Chapter 27
Review
Plantation Forestry

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Abstract Planting trees in tropical countries is becoming an increasingly important forestry activity as many tropical countries that depended on wood supply from natural forests are recognizing the need to establish plantations to augment supplies from dwindling and unsustainable natural forests. The total area of tropical forest plantations increased from about 6.7 million ha in 1965 to 109 million in 2005. Though most species used for tropical plantations are fast growing, their growth rate can be improved substantially through appropriate silviculture such as site-species matching, site nutrient management, use of hybrid species (clonal plantation), etc. This chapter reviews recent advances in tropical forest plantation establishment and management. Subjects that were specifically covered include: extent of tropical forest plantations, principles of productive forest plantation establishment and management, growth and yield of important tree species, silvicultural techniques for improvement of growth, impact of new aspects for silviculture, etc. Two insightful and demonstrative case studies were also presented to illustrate key points.

Keywords Choice of species · Forest plantations · Global extent · Growth · Nutrient management · Productive plantations · Silvicultural techniques

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S. Günter et al. (eds.), *Silviculture in the Tropics*, Tropical Forestry 8,
DOI 10.1007/978-3-642-19986-8_27, © Springer-Verlag Berlin Heidelberg 2011

27.1 Introduction

Planting trees in tropical countries is an increasingly important forestry activity. The changing emphasis from exploitative management of natural forests to managed natural forests and plantation forests, seen in temperate regions over the last 100 years, has been taking place in tropical countries largely over the last 20 years (Evans 1999a, b, c, d).

This chapter draws significantly on Evans and Turnbull's (2004) *Plantation Forestry in the Tropics,* but readers are encouraged to consult the many excellent regional accounts available, for example, Jacovelli et al.'s (2009) *Tree Planting Guidelines for Uganda,* or Kumar's (1995) *Nursery and Plantation Practices in Forestry* which focuses on India, or Wadsworth's (1997) *Forest Production for Tropical America*. In addition there are numerous accounts of the silviculture of individual species or tree genera suitable for the tropics.

27.2 Definition and Meaning of "Forest Plantation"

The difficulty associated with the definition of forest plantation has been pointed out (Kanowski 1997; Jaakko Pöyry 1999; Evans et al. 2009). This is compounded by the difficulty of distinguishing plantations from other forest land uses. It is not always easy to distinguish forest plantations from enrichment planting or from rehabilitation of degraded forest ecosystems and sometimes from natural forests; especially where the natural forests are mostly dominated by single or very few tree species. Most definitions suggested for forest plantations have adopted the degree of management to differentiate plantation forests from other forms of forest land uses (Jaakko Pöyry 1999; Carneiro and Brown 1999). The earliest definition, which was adopted during the World symposium on "man-made forests and their industrial importance" (FAO 1967) states that plantation forests are: *forest stands established artificially by afforestation on lands which did not previously carry forests or on land which carried forest within the previous 50 years or within living memory and involving the replacement of the previous crop by a new and essentially different crop*. This definition has undergone metamorphosis, culminating with the definition of FRA (2000): *forest stands established by planting or/and seeding in the process of afforestation or reforestation. They are either of introduced or indigenous species which meet a minimum area requirement of 0.5 ha; tree crown cover of at least 10% of the land cover; and total height of adult trees above 5 m.*

In 2005, FAO embarked on a Global Thematic Study of Planted Forests (FAO 2006) which led to two significant developments. First, it proved helpful to distinguish two types of planted forests: productive and protective. Secondly to recognize that many forests today, particularly in Europe, while not looking like a conventional "plantation" have a history of regeneration by planting, hence adoption of the preferred term “planted forests.” The implications of this are far reaching in our understanding of the contribution planted forests make to global would supply: an accessible account is in Evans (2009a, b).

This chapter deals with plantation forestry mainly in productive plantations, which are defined as “plantations of introduced and in some cases native tree species established through artificial regeneration, i.e., direct seeding and planting, mainly for the production of wood and non-wood goods.” Productive plantations can be subdivided into industrial plantations, and plantations for rural development.

Plantations are established for a variety of reasons and vary in composition and structure, as well as in intensity of management. Generally, forest plantations are relatively simple production systems, usually even-aged monocultures, mostly managed to optimize the yield of wood from a site, protect or reclaim an environment and provide benefits and/or amenities that are important to the community (Kanowski 1997; Evans 1998; Carle et al. 2002). Historically, the main aim of forest plantation establishment is to supplement the supply of industrial wood from natural forests (Pandey and Ball 1998; Carle et al. 2002), although there has been a continual diversification of purpose. Industrial plantations are established totally or partly to provide wood for industrial uses (sawn logs, veneer logs, pulpwood) while non-industrial plantations are established mainly for non-industrial uses (provision of fuelwood, or non-wood products, soil protection, environmental protection, etc.). While industrial plantations account for 80% of total plantation area, non-industrial plantations account for only 20%. Productive forest plantations are primarily established for wood and fibre production while protective forest plantations are primarily established for conservation of soil and water. In the last few years, industrial plantations may encompass also afforestation and reforestation activities for managing carbon stock under CDM and other mechanisms.

27.3 Extent of Tropical Forest Plantations

The area of tropical forest plantations has witnessed a phenomenal growth since the middle of the twentieth century, especially within the past three decades. Tropical forest plantations covered an area of 6.7 million ha in 1965 and 21 million ha in 1980. By 1990, the area tripled to about 62 million and almost doubled to about 100.2 million ha by the year 2000 (Table 27.1). The total area of forest plantations in tropical countries is estimated at about 109 million ha by the year 2005. Annual change in plantation area was higher between 1990 and 2000 (about 3.8 million ha) than between 2000 and 2005 (about 890,000 ha). This indicates that more plantations were established in tropical countries in the past than in the present.

Tropical Asia has by far the largest area of plantations and is planting greater area than any other tropical region (STCP 2009). For example, over 85% of new plantings between 1990 and 2005 took place in Asia, with China and India accounting for a much greater part of the plantings (Evans and Turnbull 2004; Carle et al. 2009). In tropical South America, Brazil, Argentina and Chile are the

Table 27.1 Extent and changes in tropical forest plantations (1990–2005)

Region	Area of forest plantations			Annual change rate	
	1990 (000 ha)	2000 (000 ha)	2005 (000 ha)	1990–2000 (ha/y)	2000–2005 (ha/y)
Africa	10,029	10,586	10,864	55,730	27,800
Asia + tropical China and India	42,944	77,263	85,062	3,431,870	779,900
Caribbean	407	426	482	1,930	5,600
Oceania + tropical Australia	312	400	431	8,750	3,100
North and Central America	166	1,489	1,565	132,300	7,600
South America	8,179	10,066	10,722	188,720	65,600
Total tropical world	62,037	100,230	109,126	3,819,300	889,600

Adapted from Evans and Turnbull (2004) and FAO (2005)

leading plantation countries while South Africa, Sudan and Nigeria have the largest area of forest plantations in tropical Africa (see also Chamshama and Nwonwu 2004). In almost all the regions, annual rate of planting was higher during the period 1990–2000 compared to 2000–2005, the only exception being the Caribbean (Table 27.1). The redefinition of tropical forest plantations to include rubber (*Hevea brasiliensis*) is the principal reason for the significantly higher plantation figure in 2000 than 1990.

More than a 100 tree species are used in forest plantation establishments in the tropics and subtropics but only few species dominate. Before 2000, four genera (*Acacia, Eucalyptus, Pinus* and *Tectona*) were recognized as dominant tropical plantation species (Evans and Turnbull 2004) mainly due to the large extent of their plantations. Only three genera (*Acacia, Pinus* and *Eucalyptus*) account for more than 50% of all tropical tree plantations (FAO 2003). The inclusion of *Hevea brasiliensis* as plantation tree species has increased the number of major genera to five because its plantations account for a large proportion (5%) of tropical forest plantations.

In tropical forest plantations for industrial uses, *Eucalyptus* is the most widely planted genus, comprising 24% (8.6 million ha) of the productive forest plantation area. Pine, with 6.4 million ha, is also important, as is rubber (also 6.4 million ha, although some of this may not be available for timber harvesting). Another widely planted tree species is teak (Tomaselli 2007). Other tropical plantation species of increasing importance are *Gmelina arborea, Araucaria* spp., *Leucaena leucocephala*, *Casuarina* species, *Dalbergia sissoo, Terminalia* spp. and *Swietenia macrophylla* (FAO 2001a, b, c, d; Varmola and Carle 2002).

Both indigenous and exotic tree species are used for forest plantation establishment in the tropics and sub-tropics, with exotic species dominating. The domination by exotic species is attributed to their superiority in growth performance over indigenous species, coupled with their ability to suppress noxious weed species. Also, preliminary plantation trials in the tropics involved mostly exotic species while the indigenous species were mostly excluded from the trials for various reasons. In some occasions, when international or bilateral agencies made huge loans available for forest plantation establishment in developing tropical countries, they usually decide that exotic species with fast growth and yield for pulp and paper be planted.

Direct government investment, other policy actions, and private investment, are the main drivers of tropical forest plantation development. Government policy has been a significant factor in plantation development since the advent of large-scale plantation establishment in the 1960s. Most of the plantation estates planted prior to 1995 were established directly by governments or with government funding assistance. However, direct government investment in forest plantation establishment is currently decreasing. Governments now aim to facilitate expansion of state plantations in other ways, such as joint ventures with private landowners, taxation incentives, and loans at subsidised rates or grants. Governments continue to play a significant role in setting an institutional framework that allows for the development of an efficient plantation sector and competitive markets for plantation-based products (Jaakko Pöyry 1999).

