the appropriate spacing in India, crown spread of free-growing trees has been measured; a cord and plumb bob are used to assist the eye in determining the points on the ground that are vertically beneath the edges of the crown (Suri 1970a, 1975). Once crown spread is related mathematically to tree diameter, the spacing required between trees of any size can be determined for any projected future growth. For thinnings of *Shorea robusta* and *Tectona grandis,* made at a frequency designed to maintain 5 cm in d.b.h. growth, the required spacing for a range of mean diameters was then calculated and reduced 15 percent for triangular spacing (table 7–24).

If plantations with trees of a specified mean d.b.h. are thinned to an average triangular spacing, as shown in table 7–24, they presumably would grow well until the average d.b.h. is 10 cm larger. The differences between the two species reflect differences in their natural ratios of crown diameter to stem diameter in free-growing trees. *Tectona grandis* has a larger crown and needs wider spacing.

The crown-diameter-to-bole-diameter ratio indicates the needed intensity of thinning, but appropriate ratios must be determined not only by species but also by tree size. Studies of the rapidly growing, light-demanding tree *A. chinensis* in Sabah bear this out (Fox 1968b, 1971). Trees 10 cm in d.b.h. had a ratio of crown diameter to bole diameter of 93. At 20 cm in d.b.h., it was 52; at 30 cm in d.b.h., 39; and at 60 cm in d.b.h., 28. Nevertheless, a ratio as low as 18 has been found conducive to rapid growth of this species on the best sites.

Mathematical guides to thinning intensity have been sought for many decades. In preparing the all-India teak yield tables, Laurie (1938) derived a nearly linear formula for desired spacing as follows:

$$S = 0.2472\,d - 0.0014\,d^2 + 0.8656$$

where S = mean tree square spacing in meters and
d = mean diameter of crop trees in centimeters.

Thus, a stand with a mean crop-tree diameter of 15 cm should have an average spacing of approximately 4.25 m. For thinning, Laurie recommended that the minimum spacing be roughly 1.5 times the average so derived, which would be 6.4 m in the example used. A later formula for the spacing to leave after thinning, also derived for teak, was $S = 0.2\,d + 2.25$ (Takle and Muyumdar 1956). For the 15-cm mean diameter of the example, this formula gives a minimum spacing of 5.2 m. Matthews' spacing factor (1935) has been converted to the metric system for deriving mean tree distances as a guide to thinning regardless of species (Burger 1975):

D=d multipled by the square root of 7854 over BA

where D = mean distance between trees in meters
d = mean d.b.h. of the stand in meters
BA = mean basal area of the stand in square meters per hectare.

For a plantation with a mean d.b.h. of 30 cm and a mean basal area of 20 m^2/ha, the mean distance between trees is 5.95 m. The formula is obviously useful for determining the distance between crop trees that will be needed in the future to correspond to specified goals in terms of mean diameter and basal area. For example, if a mature stand is to average 50 cm in d.b.h. and have a basal area of 30 m^2/ha, the number of trees per hectare derived from the spacing distance (8.1 m) would be 175 with triangular spacing (153 × 1.15). An amount larger than this number (to allow for possible future losses) would apparently merit selection as crop trees, with corresponding release and possibly pruning.

Hart's spacing factor (Hart 1928) has been widely used as a guide to thinning. It is designated "S%" and expresses triangular spacing between trees as a percentage of "top height," the height of the tallest or largest 100 trees per hectare. The standard index of stocking (1.0) is S% = 20. Variants that have been used in the United Kingdom include the mean height of the largest 250 trees per hectare and square spacing instead of triangular (Hummel 1953). A number of stocking levels have been derived using the United Kingdom modification (table 7–31).

Through the use of Hart's factor, the frequency and intensity of thinnings can be guided by a fixed increment in height or by a fixed percentage of the trees removed at each thinning. Thinning according to height is illustrated in table 7–32, in which it is assumed that thinnings are to be made with each 2 m in height growth and that residual stocking is to correspond to S% = 20 (Hart 1928, Hummel 1953b). When thinning is being done according to the percentage of trees removed, with S% of 20 the maximum stocking allowed, removals may be pegged at 33 percent, as indicated in table 7–33.

Hart's spacing factor has been used in thinning teak plantations in Indonesia (Sudarmo 1957) and for *E. saligna* in South Africa (van Laar 1961). For *P. caribaea* in Suriname, thinning derived from S% is presumed to decline with age (Vincent 1970). A provisional practice for site I, starting when S% reaches 20 to 23, is illustrated in table 7–34.

Studies in Queensland, Australia, with *P. elliottii* and *P. taeda* led to the conclusion that basal area was a better basis than Hart's spacing factor for developing thinning regimes (Robinson 1968). When thinning is being done from below, there is a wide range of standing basal areas that yields maximum basal-area growth. Therefore, high volume production can be obtained from less growing stock than is generally considered necessary. The objective is to manage the stand at or below the lower limit of this basal-area range. This approach may lead to

Table 7–31.—Stocking levels adapted from Hart's spacing factor

S%	Stems per hectare at corresponding top heights (m) 10	15	20	25	Stocking
10	1,250	556	312	200	Very light
15	1,875	833	468	300	Light
20	2,500	1,111	625	400	Traditional
25	3,750	1,666	938	600	Heavy
30	6,250	2,778	1,562	1,000	Very heavy

Note : Hart's spacing factor (S%) expresses mean triangular spacing between trees as a percentage of "top height"—the height of the largest 100 trees per hectare (Hart 1928). This adaptation substitutes the mean height of the 250 largest trees (in d.b.h.) and uses square instead of triangular spacing.

unmerchantable thinnings or may lower the age of the first merchantable thinning.