FAO was asked to coordinate a process to strengthen country capacity to balance the social, cultural, environmental and economic dimensions of planted forest management and to increase their contributions towards sustainable livelihoods and land use. The process involved experts in planted forests from governments, the private sector (corporate and smallholder), NGOs and academics and identified critical niches for a set of voluntary guidelines (FAO 2006).

27.4 Purpose of Plantations and Species Selection

The purpose of plantation has usually been one of the following four categories: (a) industrial wood production, (b) domestic wood production, (c) environmental protection (see Weber et al. this volume), and (d) rural development (Franzel et al. 1996). In recent years, an additional purpose of carbon sequestration via plantations is emerging.

As already mentioned, we like to put emphasis on productive forest plantations in this chapter, so we focus on plantations for industrial and domestic wood production, whether on large or small scale. Of course, most of the economic, environmental, societal impact comes from large-scale forest plantations, which sometimes lead to critique, that must be taken seriously. On the other hand, especially the socio-economic impact of small-scale plantation projects can no longer be neglected. If this type of afforestation is both initiated and carried out by farmers, it is argued to have more positive and fewer negative impacts, e.g., less social conflict, than large-scale afforestation by non-farmers (Schirmer 2007).

Species choice is the most important decision, once a plantation project is initiated. The choice of species depends mainly on three questions: (1) What is the purpose of the plantation? (2) Which species are potentially available for planting? (3) What will grow on the sites available and how well will they grow? (see Evans and Turnbull (2004) for an overview on factors influencing the choice of species).

From the experiences with large-scale plantation projects in recent decades, we have some sound information of suitable species and related end-uses (fuelwood, pulpwood, sawn timber, etc.). The knowledge base on plantation species, including exotics, is already substantial. This is true for plantations with species of the genera *Eucalyptus, Acacia, Pinus* and *Tectona*, which cover a large area of plantations outside their native range, e.g., in Africa, Asia, and Latin America. In addition to the choice of species, the selection of the most productive provenance within a species is essential for a successful plantation project (Mead 2005). Results from the international seedlot trial for *Eucalyptus camaldulensis* on 32 sites in 18 countries showed that growth gains of several 100% can be achieved by selecting the best provenance for the prevailing condition (FAO 2002b, cited in Mead 2005).

On the other hand, large-scale plantations established with native species are still limited. There are exceptions to this, notably, *Araucaria cunninghamii* in Queensland, Australia, *Cunninghamia lanceolata* in sub-tropical China and *Tectona grandis* in India. New aspects, like the stipulation on the conservation of biodiversity or the restoration of degraded forest ecosystems, have contributed at least regionally to an increased proportion of native species in new plantation projects. Redondo-Brenes (2007) provided results from a study in Costa Rica, where the government has provided incentives for reforestation programs since 1986 and initiated a *Payment for Environmental Services* program in 1996, which yielded reforestation programs with native species throughout the country. His study aimed to provide information about growth, carbon sequestration, and management of seven native tree species (*Vochysia guatemalensis, Vochysia ferruginea, Hyeronima alchorneoides, Calophyllum brasiliense, Terminalia amazonia, Virola koschnyi*, and *Dipteryx panamensis*) growing in small and medium-sized plantations in the Caribbean and Northern lowlands of Costa Rica. The results of the research enhanced the criteria elaborated in previous research findings to improve species choices for reforestation and silvicultural management in Costa Rica and in other regions with similar ecological features. Furthermore, they support the concept that tropical plantations can serve diverse economic, social, and ecological functions that may ultimately help reduce atmospheric CO_2 accumulation.

One – and this may be the most important – reason that plantations established with native species are still at the initial stage is that availability of reproductive material, whether seed or seedlings, of native species cannot be guaranteed.

For many parts of the tropics, especially if large-scale plantation projects are envisaged, it becomes clear that native species are in fact no real alternative – apart from the important exceptions noted above – because in a limited time horizon the critical seed supply with native species is not existing or cannot be realized. This is very often the case in countries, where an organized national forestry programme and legal framework of forest regulations is still missing or at the beginning of development. In such cases, provided that the financial basis to establish a new plantation project is already there, the choice of species is solely dominated by the availability of high numbers of seeds and seedlings on the market. The consequence is that native species will still be neglected, because it is much simpler to use introduced ones which are readily available in the market in a high number with a reliable quality. If the discussions on the use of native species in large-scale plantation projects shall not remain on the academic level only, but is intended to be put seriously into practice, high emphasis must be put in developing strategic concepts on seed management and their practical implementation.

Reforestation with native species is considered a preferable option for sustainable development, overcoming some of the ecological drawbacks of the foregone deforestation and concurrently contributing to the conservation of the region's biodiversity. However, lack of knowledge of the biology of the trees providing seed resources, e.g., about population densities, mating systems and reproductive phenology, as well as of their seed germination eco-physiology and the establishment of saplings, poses a severe challenge for any reforestation project (Stimm et al. 2008).

Planning aspects for plantation programmes must focus on the conservation and sustainable use of forest genetic resources. Forest plantations with native species are not only an option to provide sustainable supply of timber and NWFPs and to minimize the pressure on natural forests but can also be an important complementary contribution to a future-oriented *dynamic conservation*.

For instance in Ecuador, only 167,000 ha of plantations were successfully established by the year 2000 (FAO 2003). Most of the plantations, however, consist of introduced species, mainly *Eucalyptus* spp. and *Pinus* spp. Nowadays more emphasis is put on plantations with native species, e.g., *Alnus acuminata*, *Cordia alliodora* or *Ochroma pyramidale* (see also Brandbyge and Holm-Nielsen 1986; Borja and Lasso 1990; Aguirre et al. 2002a, b; Predesur 2004). But very little attention is still attributed to the provenance of the material from gen-ecological zones and the importance of using autochthonous planting material. Hansen and Kjaer (1999) stressed that appropriate genetic material may not only enhance production and quality but also the health and stability of plantations.

For the South of Ecuador, Stimm et al. (2008) performed a first selection of priority species, where potentially suitable native species were selected from the more than 200-tree species using the following criteria: high local acceptance, economical value (timber and non-timber products), endangered species or species with a high significance for the ecosystem "tropical mountain rain forest" and species typical of certain successional stages such as pioneers or representatives of the climax vegetation. Finally, some 15 native species with a promising potential for reforestation were selected. Consequently, data are needed to delineate "seed transfer zones," or regions within which reproductive material, i.e., seeds or seedlings, can be moved with little or no impact on its population fitness. This problem was already approached for the Province of Loja, South Ecuador (Günter et al. 2004).

27.5 Species: Site Matching

Compared to temperate region, forest plantation silviculture is still a recent phenomenon in the tropics. Many developing countries that previously depended on wood extraction from natural forests are now recognizing the need to establish commercial wood sources, mainly due to high annual deforestation rate, coupled with the dwindling and unsustainable nature of wood supply from natural forest. Foresters agree that large-scale plantation development, especially on marginal lands, is essential in many tropical and subtropical countries (Brown et al. 1997), particularly those with high population densities, and with high forest product needs. The greatest immediate gains in yields from forest plantations will depend highly on appropriate matching of species with available site. Where there is appropriate species-site matching and when management prescriptions are effective, plantations will usually remain healthy and productive (Brown et al. 1997). Much of plantation silviculture is concerned with achieving the best match between species and planting site, a task that is not always easy given the highly variable sites and numerous species in the tropics. Individual trees and provenances may respond differently relative to each other in different environments, a situation known as genotype × environment interaction. Genotype × environment interaction analyses have been used extensively in crop science in developing high yielding cultivars. They are also used in forestry to quantify the performance of provenances or clones across a wide array of sites (Butterfield 1996). Interactions are principally with climatic parameters at variety and provenance level, which underline the need to accurately define site and the exact genetic origin of planting materials. The first step in matching species with site is to determine the limitation imposed by the environmental factors that collectively constitute the site. The second step is the screening of groups of species that will grow well in the site and that are most suitable in meeting the objective of plantation management.

In many locations where plantations have only recently been established, little is known about the potential capabilities for increasing productivity as well as potential problems that may limit yields (Brown et al. 1997). The availability as well as the quality of sites for forest plantation establishment must be known to ascertain their appropriateness to meet the objectives of the planned afforestation programme. The key is to select the site that, when planted, will lead to the establishment of successful forest plantation, which demands the description of the tree’s environmental requirements and the characteristics of the site.

The environmental potentials of a tree species’ natural habitat can initially provide the best guide to the sort of conditions the planting site should have (Evans and Turnbull 2004). In most cases, the results from a site where a tree species is growing (either natural or exotic) strictly apply only to that site; their application to another site usually involves the assumption of site comparability, an assumption that may or may not be justified. Thus, there will often be the necessity for field trials for precise matching of species and provenances to particular sites (Eldridge et al. 1993). Seven factors have been used to characterize the climate of a site (Webb et al. 1984; Booth 1996):

- Mean annual rainfall (mm);
- Rainfall regime (uniform/bimodal, winter, summer);
- Dry season length (consecutive months less than 40 mm rainfall);
- Maximum temperature of the hottest month (°C);

- Mean minimum temperature of the coldest month (°C);
- Mean annual temperature (°C);
- Absolute minimum temperature (°C).

These factors, which have been discussed in detail by Evans and Turnbull (2004), have generally proved to be useful discriminators of regions that are climatically suitable for growing particular trees. The selection of tree species through the use of analogous climates is important only as a first step; it must be amplified by an evaluation of more important localized factors such as soil, slope and biotic factors. Some tools to assess the growth capability of a tree species in a given site have been developed using climatic and soil variables, e.g., soil aeration, pH, salinity, slope and texture (Booth 1998; Hachett and Vancley 1998). The application of these tools requires some knowledge of how well the species grows in relation to these characteristics. The tools have been used in mapping locations suitable for the establishment of some plantations (Booth et al. 1989; Thwaites 2002). However, such tools can only give guidelines as to which species might be appropriate for the site. Thus, final match of species to the available planting site may not preclude the need for species trials, since climatological or ecological matching may not reveal the adaptability of a species. Without such trials, the choice of tree species may, in most cases, be a risky business, it may result to large-scale failures.

Therefore, when the best possible information has been collected on the characteristics of the potential site, the next step is the selection of the suitable tree species to be planted. The aim is to choose species that are suited to the site, which will remain healthy throughout rotation, which will produce acceptable growth and yield, and which will meet management objectives. Many tropical foresters are still in the initial stages of determining which species are best adapted to plantation management (Butterfield 1996). Choosing the appropriate tree species is the most important decision once a forest plantation project is initiated. This is because species choice to a large extent determines the success or failure of the planting programme. The species selected influences the silvicultural and management practices, as well as the utilization of the final crop. Consequently, the selection process must be carefully done. In general, tree species selected for plantation establishment on a specific site should be able to exhibit their maximum growth potential, with high productivity per unit area, and should not have negative impacts on the soils. In addition, the selected species should preferably be able to grow in monoculture and, to some extent, have the ability to grow in mixture with other species. Generally, suitable tree species are gap invaders, pioneers or early secondary species. Late secondary and climax species are often not so suitable for plantations.

The most logical action is to choose from indigenous species whose natural ranges include the target site. If the choice species are indigenous, the problem of matching them with site is of little importance. This is because indigenous trees have the virtue of a long history of inherited adaptation to environmental and site conditions of their area. However, this kind of adaptation favors the perpetuation of their own kind, which does not necessarily include high production rates, stem straightness or other desirable attributes. Where exotic species are to be used, it becomes inevitable to match species with site because not all species can grow well on sites outside their natural habitat. Before using exotic species for large-scale planting, it is necessary to have some assurance that when planted, the selected species will thrive and produce the desire products at the end of rotation. This can be achieved through detailed species field trial.

The dominance of exotic species in forest plantations in the tropics has led to enormous number of field trials in the tropics over the years. Conventional field trials, which will always be a critical part of species selection programme, are relatively straightforward and can be carried out without specialized equipments, though they are usually long-term experiments that may be subject to numerous hazards (Evans and Turnbull 2004). The trial plots can vary in size depending on the scale of trial and number of replications and should cover the whole range of ecological zones within the intended planting site. For such trials, detailed growth performance records should be maintained throughout the experimental period. They should produce results that will enable different species to be compared scientifically and the site variations to be estimated with some precision. Guidelines for field species trials in the tropics have been given by Burley and Wood (1976) and Briscoe (1990). Evans and Turnbull (2004) identified four stages for selecting species for industrial plantations:

- Species elimination: evaluate many species, eliminate failures and identify promising ones
- Species refinement: examine genetic variation within the promising species, in particular compare provenances
- Industrial scale trials: large-scale trials to provide stand growth data, to test methods of cultivation, and to evaluate the likely species on the range of sites encountered in the project
- Tree improvement: identification of land races, breeding, clonal propagation, etc. to create better forest stands for later planting and subsequent rotations

In designing species trials, certain general points have to be borne in mind. These include:

1. Carefully examining all available knowledge about the performance and requirements of species already tested and failed. The objective of the new species trials should also be defined as precisely as possible.
2. The trials must cover the whole range of sites to be planted.
3. Though the ultimate aim may be to select only one or two species for planting, a fairly large number of species may be tried before the most suitable ones can be selected.
4. Since nursery practices may influence the success or failure in plantations, the role of nursery in species trial is very important. Thus, a high degree of control over nursery conditions to ensure that they are reasonably constant and uniform is essential.

27.6 Seed Collection, Supply, and Storage

Continuous and long-term availability and supply of high quality seed and plant material for any kind of planting activity is one of the fundamental challenges for sustainable plantation management and requires the establishment of production standards. The installation of a reliable programme for managing tree seed resources on a national or regional level is a very first but nevertheless important step for the realization of successful planting activities. To conceptualize and achieve standards, the approval and monitoring of seed sources of priority species is one of the basic steps, which will be accomplished by seed certification and control of seed procurement.

In planning plantation programmes with indigenous species, the major seed sources will be a network of natural stands, where vigorous trees with desired characteristics have been observed phenologically and selected for seed collection. In areas where sustainable forest management has already been established, "seed production stands" can be assigned for seed harvesting. The establishment of such stands is a precondition for a professional management of seed production, and may include the establishment and management of conservation stands.

The provision of genetically suitable seed and other reproductive plant material of good physiological quality from selected indigenous seed sources is the main goal, which must be achieved. "Suitable" includes the location, use and maintenance of clearly defined and well-documented seed sources.

In many parts of the tropics, most of the reforestation projects still deal with exotic species of the genera *Eucalyptus* or *Pinus*, while native species have not been used in the region so far due to the reasons already mentioned. Establishing plantations with native species is an option to contribute to the conservation of the regional biodiversity, but knowledge about the reproductive biology of such species is very limited. Nevertheless, it is indispensable for the production of adequate numbers of high quality seedlings in tree nurseries.

To receive sufficient genetic amplitude for large-scale plantations, Graudal et al. (1997) recommended harvesting at least 50 individuals of one provenance or species. Unfortunately, reproductive biology and mating systems of many native species are still unknown.

For practical purposes therefore, it is necessary to monitor a higher number of individuals of a certain seed zone for seed harvesting. This, however, is very difficult in the tropics where many species appear with very low abundances. The resulting problems can be demonstrated with an example from the Rio San Francisco valley (Zamora Chinchipe Province, Ecuador): *Cedrela sp.* with DBH $>$ 30 cm has an abundance of about 0.8 ha^{-1} and *Prumnopitys montana* approx. 0.6 ha^{-1} in the lower parts of the RBSF (Günter and Mosandl 2003). Every year about 40 and 30% of the individuals in each population of these two species showed fructification. We assume that the reproductive phase of these two species starts only with a DBH of 30 cm. In this case, the establishment of a seed bank with a sufficiently broad genetic basis would require collecting seeds from an area of at least 160 ha for *Cedrela sp*. and 270 ha for *Prumnopitys montana* with respect to the Rio San Francisco provenance. Monitoring of those areas necessitates an enormous input of time and manpower. For comparison, forest inventories for African mahoganies in unlogged forest revealed a relative abundance of large individuals (e.g., ≥80 cm DBH, which is thought to be a minimum diameter for seed production of *Entandrophragma* spp.) of 0.5–2 individuals per ha. Forests containing *E. cylindricum* have been shown to fruit anywhere from zero to two times during a given year (see Hall 2010, this volume). In that case, the establishment of an *Entandrophragma* spp. seed bank with a sufficiently broad genetic basis would require collecting seeds from an area between 25 and 100 ha. The density (N/ha) of mature big-leaf mahogany *(Swietenia macrophylla)*, i.e., trees exceeding 30–40 cm diameter, in Bolivian natural forests along a gradient of increasing dry season length has been found to be between 0.2 and 0.5 individuals per ha (see Grogan et al., this volume). Applying the above-mentioned rule of thumb, this would mean that the establishment of a big-leaf mahogany seed bank for a specified provenance with a sufficiently broad genetic basis (min. 50 individuals) would require collecting seeds from an area between 100 and 500 ha.

For mitigating the scarcity in native forest reproductive material, the establishment of competent tree seed centres and tree seed programmes is of utmost importance.

27.7 Domestication and Tree Improvement

Unlike in agriculture and animal husbandry, domestication of tropical forest tree species has only been practiced since the dawn of the twentieth century. Tropical trees being domesticated are found in primary forests, secondary forests, communal fallow lands, plantations and farms. The use of provenance selection, an early stage in the domestication process, gained international importance in the 1960s, although techniques such as clonal selection have been used for centuries in a limited number of species – *Salix, Populus, Cryptomeria japonica*, etc. (Leakey and Newton 1993). In forestry, the term "domestication" has mostly been applied to genetic improvement of trees for industrial plantations but recently, it has been taken to encompass the identification and characterisation of germplasm resources; the capture, selection and management of genetic resources; and the regeneration and sustainable cultivation of the species in managed ecosystems (Fig. 27.1). The Working Group on "Product Domestication and Adoption by Farmers" during the conference on 'Domestication and Commercialization of Non-timber Forest Products in Agroforestry' (Leakey et al. 1996) defined domestication as 'a progression from collection and utilization of products, through protection, management and cultivation, which culminates with genetic manipulation'.