Stands should be held at or near the "limiting basal area" until only the final crop trees remain, after which the basal area may be allowed to build up to any level desired (Bevege 1972). Thinning schedules allow stand density to oscillate about the limiting basal area so that basal-area growth over the thinning interval is near the maximum. An example would be to allow basal area to build up to 110 percent of the limiting level and then to thin it down to 90 percent of that level. The limiting basal area appears to be independent of age but varies directly with site for *P. elliottii* in Queensland (table 7–35).

Table 7–32.—Thinning regimes according to height growth

Top height (m)	Trees left (no./ha)	Trees removed (no./ha)	Percent removed
10	2,500	0	0
12	1,736	764	31
14	1,276	460	26
16	977	299	23
18	772	205	21
20	625	147	19
22	517	108	17
24	434	83	16
26	370	64	15
28	319	51	14
30	278	41	13

Source: Hart 1928, Hummel 1953.

Tree Selection. The natural approach to selecting trees to be thinned would be to leave those that appear most promising. However, identifying the most promising trees may call for more expertise than is generally available, so systematic tree selection deserves consideration.

Systematic thinning, removing trees in accordance with their location rather than their quality, proved about as satisfactory as selective thinning with *Araucaria angustifolia* in Misiones, Argentina (Cozzo 1958). Part of an 8-year-old plantation with a basal area of 22 m^2/ha was reduced to 20 m^2 by selective thinning and another part to 17 m^2 by systematic thinning. Six years later, both treatments had a basal area of 42 m^2/ha, indicating 14 percent faster basal-area growth for the systematic thinning. Mean diameter was also 1 cm greater for the systematic thinning than for the selective thinning. There is no reason to conclude that systematic thinning is better, but it may produce results as good as those produced

Table 7–33.—Thinning regime according to 33-percent tree removal (no./ha)

Top height (m)	Trees left	Trees removed
10.0	2,500	0
12.2	1,675	825
14.9	1,122	553
18.3	748	374
22.4	499	249
27.4	333	111

Source: Hart 1928, Hummel 1953b.

Table 7-34.—Provisional S% thinning for *Pinus caribaea* in Suriname

Age (yr)	Top height (m)	S% residual (%)	Trees left (no./ha)
6	14.7	29.2	625
9	20.0	26.0	425
14	24.5	25.3	300
20	27.3	24.8	250
30	30.1	0	0

Source: Vincent 1970.
Note: S% = Hart's spacing factor (Hart 1928).

by selective thinning and, therefore, may be more practical under some circumstances. Such circumstances seem to exist in plantations where survival is high, rows are well laid out, tree form is good, and there are plenty of good crop trees. Row thinning 14-year-old *P. taeda* in the Southern United States was superior to selective thinning simply because it was much easier to apply (Grano 1971).

Triangular spacing can be adapted to facilitate row thinnings (Wong 1966a). The distance between final lines should be 0.866 times the final crown diameter, and the spacing within final rows should equal the final crown diameter. If, for example, the final d.b.h. of the crop trees is to be 0.6 m and the crown-diameter-to-bole-diameter ratio is 20, the final crown diameter would be 12 m. This amount multiplied by 0.866 gives a line spacing of 10.4 m. Within rows, the spacing would be 12 m, making the final spacing 10.4 by 12.0 m. Initial spacing on these lines can be one-fourth of these distances (2.6 by 3.0 m), allowing for early systematic and later selective thinnings.

Selective thinnings generally are "from below," that is, trees that have the poorest performance (the slowest growth) and that are likely to continue to be outstripped by the larger trees are removed. The removal of suppressed and dominated trees can normally be expected to increase the growth of the residual trees, because those removed are heavy respirers (Assman 1970). The result is more uniform stand structure. However, in plantations that have a very irregular upper story or that are so young that only the large trees are marketable, there may be reason to thin "from above" rather than from below. Such thinnings may influence basal area more than those from below. In first-generation plantations, variation in tree quality is so great that selection by form is desirable, removing abnormal trees whether large or small.

In a study of *P. taeda* in the Southern United States, 20-year-old plantations were thinned to 16, 20, and 23 m^2/ha of basal area, some from below and some from above (Bassett 1966). Yields at age 35 were nearly the same in volume and quality for the various treatments. Thinning from above left only 40 to 54 percent of the former dominants or codominants as crop trees versus 98 to 100 percent in plantations thinned from below. Thinning from above led to a slightly smaller mean final d.b.h., shorter merchantable heights, and smaller crowns, but no difference in mean form class.

A hybrid system of selecting crop trees is termed "eclectic." It utilizes plantation rows in one direction. Groups of trees within rows are selected to ensure relatively uniform distribution. The original system, called the Scottish Eclectic System, has been adapted and modified in Queensland and elsewhere. The eclectic system only selects crop trees. The degree to which they are then released may be decided concurrently but as a separate process.

Table 7-35.—Site effects on limiting basal-area growth of *Pinus elliottii* in Queensland, Australia

Site index[a]	Limiting basal area (m^2/ha)	Maximum basal-area growth (m^2/ha/yr) Age 10 yr.	Age 20 yr.	Age 30 yr.
15	21.6	1.4	1.0	0.5
21	27.1	3.1	1.3	0.8
27	32.7	3.8	1.7	1.0

Source: Bevege 1972.
[a]Site index is defined locally by tree height at a selected age.

The process of tree selection under the eclectic system involves walking down each plantation row and selecting crop trees within groups of adjacent trees (including blanks) within each row; groups number four or five, depending on the number of crop trees desired (Pudden 1955, Sawyer 1962). Using the quartet system, the best tree in the first group of four is tentatively selected. Trees are selected according to size, merchantable height, straightness, lack of stem fluting, number of small branches, and absence of injuries. If it is tree number 1, the selection is final, and the next quartet (trees 5, 6, 7, and 8) is then reviewed. If the tree selected in the first quartet is number 3, the selection is only tentative until it is compared with the additional members of its quartet in a forward direction, namely trees numbered 4, 5, and 6. If number 5 or 6 is superior (number 4 having been already found inferior), it substitutes for number 3 as the final select tree. If not, number 3 serves as the final selection, and the next quartet then begins with tree number 5. If tree 5 or 6 is selected, the next quartet begins with the next tree (or blank) in line, and the procedure continues as for quartets 1 through 4.

The next step in the Scottish Eclectic System is choosing the crop trees from among the selected trees. About 150 stems per hectare are so designated, the most promising spaced about 10 m apart (MacDonald 1961). Dominant trees competing with them are marked for removal. From among the smaller trees closely surrounding the crop trees, a few healthy, straight poles are selected, which, if given sufficient light, are likely to follow behind the crop trees. These followers are "relieved" by removing any larger or equal-sized trees (other than those selected for the crop) that would compete seriously with the selected trees.

Crop trees may be marked permanently to eliminate needless repetition of the selection process. However, some managers prefer periodic reselection to consider changes in the vigor of individual trees (Assman 1970).

Another systematic way to release crop trees within a plantation is based on their spacing and diameters. Sagreiya (1946b) long ago proposed this formula for releasing teak crop trees: If the distance between a crop tree and its neighbor (in meters) is less than the sum of their d.b.h. (in centimeters) times 0.12 plus 1.2, the noncrop tree should be removed. For example, if a crop tree is 25 cm in d.b.h., and its neighbor is 21 cm in d.b.h., multiplying their sum (46) by 0.12 and adding 1.2 gives 6.7 m as their necessary separation. If spaced closer, the neighbor is removed.

The number of crop trees to select will vary with the desired tree sizes of future harvests, intermediate and final. If 100 trees per hectare are wanted for a final harvest of sawtimber, about twice as many pole-sized trees should be selected (Assman 1970).

Thinning practice in the plantations of South Africa attracted wide attention as a result of conclusions reached in a series of experiments by Craib (1939). It has since continued to provide guidance wherever intensive thinning is appropriate. Although the densest stands always show the highest mean total annual growth, marketable growth (that above a certain stem diameter) is more important (Marsh 1957). Evidence that the production of small trees in plantations was wasteful, because they did not yield much revenue even where marketable, led Craib to recommend heavier and earlier thinnings than were traditional.

Research on thinnings of *P. patula* in 20 areas throughout South Africa showed that in plantations of 3,000 trees per hectare, the dominant trees suffered from suppression from the third year on (Anon. 1947c). In plantations of 1,500 trees per hectare, suppression of the dominants began in the fourth year. With 750 trees, suppression began in the sixth year; with 500, in the seventh; with 370, in the eighth; and with 250, in the ninth. These findings support Craib's recommendations for early and heavy thinning.

Later, Craib (1947) concluded that neither species nor site influences the age at which nutritional competition in a stand of a given density commences. He suspected that even climate makes little difference. He also concluded that as density of stocking decreases, mean diameter increases. This increase, due to increased growing space, is small during youth and increases with advancing age. As stocking density decreases, mean height increases—but only slightly. As stocking density decreases, total volume production per unit of land area also decreases. Maximum sawtimber volume is generally produced by stockings of 750 to 1,250 trees per hectare, or initial spacings of 2.7 by 2.7 m to 3.7 by 3.7 m. Maximum early sawlog returns come from wide, not close, spacing. The goal has been uniform ring width, about 2.4 cm without knots, grown over an unpruned core of wide-ringed wood. Even where the aim is for maximum sawtimber volume, the bulk of the yield is in stems of lower value.

Craib (1947) further concluded that the longer thinning is delayed, the greater will be the loss in total volume growth thereafter. Under local conditions, financial returns from heavily thinned stands were likely to be much greater than those from lightly thinned stands. For *P. caribaea,* he recommended the schedules shown in table 7–36.

In a review of Craib's methods, Hiley (1948) concluded that such early thinning removes the option of selecting trees for quality and requires much pruning; but under South African conditions, these were not serious problems. The thinnings prescribed were so early that they yielded little or no marketable wood. Nevertheless, Hiley concluded that wood quality does not suffer, because it is a function of age, not growth rate.

South African thinning practice has been defended because of a lack of markets for small material (Villiers and others 1961). Wood defects, such as high longitudinal shrinkage, uneven texture, knottiness, compression wood, and spiral grain, all exist to some degree, but occur chiefly in the first 5-year core of juvenile wood. Planting at 2.7 by 2.7 m instead of 3.7 by 3.7 m reduces the diameter of this defective core by only 2.5 cm. Moreover, the lower yield (17 percent) with the wider spacing is more than compensated for by a 76 percent higher value for the total harvest at 40 years.

Table 7–36.—Thinning schedules for *Pinus caribaea* in South Africa

Age (yr)	No. of trees to leave per hectare	
	Site I[a]	Site III
0	1,310	740
6	all	440
8	740	all
12	490	all
18	320	all
20	all	all
25	230	all
30	0	210
35	0	0

Source: Craib 1947.

[a]Site classes are defined locally on the basis of tree height at a selected age.

The appearance of pulpwood markets in South Africa changed the emphasis on large diameters recommended by Craib (Johnston 1962). Craib's stands, about 65 percent sawlogs, yielded too little pulpwood to support processing facilities. The new pulpwood markets dictated less concern with spiral grain and knottiness than with fiber length and fibril angle. Spacing was reduced to 2.1 by 2.1 m to increase selectivity for the final crop, to provide more pulpwood, to reduce taper and knot diameter, and to help suppress the ground vegetation. Closer spacing does not reduce the amount of juvenile wood but merely puts it on more trees (Johnston 1962).