Tree domestication is a dynamic process, which develops from deciding the tree species to domesticate and proceeds through background socioeconomic studies, the collection of germplasm, genetic selection and improvement to the integration

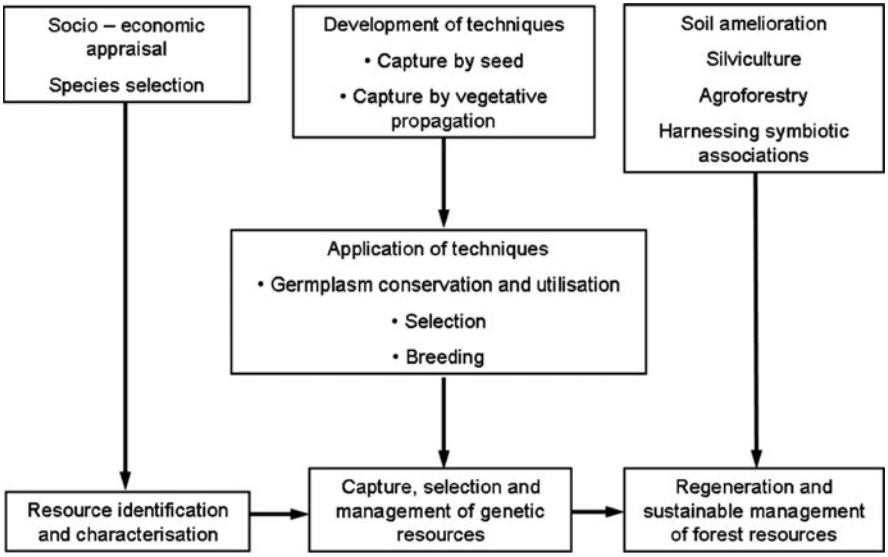

Fig. 27.1 Aspects/stages involved in the domestication of tropical trees
Source: Leakey and Newton 1993

of domesticated species in land use. It should be an ongoing process in which genetic and cultivation improvements are continuously refined. However, domestication is not only about selection. It integrates the four key processes of the identification, production, management and adoption of tree resources. It is highly species-specific and thus, an extremely variable process.

Techniques for selection and breeding can be very simple or quite complex. Finkeldey and Hattemer (2007) gave a comprehensive account on these techniques and on breeding strategies as well. For majority of species, it may consist simply of identifying and collecting seeds from individuals with desirable traits and developing appropriate propagation and cultural practices. For widely planted and important timber species, the full domestication process may involve the systematic sampling and characterisation of genetic variation, development of optimal propagation and silvicultural techniques, and intensive breeding, including the use of molecular genetics technologies and sometimes hybridization (Finkeldey and Hattemer 2007). Domestication seeks to bring out the maximum human benefit within a species as it is genetically refined from a wild tree to a cultivated plant.

Breeding research is focusing on heterosis breeding, where heterosis is defined as superior trait expression of heterozygous genotypes in comparison with corresponding homozygote (Finkeldey and Hattemer 2007). One method of heterosis breeding is hybridization between forest species, which can result in an improvement of desired trait expressions, such as better resistance against pests and pathogens or better growth performance. Finkeldey and Hattemer (2007) summarized some illustrious examples in their textbook. The establishment of seed orchards, either clonal or seedling seed orchards, is one of the cornerstones in breeding programmes, e.g., for teak in Thailand (Finkeldey and Hattemer 2007).

In this context, the development and application of vegetative bulk propagation techniques has contributed essentially to the success of breeding programmes, e.g., on eucalypt hybrids in Brazil (Finkeldey and Hattemer 2007). In Aracruz, Brazil, within the last 30 years, Eucalypt plantations established from seedlings have successively been replaced by clonal plantations, which grow enormously fast with a MAI of 60 m^3/ha/year and more. In the case of development of clonal plantations, it is reasonable to use a large clone assortment. As for seed collections, where seed should be collected from at least 20–50 trees of a population (see Dawson and Were 1997), care needs to be taken to maintain a broad genetic diversity (Finkeldey and Hattemer 2007). Hence clonal mixtures are recommended (where in some countries the law regulates the number of clones that must be contained in any one mixture, e.g., in Canada >50) (Zsuffa et al. 1993).

The tropical forest ecosystem is rich in natural resources, particularly trees that provide food, fuel, fibre, medicines and various other products, including construction and building materials that have provided indigenous people with many of their daily needs for millennia. These resources are particularly important for rural economies, enhancing economic empowerment, rural employment, etc. It has been predicted that food tree species will become of greater importance within the next few years (Ayuk et al. 1999), especially for sustainable development of rural livelihoods that depend on them. This is based on the increasing demand and the emerging domestic and international markets for their products. However, despite their importance, these tropical forest resources have been greatly neglected. Most of them have continued to grow in the wild, with continual decreasing yield due to old age and the fact that they have been harvested for decades. Consequently, a lot of them have died or are in the process of doing so, while many others are currently endangered, with a high possibility of going into extinction in the near future. In Nigeria, quite a number of forest food tree species (e.g., *Vitellaria paradoxa, Chrysophyllum albidum, Irvingia gabonensis, Treculia africana,* etc.) have been classified as endangered (FORMECU 1999). Allowing them to go into extinction will endanger the livelihood of millions of rural dwellers in the tropics and reduce the rich biological diversity of the tropical ecosystem. Artificial regeneration and subsequent improvement of the species (domestication) appears to be a very viable option of saving these species and ensuring that their products are supplied on sustained basis. The objective of domestication is to enhance the performance of trees in terms of improved products (e.g., timber, fruits, and medicines) and/or improved environmental services (e.g., amelioration of soil fertility) (Simons and Leakey 2004). The genetic benefits obtained from the domestication of mango (*Mangifera indica* L.), *Citrus* spp., breadfruit (*Artocarpus altilis* (Z) Fosb.) and avocado (*Persea americana* Miller) in the tropics has shown that large genetic gains are possible with the domestication of wild tropical forest food tree species.

There is great urgency to achieve these benefits if the severity of the current man-made episode of species extinction (the so-called “Sixth Extinction” (Leakey and Lewin 1996)), is to be defused. In this respect, Sanchez and Leakey (1997, cited in Leakey and Simons 1998) sees domestication of forest food trees as one of the three determinants for balancing food security with natural resource utilization.

Strategies for individual species vary according to their functional use, biology, management alternatives and target environments (Simons and Leakey 2004; Finkeldey and Hattemer 2007). Domestication can occur at any point along the continuum from the wild to genetically transformed state. The intensity of domestication activities for a single species will be dictated by a combination of biological, scientific, policy, economic and social factors. The need to rapidly domesticate tropical forest food tree species has been stressed and is now one of the three pillars of World Agroforestry Centre (formerly known as International Centre for Agroforestry Research, ICRAF) programme (Leakey and Simons 1998).

The selection of an elite tree for domestication could vary depending on the desired product(s). For indigenous forest food tree species, rapid progress will be made if indigenous knowledge is used. Usually, indigenous people know the best individual trees in terms of yield, fruit size, taste, flavour, etc. The people can be asked to report the existence of superior trees, thus reducing the task of screening large numbers of trees. Unlike fruit trees, chemical screening process may be required for medicinal trees. However, the magnitude of this task can probably be reduced by starting on a population basis, since it is likely that trees from certain environments will be richer in the required components. For timber trees, stem form, bole straightness, log size are the first selection criteria. Various forms of "plus-tree" (i.e., elite selection) provenance and progeny selection are well known. For fruit trees, crown size, fruit yield, fruit size, fruit taste, etc. are the main selection criteria.

Research work on the domestication of forest food tree species in the tropics is still at preliminary stage and covers seed germination and methods of seed pretreatments (Onyekwelu 2004), prospects of vegetative propagation (Shiembo et al. 1996), phenotypic variation of fruits and kernels (Anegbeh et al. 2003), selection of multiple traits for potential cultivars (Atangana et al. 2002; Ngo Mpeck et al. 2003), germplasm collection focused strongly on the species identified through farmers' input, priority setting exercise (Leakey and Simons 1998); integration into agroforestry (Leakey et al. 2003; Kumar and Nair 2004; Simons and Leakey 2004); uses, management, economic and nutritional importance (Okigbo 1978; Ayuk et al. 1999; Leakey 1999; Okafor 1991). Atangana (2000) quantified the morphological variability of fruit and kernel traits of *I. gabonensis* in Cameroon and Nigeria respectively. However, phenotypic variation in the fruit has only been descriptive and limited to only *I. gabonensis* (Ladipo et al. 1996; Anegbeh et al. 2003) while no known documented study on the silviculture of the tree species in the nursery and plantation exists, which should be the next step in the effort to domesticate these species.

Since 1998, the World Agroforestry Centre, in collaboration with a range of partners, has been developing a participatory approach to domestication of indigenous trees. In Solomon Islands, several varieties of nut have been selected and domesticated (Evans 1999b), including *Canarium* (ngali nut, three species), *Barringtonia* (cut nut, three species), *Terminalia catappa* (beach almond), *Gnetum gnemon* and *Pandanus* (screw pine, several species and numerous varieties). Much of the current work of the Tree Improvement and Genetic Resources Programme at CSIRO Forestry and Forest Products (CSIRO FFP) is conducted within the context of species domestication. Presently, the Australian Tree Seed Centre (ATSC), in collaboration with its many research and development partners, has started to domesticate 70 species in 22 genera. An essential precursor to this work has been the assembly of biogeographic information on particular species and genera, which are frequently published in monographs and annotated bibliographies and as electronic Forestry Compendium (Doran and Turnbull 1997; CABI 2000; Kalinganire and Pinyopusarerk 2000).