By 1971, further market shifts toward smaller trees had led to closer spacing and lighter thinnings (Villiers 1971). More recent practice in South Africa with *E. grandis* for sawlogs and veneer logs has been to plant at 2.7 by 2.7 m, or 1,370 trees per hectare, thin to 750 per hectare at 3 to 5 years, then to 500 per hectare at 7 to 9 years, and to 300 per hectare at 11 to 13 years; the rotation length is 14 to 30 years (Poynton 1981).

Thinning studies with teak date back to 1900 (Krishnaswamy 1953). Teak is intolerant of crown "friction" and incapable of maintaining a closed canopy except early in life (Mirchandani 1941). A mixed understory normally develops and does not interfere with the growth of the teak. On good sites in India, teak has been thinned at 3, 6, 10, 18, 30, and 44 years (Krishnaswamy 1953). Heavy thinnings are recommended. Examples of thinning schedules are presented in appendix J.

Pruning

Pruning, removing branches to improve tree form or wood quality, has most often been done in the Tropics in conifer plantations. Other timber species, whether in natural or planted forests, tend to self-prune at conventional spacings and thus seldom require artificial pruning.

To improve wood quality, pruning must be done early, before the stems are so large that little knot-free wood can be produced before maturity. A good guide is the diameter of the knotty core that will be acceptable, generally 10 to 15 cm. Achieving this goal requires not only early pruning but also progressive pruning as the trees grow in height and as the critical diameter rises up the stem. In reality, the knotty core may be up to 5 cm larger than 15 cm when the pruning is done because of the area of occlusion (wound healing) over pruned stems (Robinson 1968). For early pruning of *C. lusitanica* in east Africa, a U-shaped stem caliper (or pruning gauge) was developed to facilitate locating the upper limit of the prescribed knotty core (Graham 1945).

For most conifers in east Africa, the best time to start pruning is at age 5 to 7 (Pudden 1955). With *Cupressus,* pruning may begin as early as the second year and be repeated every 2 years thereafter. Rapidly growing trees such as *E. saligna* must be pruned more than once per year (Luckhoff 1967). Less frequent, heavier prunings tend to set up undesirable wood stresses in this species.

Early pruning also promotes rapid occlusion. In South Africa, *P. caribaea* at age 4 heals over to straight wood on 84 percent of the wounds in 5 years and 100 percent in 10 years (Anon. 1954c). When trees were pruned at age 15, only 30 percent of the wounds healed over in 5 years and only 80 percent even after 11 years.

The time of year that pruning is done affects the rapidity of wound occlusion and rebranching. In Kenya, rapid occlusion occurs when pruning is done just before the rainy season (Anon. 1954i). In Puerto Rico, epicormic branching in teak resulting from pruning is most vigorous in the dry period immediately preceding leaffall (February) and least vigorous during the rainy period (August) (Briscoe and Nobles 1966). The influence of the season of pruning on the rapidity of wound occlusion is seen in data from a 3-year-old *C. lusitanica* plantation in Kenya (Anon. 1954i):

Month pruned	Months to occlusion
February	41
March	41
April	18
June	18
August	25
October	29
December	40

Because trees will benefit from pruning only if they are allowed to grow a long period thereafter, trees soon to be thinned should not be pruned, except perhaps to a height of about 2 m to provide easy access. Higher (and more costly) pruning should be limited to the potentially final crop trees. For example, pruning *A. cunninghamii* in Queensland, Australia, has been restricted to 620 trees per hectare to a height of 3 m, and 400 trees per hectare to 6.7 m, for a final crop expected to be 185 trees per hectare (Grenning 1957). For the southern pines of the United States, pruning of 370 to 490 trees per hectare has been recommended (Wakeley 1954).

Pruning intensity has been widely studied. When pruning is done earlier and higher, the prospect for reducing tree growth is greater, but the proportion of knot-free wood is also greater. It was concluded long ago that pruning southern pines in the United States to 5 m when the trees are 10 m tall promises greatly increased profits from plantations producing sawtimber and veneer bolts (Wakeley 1954).

A. cunninghamii has commonly been pruned to 7 m in height in Queensland (Grenning 1957) as have other conifers in South Africa (Johnston 1962). Even at this height, much of the wood in mature trees 30 m tall is still knotty.

Pruning intensity is usually measured in terms of the percentage of the tree's total height. A test of *P. elliottii* in Misiones, Argentina, showed that pruning 5.5 m tall trees to half their total height did not reduce diameter growth during the subsequent 3 years (Molino 1972). Even pruning to three-quarters of the total height prompted no significant reduction. In Kenya, *C. lusitanica* has been pruned to about 60 percent of the total height; on pines, one whorl has been left below the 60-percent level (Pudden 1955). The standard of half-tree height has also been used with *G. arborea* at Monte Dourado, Brazil (Anon. 1979e). South African experience suggests that the guide there should be mean tree height, not height of the dominants (Sherry 1961).

Experience with *P. elliottii* and *P. patula* in South Africa showed that pruning up to one-third of the live crown at age 4.5 years caused only a small loss in d.b.h. growth, and this decline lasted only 15 months (Sherry 1961). *Eucalyptus saligna* is capable of surviving after pruning up to 40 percent of the live crown, but wood stresses may result. Studies with *P. elliottii* and *P. taeda* in Queensland indicate that if significant losses in diameter growth are to be avoided, a knotty core of less than 15 cm in diameter is unattainable (Robinson 1968). In Kenya, the same conclusion was reached where pruning of conifers was no more than half the total height (Pudden 1955).

Pruning of *Simarouba amara* in Suriname was limited by a tendency for new branches to develop immediately above the uppermost whorl that had been pruned (Schulz and Vink 1966).

In a study of *P. elliottii* in southern Brazil, Fishwick (1977a) set, as a primary standard, a maximum diameter outside bark of stem core within which all knots (branch stubs) must be confined. Having set two of these maximum diameters, 10 and 15 cm, he applied the necessary treatments, attempting to keep the prunings to a reasonable number and to avoid excessive removal of the live crowns. He concluded that the time to prune should be dictated by the average total height of the 500 best trees per hectare. To confine knots to a 15-cm core, the first pruning should be done to a height of 5 m when the total height reaches 9 to 10 m (age 6 to 7 years), and the second and final pruning should be done to 7 m when the total height is 12 to 13 m, about 2 years later. For a 10-cm core, four prunings would be needed, to 2 m (total height 5 to 6 m), 4 m (total height 7 m), 5.5 m (total height 9 m), and 7 m (total height 11 to 12 m).

The response of plantations to pruning is complex. A few general observations from South Africa follow (Craib 1947):

- Pruning live crowns retards diameter growth much more than height growth. Removing 25 percent of a vigorous crown has no effect on diameter or height growth.
- Removing 50 percent of a vigorous crown has a significant effect only on diameter growth.
- Removing 75 percent of a vigorous crown significantly affects both diameter and height growth.
- Recovery of normal growth is rapid, even in the worst case, by the fourth year.
- Loss of volume as a result of pruning is never regained.

Similar observations were made on *P. elliottii* in the Southeastern United States (Bennett 1955). Diameter growth decreased very gradually after the elimination of up to 50 percent of the live tree crowns, but as pruning intensity progressed from 50 to 90 percent, diameter growth decreased rapidly. However, height growth was little affected by the loss of up to 80 percent of the live crown. Studies of the 2-year response of a 4.5-year-old plantation of *A. cunninghamii* in Nigeria produced similar results (Anon. 1961a).

Pruning in a 7.5-year-old plantation of *P. patula* in Malawi (Foot 1968b) led to the growth responses summarized in table 7–37.

Experience in South Africa has shown that selective pruning puts the pruned trees at a disadvantage relative to their unpruned competitors (Luckhoff 1949). Selective pruning also much more severely affects growth of 4-year-old trees than the growth of 8-year-old trees. If all the trees are pruned, even to the extent of 75 percent of their live crowns, diameter growth recovers in only 2 years. But with selective pruning, recovery may take 5 years or longer. The effect of selective pruning on diameter growth and the delay in recovery is less on poor sites than on good sites.

The detrimental effect of pruning on diameter growth can be greatly reduced by thinning just before pruning (Sherry 1961). In South Africa, it is recommended that plantations of *P. elliottii* and *P. patula* be reduced to 860 to 980 stems per hectare before the first pruning. After pruning, the radial stem growth was greatest immediately below the lowest branch and decreased with distance from the crown. The heavy pruning thus reduced taper. A pruning schedule proposed for *P. elliottii* and *P. patula* in South Africa is summarized in table 7–38 (Sherry 1961).

Studies of *P. patula* in South Africa have shown that pruning to 7 m does not increase branch size above the level of pruning, which is from 8 to 12 m above the ground (Villiers and others 1961). Pruning 30 to 50 percent of the live crowns of *E. grandis* in South Africa had no effect on the specific gravity of the wood but did prevent trees from attaining pole size by age 10 (Schonau 1974).

Although pruning *C. lusitanica* in Kenya was found to depress d.b.h. and height growth, it appears that more high-pruned trees can be carried than low-pruned trees (Pudden 1957b).

Pruning practice is straightforward. Where low branches are persistent, all trees are generally pruned to head height for easy access as soon as this can be done without exceeding half their total height. Thereafter, the selected crop trees are pruned repeatedly to the established standard (Pudden 1955). Thinning is generally

Table 7–37.—Growth responses to pruning of 7-1/2-year-old *Pinus patula* in Malawi

Yrs. since pruning	Growth response as percentage of control			
	Pruned to 18% of height (control)	Pruned to 42% of height	Pruned to 57% of height	Pruned to 77% of height
	Basal area growth			
1	100	81	52	14
2	100	84	60	21
3	100	96	87	49
4	100	112	126	92
	Height growth			
1	100	88	82	64
2	100	95	95	81
3	100	101	94	81
4	100	107	99	100

Source: Foot 1968b.

concurrent, confining pruning to the most promising trees. Pruning is normally done manually with curved pruning saws mounted on long poles. The final pruning height is usually less than half the total tree height. Pruning clearly should stop where the stem ceases to be straight. A practical limitation of 5 to 7 m on pruning height is dictated by the pruning pole length. Pruned limbs should be removed from the base of crop trees to reduce fire risk. Pruning is done close to the stem to minimize the size of the knotty core and to accelerate occlusion. Special care is required with some genera such as *Cupressus* and *Tectona* to minimize wounds that expose wood to insects and decay.

Coppice

The capacity of many plantation species to sprout vigorously after harvest to an advanced age can minimize the cost of regeneration and has led to various forms of coppice management. Not only is such regeneration less expensive, but coppice crops may produce higher yields sooner. Early experiments with 13 species of *Eucalyptus* in Guarani, Brazil, yielded 15 to 33 m^3/ha/yr from the seedling crop at age 7, whereas the first coppice crop, at age 6, yielded 17 to 42 m^3/ha/yr (Navarro de Andrade 1939).

The advantages of coppices are clear with Mysore gum, a variety of *Eucalyptus* with morphological characteristics of *E. botryoides, E. camaldulensis, E. robusta,* and *E. tereticornis* that is widely planted in India. Because the species is grown mostly for pulpwood and firewood, its productivity is measured in terms of biomass. At a rotation of 8 years, a test plantation yielded a mean annual increment of 19.6 t/ha/yr green weight (Singh 1967). At 14 years, the growth was 14.5 t/ha/yr. However, if the plantation is cut at 8 years and coppiced for 6 more, the 14-year yield averages 20.7 t/ha/yr; the coppice rotation averaging 22 t/ha/yr.