New aspects have evolved quite recently: The introduction of biotechnology, including genetic modification (GM) of trees, to plantation forestry has the potential to increase the productivity of planted forests and create novel products and desired qualities (Sedjo 1999, 2004). Genetic transformation has been reported for poplars and some other, mainly temperate, tree species (Owusu 1999; Fladung and Ewald 2006; Ishii 2006). Prospective benefits, like a reduction in lignin content, ability of phytoremediation or resistance against pests and diseases, need to be balanced against the risks associated with genetic transformation, e.g., horizontal gene transfer from GM trees to non-target organisms. Burdon and Walter (2004) reviewed risks of transgenic exotic pine and eucalypt plantations and strategies of risk management.

27.8 Plant Propagation

Another problem is the propagation of plants, especially from seed of lesser known species. As with many tropical tree species, the knowledge of optimum propagation is scarce (but see Kumar 1995; Vozzo 2002; Schmidt 2007). Our experiments with native Ecuadorian species (Stimm et al. 2008) corroborate the need to develop species-specific appropriate propagation techniques and protocols, otherwise planting material for reforestation purposes might not meet the high qualitative standards and required numbers.

The development of vegetative propagation techniques is often complementary and aims at the identical reproduction of plants with desirable features such as high productivity, superior quality, or high tolerance to biotic and/or abiotic stresses (Jaenicke and Beniest 2002; Ishii 2006). The reasons for vegetative propagation very often include an irregular seed production in nature, low survival of seeds in storage and seed quality, realisation of gain in domestication and tree improvement programmes, production of uniform material and genetic modification. Cutting propagation has been reported for a number of tropical and subtropical species (Rimbawanto 2002; Ahmad 2006; Baker and Walker 2006). Rooting success is species-specific as well as clone-specific. Most important factors for the rooting of cuttings, their survival and subsequent growth is the age of the mother tree (e.g., the younger the tree the better the rooting), time of harvesting the cuttings, substrate, humidity, hormones and sugars. Rejuvenation of physiologically old plant material can be initiated through (repeated) hedging of mother stock from clonal gardens.

Especially, tissue culture techniques give the possibility for bulk propagation on a small area, independence of season, and the possibility to produce virus-free plant material (Ishii 2006; Jain and Ishii 2003; Jain and Häggman 2007). Nevertheless, these techniques can have some shortcomings, e.g., a relatively high financial investment for the basic facilities and equipments, high running costs, and a higher incidence of mutations through somaclonal variation. The most common techniques in use are shoot tip micropropagation, multiplication via axillary shoot formation, nodal segments or adventitious shoots, embryo culture from seeds and somatic embryogenesis.

The overall objective in nursery production is high quality planting stock, which is a prerequisite for high survival and good early growth in the field (Mead 2005). Fertilization in the nursery aims at the supply of essential mineral nutrients for accelerated seedling growth and is therefore one of the important cultural activities in forest nurseries. Nursery stock make a considerable demand on soil nutrients and there is little or no nutrient cycling in the nursery because their leaves are hardly shed off, coupled with the short life span of seedlings in the nursery. The loss of organic matter during cultivation, leaching and activities of microorganisms, which results to degradation of nursery soils regardless of the original fertility of the site (Nwoboshi 2000), makes the use of fertilizers in forest nursery almost inevitable. There is ample evidence that the application of fertilizers in the nursery improves seedling growth and maintains or improves nursery soil fertility. Fertilizer application has been shown to markedly improve the physiological quality of planting stock. For some tropical plantation tree species (e.g., *Tectona grandis*, *Gmelina arborea, Pinus* spp., etc.), fertilizers are applied at the nursery stage to enhance their survival and initial growth after transplanting to the field.

Suspected nutrient deficiencies, indicated by symptoms such as chlorosis, should always be confirmed by soil or foliage tests because symptoms can be caused by many factors. Unless those tests show other nutrient deficiencies, nitrogen and potassium are the only fertilizers that are typically applied to nursery stocks during the growing season. Application rates are determined by experience or from soil or foliage tests, and the fertilizers applied by drop or rotary spreaders. Some nurseries inject soluble fertilizer solutions into the irrigation system or apply them through a spray boom behind a tractor. Liquid fertilizer solutions are injected into the irrigation lines in the headhouse and applied to the crop through nozzles.

A promising approach to the improvement of seedling quality in nurseries for reforestation purposes could be the inoculation of seedlings with mycorrhiza (see also Suzuki et al. 2006). Urgiles et al. (2009) successfully applied mycorrhizal roots which enhanced the growth of tropical tree seedlings in the nursery. Most tree species in tropical mountain rain forests are naturally associated with arbuscular mycorrhizal fungi. Previous studies in southern Ecuador of 115 tree species revealed that only three species were not associated with arbuscular mycorrhizal fungi. Urgiles et al. (2009) suggested that seedlings of tropical tree species raised in the nursery may need to be associated with arbuscular mycorrhizal fungi to survive transplantation shock in higher numbers. Methods for establishing plantations with native tree species are not yet established for Ecuador. Assessment of plant growth and mycorrhizal status of 6-months-old *Cedrela montana* and *Heliocarpus americanus* revealed an improvement in growth and diverse associated fungi through mycorrhizal root inoculation in comparison with moderate fertilization. Moderate fertilization did not suppress mycorrhization.

27.9 Plantation Establishment

Satisfactory establishment of tropical plantations depends on adequate site preparation. This is important for all species but absolutely critical for Eucalypts. The latter require weed-free conditions and well-cultivated soil to achieve the remarkable growth rates of which they are capable.

Physical properties of soil, e.g., soil compaction, are often responsible for the poor establishment of trees. Soil cultivation of various types and intensities, ranging from simple pit planting to mechanical ripping, may help to overcome this problem. Physical treatments – cultivation – aim to significantly improve root development and rooting depth by reducing soil bulk density, improving internal drainage and temporarily effecting weed control. Site preparation for the next rotation has to be done sensitively and should focus especially on conservation of organic matter (Evans 1999a, b, c, d).

27.9.1 Spacing

Usually two patterns of planting are used in tropical plantation establishment, square (the most common) and rectangular planting patterns. Triangular or other alternative patterns are seldom practiced (Evans and Turnbull 2004). The stocking (planting density; number of trees planted per hectare) is one of the main silvicultural decisions in the establishment of plantations and is realised in the distance between trees (spacing). On the one hand, it is a factor affecting cost, because close spacing requires a higher number of seedlings, but on the other hand, close spacing can induce the self-pruning of trees from branches, especially in hardwood species, and hence improve the quality of timber. In close spacing, a higher number of stems also improve the opportunity for a selection for desired growth form and other important silvicultural characters. Spacing in combination with thinning is used to manipulate not only the quality but also the size of the crop trees, e.g., at close spacing (high densities) the mean size of the average tree will be low, whereas at wide spacing the mean size will be high. In forest plantations in the tropics, initial spacing smaller than 5 × 5 m (growing space per tree is $< 25\ \text{m}^2$, stocking is > 400 trees/ha) are generally implemented, and spacing of 3 × 2 m (rectangular pattern; growing space per tree is 6 m^2, stocking is 1,667 trees/ha) or 3 × 3 m (square pattern, growing space per tree is 9 m^2, stocking is 1,111 trees/ha) are common in plantations established for timber production. For biomass and fuelwood plantations much smaller spacing is used, e.g., 1 × 1 m (growing space per tree is 1 m^2, stocking is 10,000 trees/ha). The description of impacts of various spacings on environmental features, on the management of stands and on costs and revenues go beyond the scope of our current review, therefore we recommend the study of this topic elsewhere (e.g., Evans and Turnbull 2004).

27.9.2 Weed Control

Weed control until canopy closure greatly aids the establishment of trees. A good compromise is to maintain a 1-m diameter weed-free zone around every tree from the time of planting until canopy closure. This can be made manually, mechanically or via the application of specific chemicals (herbicides). The intensity of weed control varies according to species, site and climate, i.e., in areas with year-round rainfall, weed control may be needed six or more times in the first year. For details on weed control, weeding practices and methods we refer to the comprehensive review of Evans and Turnbull (2004).

27.9.3 Protection

Fire poses a major threat to tropical plantations, especially in the drier tropics and sub-tropics, and savanna habitats. Fire damage is often heavy, in particular when plantations are poorly maintained and a large amount of fuel from woody debris and litter is available (Saharo 1999). All tropical plantations will require protection from browsing animals, domestic livestock or wild, until trees are at least 4 m tall and sturdy enough to resist damage. Both fencing and shepherding are commonly used to prevent such damage. Many tropical plantations suffer from termite damage, and local control, e.g., by termiticides, will be necessary.