Coppicing proved highly productive in *Eucalyptus* shelterwood plantations that covered more than 22,000 ha at Belgo Mineira, Brazil (Osse 1961). The practice was to make a first cut at age 8 or 9, yielding 210 m^3/ha, or 23 to 26 m^3/ha/yr. The second cut, made 7 years later

Table 7–38.—Pruning schedule for *Pinus elliottii* and *P. patula* in South Africa

Tree height (m)	Pruning height (m)	Living crown removed (%)
4.9	1.8	37.5
7.3	3.7	33.3
9.1	5.5	33.3
11.0	7.3	33.3
12.8	9.1	33.3

Source: Sherry 1961.

at age 15 or 16, yielded 250 m^3/ha, or 36 m^3/ha/yr. The third cut, at age 22, yielded 200 m^3/ha, or 29 to 33 m^3/ha/yr. The aggregate 22-year yield was 30 m^3/ha/yr.

An extensive test with more than a thousand growth plots in the Brazilian States of Paraiba and Sao Paulo showed superior coppice yields on a variety of rotations for *E. alba, E. grandis, E. rostrata, E. saligna,* and *E. tereticornis* (table 7–39; Heinsdijk 1972). Yield tables shed light on wood production potentials of *Eucalyptus* for both the seedling crop and the first coppice. Note that MAI culminates earlier and higher in coppices than in the first crops. The initial difference was due chiefly to the number of stems, not differences in diameters. At 4 years, the coppice stands had about 25 percent more basal area, an excess that disappeared in about year 8. By year 14, the coppice basal area was 10 to 15 percent less than that of the first crop, and MAI was declining much more sharply because of slower diameter growth.

Coppicing has long been applied to *Senna siamea* and *T. grandis* in the Ibadan fuel plantations of Nigeria (Collier and Lockie 1940). Started in about 1924, these plantations were managed for decades by clearcutting and coppicing on a 10-year rotation.

The early sprouting vigor of *L. leucocephala* was illustrated by a test in India (Pathak and others 1981). The mean annual increment in bole and branch biomass per tree of the seedling crop at age 3 was 1.73 kg, but that rate was equalled by coppice trees in half that time.

The number of coppice crops that may be obtained from a planting depends on the longevity of the coppicing power of the stumps. The Ibadan fuelwood plantations in Nigeria have produced in some areas as many six successive coppice crops over 53 years (King 1966). Tests with blue gum *(E. globulus)* in Madras, India, showed the cost in terms of reduced yield of continuing coppice rotations for many years. With 15-year rotations for fuelwood, the yield dropped 9 percent in the third rotation and 20 percent in the fourth (Krishnaswamy 1957b). In Brazil and South Africa, the third coppice crop of *Eucalyptus* is generally the last, each crop being made up of fewer trees. The same three-crop scheme was proposed for *G. arborea* at Monte Dourado, Brazil (Anon. 1979e).

Early Brazilian experience with an 8-year-old coppice of eight species of *Eucalyptus* at Rio Claro indicated that the number of sprouts left had little effect on yield (Navarro de Andrade 1939). Coppices where only one sprout was

Table 7–39.—Wood production potentials of *Eucalyptus* spp. in Brazil

	No. of trees per hectare		Mean d.b.h. (cm)		Mean annual increment (m^3/ha/yr)	
Age (yr)	1st crop	1st coppice	1st crop	1st coppice	1st crop	1st coppice
			Site 1 (24–28 m at 8 yr)			
4	1,640	2,170	10.0	9.9	34	36
5	1,340	1,570	12.4	12.4	42	66
8	980	1,340	16.6	13.7	56	65
11	860	1,180	19.1	15.0	56	58
14	790	1,100	20.4	15.9	54	54
			Site 3 (16–20 m at 8 yr)			
4	1,760	2,580	9.2	8.6	16	28
5	1,430	1,880	11.1	10.8	20	33
8	1,060	1,600	15.0	12.1	26	32
11	920	1,400	16.9	13.4	26	29
14	850	1,310	18.1	13.8	25	26

Source: Heinsdijk 1972.

left per stump produced trees 21 to 25 cm in d.b.h. and a basal area of 34 to 70 m²/ha. Coppices with several sprouts per stool produced trees 18 to 21 cm in d.b.h. and a basal area of 20 to 72 m²/ha.

In Kenya, the usual practice with *E. saligna* fuelwood coppices has been to thin to two sprouts per stump (Dyson 1974). Leaving three sprouts gives a higher gross yield, but where the size of the fuel billet is important, two sprouts are preferable (Howland 1969). In one test, stumps were thinned to one sprout, three sprouts, or left unthinned (an average of 5.5 sprouts) and growth was compared at age 6-1/4 years (table 7–40).

With *E. saligna* in South Africa, leaving only two shoots per stump can obviate the decline in volume production that occurs with an increasing number of coppice generations (van Laar 1961). Another factor affecting the number of shoots left per stump is harvesting efficiency. In Australia, the use of mechanized systems may favor the single stump even if yields are lower (Carter 1974).

A special type of coppice has been applied to *Shorea robusta* in Indian taungya plantings (Huq 1945). The tree commonly puts up several basal shoots, particularly when fully exposed to side light. It was found that cutting the sprouts back at age 5 produced a single straight sprout without extra shoots. Coppicing of *Paulownia tomentosa* in the Philippines by cutting back the 1-year leaders also subsequently leads to an extremely straight stem.

South African coppicing experience with *E. grandis* for short-rotation crops has led to the following conclusions (Stubbings and Schonau 1980):

- For high yields, initial survival must be 95 percent or higher. If less, immediate replanting is necessary.
- High stumps lead to poor coppice attachment.
- Stump mortality averages about 5 percent per rotation. It is greater if felling is done during the driest part of the year.
- Shoots should not be thinned during the windy season.
- Shoots should be thinned in two steps, once when dominant height is 3 to 4 m and a second time when dominant height is 7 to 8 m.
- Retained shoots should be dominants of good form arising as low on the stump as possible.
- If more than one shoot is selected, the diameters should differ by no more than 1 cm. A wide range in shoot diameters cannot be evened up.

A special case of coppice management has been the production of pitprops of *G. arborea* in eastern Nigeria. About 6 months after harvesting, all but the best three or four shoots per stump are removed (Pringle 1950). Six months later, these are reduced to one per stump. The rotation is 10 to 15 years, and four-fifths of the remaining sprouts have been of pitprop quality.

The coppice-with-standards method (leaving superior trees after an early selective harvest) has been tested in what is now Rwanda and Burundi, with *E. maideni* and *E. saligna* on sites too poor for high forests (Reynders

Table 7–40.—Thinning effects on a *Eucalyptus saligna* coppice in Kenya

Index	Unthinned	Three sprouts per stump	One sprout per stump
Basal area (m²/ha)	5.9	5.5	3.6
Volume by d.b.h.[a] (m³/ha)			
>5 cm in d.b.h.	32.8	34.9	24.6
>10 cm in d.b.h.	27.2	31.1	24.1
>15 cm in d.b.h.	3.0	2.1	9.6

Source: Dyson 1974.
Note: Stand age = 6.25 years.
[a]Inside bark to a 5-cm top diameter.

1963). The products were used for house posts and other local timber needs, including fuel. The best cutting treatment left 200 to 250 standards per hectare. The standards were later thinned to stimulate further coppicing.

Bamboo Management

Experience in managing natural and planted bamboo groves has led to a few conclusions applicable to *D. strictus,* by far the most widely distributed and important of all bamboo species (Dass 1960). Harvesting can begin 8 to 15 years after planting from seeds (Singh, S. P. 1973). This species responds well to heavy thinnings (table 7–41; Wilson 1936). Felling cycles range from 2 to 4 years (Prasad 1948). New culms are not felled, and some old culms are retained. The life of this species (between flowerings) varies by locality from 21 to 38 years. The stems are suitable for pulp and make good paper up to 4 years after flowering.

Experiments in India with *Dendrocalamus* harvesting from 1934 to 1947 led to the following conclusions (Krishnaswamy 1956a):

1. Felling cycles of 2, 3, and 4 years produced about the same number of new culms. The poorest performance came from the 2-year cycle, which is also the most costly.

2. With a 3-year felling cycle, the quality of both the harvested and new culms was unaffected by cutting intensity, which ranged from leaving only the same number of old culms as new culms to leaving eight times as many old culms as new.

Table 7–41.—Postthinning recovery of *Dendrocalamus strictus*

No. of culms per clump		
Before Thinning	After thinning	New in 4 yr.
19	7	20
68	13	45
96	13	64
105	13	45
146	24	96

Source: Wilson 1936.

3. With a 5-year felling cycle, when no old culms were reserved, the new culms were fewer in number and inferior in quality to those produced in areas where one to eight times as many old culms as new were preserved.

The advantages of longer felling cycles became apparent with later growth studies in India (Kaul 1963). The number of new culms per clump in the fourth year after felling was almost triple the number in the second year. By 1967, the felling cycle was generally 3 to 4 years, and about 66 percent of the existing culms were removed in each felling (Zakiruddin 1967).

Another commonly planted species of bamboo is *Bambusa vulgaris.* There are two periods of growth each year, and the culms reach full height in 12 to 13 weeks, assuming their normal appearance in 8 to 9 months. The first partial harvest should be delayed 6 or 7 years and could be scheduled every 2 to 3 years thereafter (Groulez 1966). In what was formerly Zaire, the species has been planted at 5 by 5 m and produced from 22 to 31 t/ha/yr fresh weight (11 to 16 dry weight). The cellulose yield is from 6.6 to 9.4 t/ha/yr. Under optimum conditions, production might be increased 50 percent (Maudoux and Abeels 1958).

Bambusa tulda matures from seedlings in 8 to 10 years and lends itself to a 4-year felling cycle (Prasad 1948). Culms that are less than 1 year old should not be cut, and at least six mature culms per clump should be left. No culm with rhizomes should be removed. Stumps should be less than 30 cm in height.

Bambusa arundinaria is similarly managed (Prasad 1948). Mature culms are ready by the fifth year. Selection felling—a thinning out of the older culms—is the only practical method of management. Cutting more than half the culms jeopardizes the health of the clump and requires a recovery period of several years. The cutting cycle is 3 to 4 years, and the life cycle is 30 to 32 years. Felling should leave stumps no higher than 30 cm, take no culms less than 18 months old, and leave at least eight culms per clump plus the exterior shoots.

Harvesting

In forest plantations, the current annual growth of usable wood volume generally rises sharply in the early years and then drops gradually as the canopy closes and the trees compete for space or as thinning progressively reduces the stand volume. The mean annual volume growth—derived from total volume (plus thinnings) divided by age—rises more slowly. The curve of mean annual value growth (or prospective financial returns) rises more slowly still, but the greater value per unit of volume sustains the curve longer.

The curves of production and economic yields are flat enough that they rarely affect the decision concerning precisely when to harvest most plantations. They are most significant for large-scale, cellulose operations, where extensive planted areas provide a sustained supply to a large industry. Even there, however, fluctuations in the market (or temporary social conditions) may influence the precise timing of the harvest more than volume production or stumpage return.