27.9.4 Mixtures

Critical views, especially on large-scale plantations are coming up regarding the goods and services provided to regions and rural communities (FSC certification etc.). Although biodiversity levels in plantations are often assumed to be lower than those in natural forests, plantations can host a high number of native animal and plant species endemic to primary and secondary forest ecosystems. Currently biologists and foresters are seeking a better understanding of the value of planted forests for biodiversity conservation (see Carnus et al. 2006). Barlow et al. (2007) did a comparison of bird communities of these habitats and neighbouring primary forest in north-east Brazilian Amazonia. They demonstrated that species richness was highest in primary forest and lowest in *Eucalyptus* plantations, and community turnover between habitats was very high. Monthly line-transect censuses conducted over an annual cycle showed an increase in the detection of canopy frugivores and seed predators during the peak of flower and fruit availability in primary forest, but failed to suggest that second growth or *Eucalyptus* stands provide suitable foraging habitat at any time of the year. The conservation value of both secondary forest and plantations was low compared to conclusions from previous studies. Their results indicate that while large-scale reforestation of degraded land can increase regional levels of diversity, it is unlikely to conserve most primary forest species, such as understory insectivores and canopy frugivores.

Brockerhoff et al. (2008) provided a comprehensive review of the function of plantation forests as habitat compared with other land cover, examined the effects on biodiversity at the landscape scale and synthesised context-specific effects of plantation forestry on biodiversity. Natural forests are usually more suitable as habitat for a wider range of native forest species than plantation forests but there is abundant evidence that plantation forests can provide valuable habitat, even for some threatened and endangered species, and may contribute to the conservation of biodiversity by various mechanisms. Afforestation of degraded or abandoned agricultural land can provide complementary forest habitat, buffer edge effects, and increase connectivity. The authors provided context-specific examples and case studies to assist impact assessments of plantation forestry, and offered a range of management recommendations.

Cummings and Reid (2008) presented an overview of stand-level approach practices they have adopted in managing flooded gum (*Eucalyptus grandis*) plantations infested with lantana (*Lantana camara*) to enhance their biodiversity value. Experiments designed to overcome barriers limiting regeneration of native forest trees yielded insights into the management of former timber plantations for biodiversity. Thinning and burning stimulated regeneration of native species. Retained canopy cover was proportional to the richness or abundance of native woody shrubs, understory trees and native perennial herbs, indicating that management intensity can be varied to promote a range of conservation values.

To compensate for the large-scale reduction in biodiversity, a landscape approach including a mix of production areas with habitat components and corridors for biodiversity seems to be a powerful instrument (van Bodegom et al. 2008). Other measures, e.g., increasing the level of genetic diversity, are a complementary and hence useful instrument. In this sense, one measure to facilitate biodiversity rehabilitation in plantations is to establish mixtures of tree species, preferably mixtures of native species, and/or with exotics. Marjokorpi and Salo (2007) analyzed operational standards and guidelines for biodiversity management in tropical and subtropical forest plantations.

Additional reasons for an establishment of mixed species plantations may include (1) providing a diverse range of products, including NWFPs, (2) diversification of risk of production, (3) obtaining a greater yield of products, (4) providing a nurse crop (see e.g., Kelty 2006; West 2006).

From a silvicultural point of view, it is necessary to reflect on the patterns of mixtures, i.e., whether to establish small areas of monocultures (stands) of each species, i.e., “coarse grained” mixture or (stand) “mosaic,” or whether the plantation (stand) should be established as a “fine grained” or “intimate” mixture of different and intermingled tree species. Kelty (1992) and Binckley et al. (1997) have reviewed the experience with tree mixtures, but only recently more information on mixtures was added from the tropics and subtropics (Kelty 2006; West 2006).

Because of the different biological characteristics of the various species, it is often assumed that species in mixture are able to occupy different niches in the ecosystem, which can overlap, and that mixtures are able to exploit the resource more economically than monocultures. Besides this complementary resource use between species, a facilitative improvement in nutrition of a valuable timber species growing in mixture with a nitrogen-fixing species may arise (Carpenter et al. 2004; Forrester et al. 2005, 2006; Kelty 2006; Bouillet et al. 2008; Piotto 2008; Oelmann et al. 2010). This means that the combination of species in mixtures and their growth and production can be greater than the production in monocultures and can improve economic returns (see also Montagnini and Piotto, this volume).

Kelty (2006) and West (2006) cited some examples of the better performance of mixtures, e.g., experimental plantations with mixtures of *Eucalyptus saligna* and *Falcataria moluccana* in Hawaii (DeBell et al. 1997), *Cedrela-Cordia-Hyeronima* in Costa Rica (Menalled et al. 1998), and *Grevillea robusta* and *Toona ciliata* in North Queensland, Australia (Keenan et al. 1995). Erskine et al. (2006) could demonstrate for the humid tropics of Australia that diverse plantations can achieve greater productivity than monocultures. In Costa Rica, *Jacaranda copaia* and *Vochysia guatemalensis* grew significantly faster in mixtures than in monocultures. A mixture of *J. copaia, V. guatemalensis*, and *Calophyllum brasiliense* produced 21% more merchantable volume than a monoculture of *J. copaia*, which grew the fastest among the three species (Petit and Montagnini 2006).

In a meta-analysis, Piotto (2008) found that mixed plantations did not have higher height growth rates, but that the diameter growth rate was higher in mixed plantations, with a moderate but statistically significant size effect. Nitrogen-fixing tree species had a positive effect on the diameter growth rate of non-fixing species, with a large and statistically significant size effect. This study suggests that mixing tree species generally increases plantation growth rate. Piotto stated furthermore that mixed tree plantations can play an important role in satisfying economic needs by shortening rotations yet adding other ecological benefits.

27.10 Nutrition of Tree Crops

Most tropical soils available for forest plantations (e.g., Oxisols, Alfisols, Ultisols, etc.) are naturally low in inherent fertility and deficient in nutrients such as Calcium (Ca), Magnesium (Mg), Potassium (K) and Phosphorus (P), but contain excessive quantity of Aluminium (Al), Iron (Fe) and Manganese (Mn) (Lal 1997). Also, Boron (B) deficiency is widespread in tropical plantations (pines and eucalypts) leading to shoot dieback, forking and multiple leaders. In addition, there are some measures of nutrient losses from plantation site during rotation, through leaching or chemical reactions in the soil by which nutrients become bound permanently to soil particles. Because the nutrients available for tree growth are vulnerable resources, it is important for losses to be minimised or replaced both in the short term during any one rotation and in the long term over many rotations or else tree growth and health will be compromised. This can be achieved through efficient site nutrient management (Nambiar and Brown 1997; Nambiar 2008). Unlike in natural forests, site nutrient management is particularly important in forest plantations given their intensive management system. However, since tropical forest soils differ greatly both in their ability to supply essential nutrients and in the extent to which they may lose nutrients through leaching, it is very difficult to generalize about how nutrients should be managed on any plantation site. Site nutrient management begins with assessment of the nutrient status of the site. At present, there is no simple and straightforward method of going to any site and easily assessing its nutrient status, often the assessment requires complex and long-term experimentation (West 2006). Using simply measured characteristics of a particular site to determine the nutrient deficiency of the site is usually difficult.

The ultimate test for determining the nutritional requirements for forest plantation site is through long-term field fertilizer experiments (Evans and Turnbull 2004). These experiments can be preceded by series of integrated short-term experiments (e.g., soil analysis, foliar analysis, plant tissue analysis, etc.), which can provide immediate information on the need for fertilization. This integrated approach has been used to identify deficiencies of macro- and micronutrients for tropical plantation tree species. However, it is possible to maintain or improve the fertility of forest plantation sites without fertilization, e.g., through efficient nutrient cycling and residue management.

27.10.1 Fertilizer Application

Although fertilization has not been a common practice in tropical forest plantation establishment and management, it is increasingly becoming an important means of improving tree nutrition, thereby accelerating the rates of nutrient cycling and tree growth on nutrient-deficient sites (Nwoboshi 2000; Evans and Turnbull 2004). With the intensification of silviculture through conversion to high density, high yielding, short rotation forest plantation systems, the use of fertilizers to improve the growth of forest stand will more and more become an accepted cultural practice. The huge success of tropical pine plantations in Australia has been attributed to the use of fertilizer (Simpson 1998). Singh and Singh (2001) reported greater growth rate in NPK fertilized plots than in unfertilized plots for nine tropical plantation species in India. In many parts of Asia, P-fertilizer application at planting is the standard practice for *Gmelina arborea* and *Acacia mangium* plantations (Evans and Turnbull 2004).

In plantation forestry, fertilizers are used to: (1) correct a specific deficiency; (2) establish a crop on nutritionally poor site or (3) stimulate tree growth (Evans and Turnbull 2004). In addition, fertilization will be needed to sustain rapid growth on all but the most fertile sites (Fox et al. 2006).

Nevertheless, fertilization in forest plantation is very expensive; it should only be used if the resulting gains in production can be justified economically, which can be judged by the size of growth response (i.e., higher yield or shorter rotation); in addition to the cost of application, interest rates, etc. It is very important that for each species the right kind of fertilizer is used and in the right amount and time to match the requirements of the tree. If excess amount of fertilizer is applied, the nutrients will be leached while insufficient quantity will not produce the desired growth response from the trees (Bruijnzeel 1997). This is because forest soils differ greatly in their ability to supply the nutrients and the extent to which they may lose nutrients through leaching (West 2006).

27.10.2 Time of Fertilizer Application

Fertilizers can be applied in a forest plantation at any one of four stages Evans and Turnbull (2004): (1) at establishment, usually within 3 months of planting; (2) during the post-establishment phase up to canopy closure when deficiencies begin to show; (3) at pole stage to boost thinning response and generally stimulate growth and (4) as a pre-felling application, 3–10 years before felling, to add increment before the end of rotation. In stages (1) and (2), care has to be taken that fertilization is not fostering competing weeds and grasses, too. No matter the stage, fertilizer application should coincide with the nutrient demand and expected growth response.