If plantations are normally harvested after the culmination of mean annual volume growth, harvesting should be done before the culmination of mean annual value growth, that point where decline in vigor offsets increasing value per unit of volume because of tree size. For pulpwood, the limit is more likely to be decided by such factors as the maximum diameter acceptable to chippers. For larger products, the capacity of logging equipment and carrying charges may dictate the upper tree-size limit.

The task of moving harvested material to an all-weather road is so large a part of production costs that feasibility and practical alternatives should be explored before planting sites are chosen. Mechanized equipment is virtually essential. If the terrain and layout of the plantation permit the equipment to be operated between the rows, both thinning and harvesting are greatly facilitated. Otherwise, winching with cables, either ground lines or some form of skyline, is needed. Both of these systems operate best at relatively short distances from haul roads and with large volumes of high stumpage value per unit of land area.

Yields

The volume yield standards by which plantations in the Tropics are generally judged are those of eucalypts and pines. Extensive research in Brazil (Heinsdijk and others 1965) indicates that first-crop eucalypts at age 8 produced on the four best site classes an MAI ranging from 16 to 52 m^3 (without bark). An example is seen in table 7–42, based on plantations in Sao Paulo (Simoes and others 1980). Clones of *E. grandis* and *E. urophylla* in Espiritu Santo have yielded as high as 73 m^3/ha/yr (Rance 1976), and higher yields are reported from specially selected clones of Aracruz, near Victoria, Brazil.

Yields of 10 species of *Eucalyptus* in Brazil averaged as follows: seedling rotation, 7 years—18.3 m^3/ha/yr; first coppice, 7 to 14 years—17.0 m^3/ha/yr; and second coppice, 14 to 21 years—14.7 m^3/ha/yr (Ayling and Martins 1981).

Gmelina arborea at Jari, in the Amazon Basin, attains a maximum MAI of 38 m^3/ha of pulpwood at age 6. For *E. deglupta,* the comparable yield at the same age is 42 m^3/ha. For *P. caribaea* at age 12, it is 25 m^3/ha (Woessner 1980a)

Information on plantation yields of a few species common throughout the Tropics has recently been compiled (Lugo and others 1988). Data of general interest from that study, arranged by Holdridge's life zones (Holdridge 1947), appear in table 7–43.

Regeneration

Plantations seldom regenerate naturally, except by coppice, although seedlings of many genera, such as *Gmelina* and *Swietenia,* may appear in abundance beneath old plantations after thinning. These new trees may benefit from natural mass selection in the previous crop but should sooner or later be surpassed in quality by intensively selected and bred progeny. Both *Gmelina* and *Swietenia* have been successfully grafted. The high cost of plantations demands the use of such superior stock.

Plantations should be regenerated at least partly with the best trees in existing plantations. These are of proven adaptability and, if from selected seed sources, should provide superior genotypes as well as phenotypes. Superiority may be in growth rate, form, disease and insect resistance, and wood quality. Improvement of 50 percent or more may be expected.

Genetic quality may be improved in several ways, as is exemplified by Cuba's program with *P. caribaea caribaea* (Betancourt-Barroso 1972), which began in 1965. Included in this program are provenance studies, mass selection, superior-tree selection, progeny studies, vegetative reproduction of superior genotypes, and clonal seed orchards. At the time of this report, 11 provenances had been compared, 1,100 ha of seed source areas had

Table 7–42.—*Eucalyptus* plantation yields in Sao Paulo, Brazil

Species	Age 5 yr. 1.5 by 3 m	Age 5 yr. 2 by 3 m	Age 9 yr. 1.5 by 3 m	Age 9 yr. 2 by 3 m
	Steres per hectare per yr			
E. grandis	74	69	59	60
E. saligna	68	59	45	42
	Tonnes per hectare per yr			
E. grandis	21	22	17	17
E. saligna	20	19	13	13

Source: Simoes and others 1980.

been mass selected, and 118 superior phenotypes had been identified. The Forestry Division of Trinidad has been working along similar lines with *P. caribaea hondurensis* since 1959 (Lackhan 1976). Vegetative propagation for seed orchards has been done chiefly by grafting.

Mass selection of nursery seedlings of *P. elliottii* in Brazil led to more rapid early growth in the forests (Shimizu and others 1977). Nine-month-old seedlings were selected in the nursery at the rate of 1:3,500. Their superiority in height increased to 45 percent in the second year. This advantage could be important in reducing the period of weeding.

Insects and Diseases

No attempt is made here to describe plantation pests and diseases or to prescribe treatments. They are important nevertheless. Locally, pathologists and entomologists at agricultural research stations are available to foresters in the Tropics. Several publications listed in appendix K may also prove useful.

In summary, it should be evident that plantation management is a necessary obligation after the initial investment in establishment. It should also be apparent that there are many options and intensities to choose from. Despite vast experience gleaned under many different conditions, foresters must test new projects before applying practices that have been successful in other places.

Table 7–43.—Typical plantation yields of tropical species by Holdridge's life zones

Mean temperature, annual rainfall	Species	No. of plantations	Yield at 10 yr. (m^3/ha/yr) Maximum	Yield at 10 yr. (m^3/ha/yr) Average
>24° C, 2–4 m	*P. caribaea*	47	31	22
>24° C, 1–2 m	*P. caribaea*	89	25	13
18–24° C, 2–4 m	*P. caribaea*	194	40	25
18–24° C, 1–2 m	*P. caribaea*	112	38	20
	P. patula	79	40	21
	Eucalyptus grandis	18	21	15
	Cupressus lusitanica	24	21	10
12–18° C, 1–2 m	*P. patula*	100	33	20
	C. lusitanica	88	24	13

Source: Holdridge 1947, Lugo and others 1988.