27.10.3 Plantation Establishment and Pre-canopy Closure Application

While application at planting enables seedlings to establish a vigorous root system essential for its good functioning, post-establishment application facilitates rapid growth rate and augments the high nutrient demand of the young seedlings. Fertilizer application at establishment is done to accomplish the following: correct known nutrient deficiencies; minimize planting shock to the seedlings by making nutrients liberally available; hasten crown closure; minimize the period the seedlings are subject to mortality. Some fertilizers are most conveniently applied at the time planting e.g., a one-off application of 15 g of borax which will correct boron

Table 27.2 Effect of fertiliser application on the growth of tropical forest plantation species 36 months after planting (adopted from Otsamo et al. 1995)

Species	Treatment	Height (m)	DBH (cm)	Basal area (m^2/ha)	Crown diameter (m)
Gmelina arborea	Plowing + NPK	5.3	7.2	11.3	3.4
	Plowing	3.7	4.1	4.0	2.9
Acacia mangium	Plowing + NPK	10.4	9.9	21.8	3.4
	Plowing	8.9	7.7	13.5	3.0
Paraserianthes falcataria	Plowing + NPK	9.3	10.3	22.8	4.3
	Plowing	5.0	5.5	6.3	3.8

deficiency for the rest of the rotation. Waring (1973) demonstrated that delaying the application of fertilizer on P-deficient sites could result in a loss of productivity that may never be recovered. This necessity for early fertilization also holds true for other elements, especially when they are so deficient as to restrict survival, establishment and early stand development.

Seedlings should not be fertilized the year of planting unless the fertilizer is a low release formulation, the fertilizer is thoroughly mixed into the surrounding soil prior to planting, or it is uniformly broadcast on top of the soil just prior to or after planting (McKenna and Woeste 2006). This is because the roots of young trees are damaged by contact with concentrated nitrogen fertilizers, and bare-root seedlings planted with fertilizer near the stem are prone to drought. Since fertilizers increase the growth of weeds that retard the growth of first-year seedlings, first-year seedlings should not be fertilized unless good weed control programme is planned (Pope et al. 1982; McKenna and Woeste 2006). Additional fertility will not help if factors such as water or light are limiting growth.

The higher the rate at which nutrients are supplied to seedlings, the faster their growth, thus the quantity of fertilizer needed by the seedlings will have to be increased steadily as the seedlings grow larger. Thus, throughout the early years of the plantation until canopy closure, fertilizer could be applied as often as practicable and the amount should increase progressively with time (exponential loading) to keep pace with the ever-increasing amount needed by the seedlings (West 2006). The application of NPK fertiliser significantly increased the growth of young plantations in Indonesia (Table 27.2). Seedling response to fertiliser application is dependent on tree species as shown by Bennett et al. (1996).

27.10.4 Post-canopy Closure Application

After canopy closure, leaf mass remains constant and litter breakdown and translocation of nutrients within the tree provides the nutrients necessary for new growth (Miller 1995). With the reestablishment of nutrient cycling system associated with forest canopy closure, the demand on soil nutrient capital is reduced and growth response to fertilizer application at this stage is usually variable (Nwoboshi 2000).

Provided nothing happens to disrupt this nutrient cycling, the nutrients in the plantation site should remain more or less in a steady equilibrium, thus eliminating any need for fertilization. However, if the effects of the fertilizers applied during pre-canopy closure stage wears off and stand growth stagnates, fertilizers may be applied after canopy closure and positive responses (in terms of additional growth) obtained. Thus, where the nutrients' demand of the plantation has not been fully satisfied during the early years, fertilizer application may be beneficial for post-canopy closure stand growth. Post-canopy closure fertilizer application should only be embarked upon where the value of the tree's economic component increases with stand age (Nwoboshi 2000). It is widely held that post-canopy closure fertilization will lead to a marked increase in growth rate if the stand is thinned at the same time with fertilizer application (Miller 1981; Carlyle 1995). Thus, to maximize returns on investment, post-canopy closure fertilization should be conducted in conjunction with a first or second thinning operation (Fox et al. 2006). To fully reap the benefits of post-canopy fertilization, it should be concentrated on the sites and tree species that will be most responsive to the treatment.

27.10.5 Soil Fertility Management Without Fertilizer

Although the years preceding canopy closure in forest plantations are characterised by major shift of nutrients from soil to tree biomass, the years proceeding canopy closure are characterised by efficient internal nutrients re-use, which implies that there can be a rapid recharge of soil exchangeable nutrients. The efficient management of this internal nutrient re-charge and nutrient cycling can lead to long-term forest plantation site fertility and site nutrient sustainability, thus precluding fertilizer.

Nutrient accumulation and export from fast-growing plantation sites has become an important consideration for long-term site quality and sustainability of production in short rotation, high-yielding forest plantation ecosystems. Some nutrients are lost through timber removal, while others are lost through the bark, branches, leaves, twigs, etc., especially where whole tree harvesting is practiced. Some researchers hold that the fast growth rate of tropical plantation species depletes site nutrient base and thus portends danger for long-term sustainability of production, while others opine that the decrease in productivity in successive rotations, where it exists, is due to inappropriate management practices such as soil compaction during site clearing and preparation, topsoil and litter repositioning, removal or burning of logging debris, harvesting methods, management of harvest residues, etc. (Khanna 1998; Kumar et al. 1998; Chen et al. 2004; Onyekwelu et al. 2006). Evans (1998) concluded that plantation forests are likely to be sustainable in terms of wood yield provided that good practices are maintained.

It is possible not only to sustain but also to increase productivity in successive rotations. However, this requires clear definition of end-use objective(s) and a holistic management view (Carle et al. 2002). To be sustainable, successive rotations will require the integration of the following strategies into the management plan (Carle et al. 2002): (1) tree improvement programs, (2) nursery practices, (3) site and species/provenance matching, (4) appropriate silviculture (site preparation, establishment, weeding, fertilizing, pruning, thinning), (5) forest protection, and (6) sound harvesting practices. Burning and excessive cultivation during site preparation, mechanical land clearing, soil compaction, inappropriate harvesting methods, and poor forest protection must be avoided. If well managed, increased productivity might result as was reported for second rotation stands of some species (Long 1997; Evans 1999a). If current plantations are not harvested by whole tree method and if successive stands are managed on long rotations, site nutrient capitals in successive rotations are likely to be maintained at the original level (Kimmins 2004; Onyekwelu et al. 2006). In addition, management of soil organic matter is of particular importance as it contains the bulk of the nutrients (Evans 1999a; Mathers and Xu 2003). Since the foliage, branches and bark, contains a reasonable amount of the nutrients, site fertility and productivity can further be improved by leaving these components on the site following harvest. Evans (1999a) concluded that "under certain conditions, nutrient export may threaten sustainability, but usually more important for maintaining site (plantation) quality are care with harvesting operations, conservation of organic matter, and management of weed environment. Plantation forestry appears to be entirely sustainable under conditions of good husbandry, but not where wasteful and damaging practices are permitted."

Using the example of *Pinus patula* plantations in Usuta forest in Swaziland, Evans (2002) demonstrated how a forest plantation can be productive over three rotations without the use of fertilizers (Tables 27.3 and 27.4). The report further demonstrated that productivity of plantations can be improved in successive rotations if they are properly managed. Also, the case study by Onyekwelu (2011, in this volume) on the sustainability of site productivity in *Gmelina arborea*

Table 27.3 Comparison of second and third rotations of Pinus patula on granite and gneiss derived soils at 13/14 years of age (Evans 2002)

Rotation	Stocking (n/ha)	Mean height (m)	Mean DBH (cm)	Mean tree vol. (m^3)	Vol/ha (m^3/ha)
Second	1386	17.5	20.1	0.205	294
Third	1248	18.7	21.2	0.233	326
% change		+7.1	+5.6		+11.0

Table 27.4 Comparison of second and third rotations of Pinus patula on gabbro dominated soils at 13/14 years of age (Evans 2002)

Rotation	Stocking (n/ha)	Mean height (m)	Mean DBH (cm)	Mean tree vol. (m^3)	Vol/ha (m^3/ha)
Second	1213	16.7	20.0	0.206	244
Third	1097	16.8	21.7	0.227	255
% change		+0.05	+8.3		+4.6

plantations demonstrates how the nutrient status of a tropical forest plantation site can be built up to its original level without the use of fertilizer.

27.11 The Dynamics of Stand Growth

Forest tree growth in the humid tropics is continuous due to the long duration of rainy season and because precipitation exceeds or equals potential evapotranspiration, thus the soil is continuously moist and there is hardly any season in which the soil dries out (Nwoboshi 1982; Evans and Turnbull 2004). This favourable condition results in a fast growth rate of trees. Many tropical forest plantation tree species, especially the exotics, are noted for their fast growth rate and the ability to attain rotation within a relatively short time, a situation that makes them attractive for short rotation forestry. This fast growth rate could be attributed to the ability of the trees to effectively utilize site and environmental resources.

Forest stand growth is dynamic, and continually changing. Forest stand dynamics is defined as the changes in forest structure, function and composition through time (Oliver and Larson 1996). Thus the dynamism of forest stand leads to changes in stand density, stand composition and stand structure. The knowledge of forest stand dynamics is applied in many areas of forest plantation establishment and management (Cannell and Last 1976; Kerr 1999). Several characteristics of the growth dynamics in forest plantations set them apart from uneven-aged stands and other types of forest structure (Bettinger et al. 2009). These differences are summarised in Table 27.5. Forest plantation stand does not usually end with the same number of trees it had at establishment. Although seedlings are almost uniform at stand establishment, the dynamic nature of forest stand results to the differentiation

Table 27.5 Comparison of several characteristics of the growth dynamics of forest plantations and uneven-aged forests

Growth characteristics	Forest plantations	Uneven-aged forest stands
Tree per unit area	Decreases with age	Varies through time
Mortality rate of stems	Decreases with age	Stays relatively constant over time
Mortality rate of volume	Decreases with age	Stays relatively constant over time
Height of canopy	Increases with age, then plateaus	Stays relatively constant over time
Canopy cover	Ranges from non to full	Ranges from full to one containing gaps
Average tree diameter	Increases with age	Fluctuates with harvest entries and mortality
Diameter distribution	Bell-shaped curve	Reverse J-shaped curve
Basal Area	Increases with age, then plateaus	Fluctuates with harvest entries and mortality
Timber growth rate	Rises, peaks, then declines	Stays relatively constant over time
Timber yield	Increases with age, then plateaus	Fluctuates with harvest entries and mortality

Source: Bettinger et al. 2009

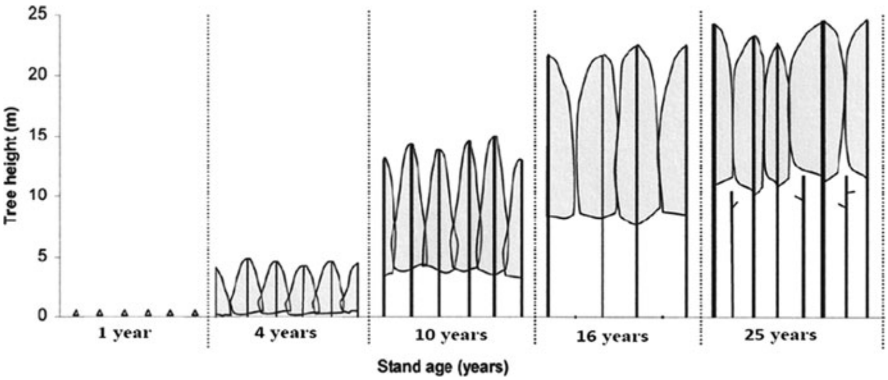

Fig. 27.2 Schematic presentation of forest stand development from establishment to maturity. The diagrams represent spacing, tree height and crown dimensions. The diagram for 16 years stand demonstrates the effect of thinning, which has resulted in a smaller number of trees but with large, uniform crowns (Wilson and Leslie 2008 – modified)

of trees into different tree sizes (Fig. 27.2). The change from one stage of development to another in forest ecosystem is influenced by species, site, climate and exogenous disturbance events (Wilson and Leslie 2008).

Four major stages can be distinguished in forest plantation development: (1) seedling stage, (2) sapling stage, (3) pole stage and (4) mature stage. The age at which each stage occurs depends on species and location. Fast growing species attain and transit from one stage to the other earlier than slow growing ones. However, each stage of the sequence may be disrupted by management interventions or natural disturbance (Kimmins 2004; Johnson and Miyanishi 2007). At the seedling stage, tree density is often very dense, usually in thousand(s) per hectare depending on the purpose of management. As individual trees become larger and transit to the other stage, the number of trees decreases due to the natural mortality (self thinning) of trees that had become weaker and overtopped from competition between the trees.

In even-aged stands, the differences in the performance of individual trees quickly sort them into crown classes, which apart from competition, could be caused by genetic differences between seedlings, site productive capacity, initial planting density, growth rate, differences in establishment after planting, and damage to seedlings (Kental 1988; Naidu et al. 1998; Evans and Turnbull 2004). Onyekwelu (2001) grouped trees in *Gmelina arborea* and *Nauclea diderrichii* plantations in Nigeria into two broad crown classes: suppressed and dominant classes. After crown closure in even-aged stands, growth and vigour of trees are strongly correlated with crown class, with trees in the dominant crown class performing better than those in the suppressed crown class (Fig. 27.3). This is because dominant trees compete better and capture more site resources than suppressed trees. Thus, crown expansion early in the life of the plantation and its subsequent restriction are critical in the growth dynamics of individual trees and their competitive advantage (Evans and Turnbull 2004).

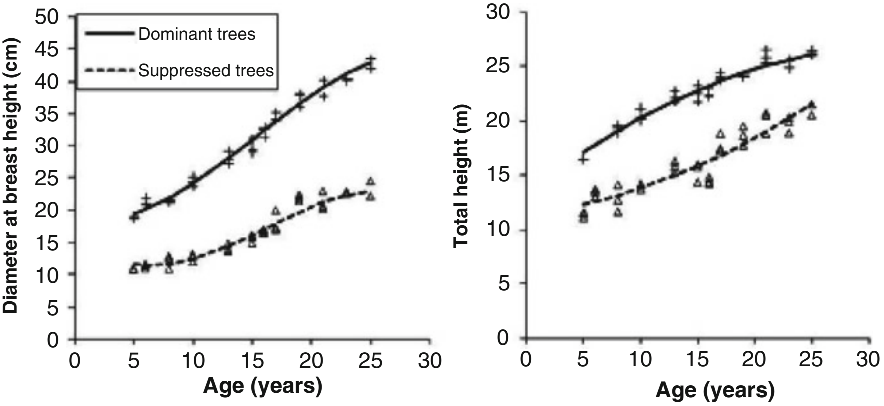

Fig. 27.3 Development of stand diameter at breast height and total height for two crown classes in Gmelina arborea plantations

27.12 Growth and Yield of Important Tropical Plantation Species

Fast-growing tropical plantation species such as *Eucalyptus* spp., *Albizia procera*, *Pinus caribaea* [*not radiata*], *Acacia mangium*, *Gmelina arborea*, etc. have high diameter growth which begins early in the life of the stand. Some of these species can attain a diameter (at breast height) of about 7 cm during the first year of growth (Lugo et al. 1990), but on an average, they are capable of maintaining rapid DBH growth rate of 3–5 cm/year (Hopmans et al. 1990; Panitz and Yaacob 1992; Onyekwelu et al. 2003a, b).

Rapid height growth has also been reported for species, like *A. mangium, Casuarina equisetifolia, Eucalyptus* spp*, Gmelina arborea, Tectona grandis,* etc., which can maintain height increment of between 2.7 and 6.0 m/year (Lugo et al. 1990; Gonzalez and Fisher 1994; Mok et al. 1999; Morataya et al. 1999; Krishnapillay 2000; Henri 2001; Onyekwelu et al. 2003a, b). However, this vigorous diameter and height growth are only maintained by the species at young ages. It is evident from reports in literature (see Table 27.6) that both diameter and height growth of tropical plantation species are rapid during the early years of growth and plateaus with increase in age (Bettinger et al. 2009). For most of these species, the maximum diameter and height increment are attained before the age of 10 years.

The high and rapid growth rates of tropical plantation tree species, coupled with their high density and intensive silviculture, translates to high basal area and volume production (Table 27.6), which has contributed to making them very important in meeting the world's growing demand for wood products, especially timber. Tropical plantations have been noted to have the ability of producing high amount of biomass within a relatively short period of time. Tropical forest

Table 27.6 Summary of growth and yield of selected tropical forest plantation species

Age (years)	Density (per ha)	Mean height (m)	Mean DBH (cm)	Basal area (m^2/ha)	Volume (m^3/ha)	MAI (m^3/ha/year)	References
Acacia mangium							
3	–	8.1	19.3	63.0	187.5	–	Newaz et al. (2005)
6	–	19.7	27.1	80.5	376.3	–	
9	–	25.5	30.4	87.4	474.7	–	
12	–	28.9	32.1	91.0	533.1	–	
1.5	1,667	11.5	11.0	–	76.9	35.0	Mok et al. 1999
3.7	1,533	18.7	14.0	–	176.9	47.8	
5.2	1,200	23.8	16.8	–	246.1	46.4	
Tectona grandis							
4.5	1,324	13.8	12.29	19.00	119.24	26.52	FAO (2002a, b)
10.5	468	22.5	23.9	36.88	329.85	31.41	
15	288	24.6	30.00	48.16	438.05	29.20	
20	249	25.3	34.5	54.12	505.12	25.30	
Gmelina arborea							
5	1,232	14.1	15.1	24.3	242.7	–	Onyekwelu et al. (2003a)
10	1,147	17.0	18.0	33.8	418.0	–	
15	1,184	18.0	21.1	48.3	630.7	–	
21	864	22.9	30.2	71.5	1165.0	–	
25	874	23.2	33.6	89.5	1519.3	–	
Pinus caribaea[a]							
6	–	9.0	–	–	37.5	6.2	Adegbehin et al. (1988b)
16	–	20.1	–	–	275.3	17.2	
26	–	27.0	–	–	615.0	23.6	
34	–	29.7	–	–	814	23.9	
Eucalyptus tereticornis[a]							
4	–	14.0	–	–	47.9	12.0	Adegbehin et al. (1988b)
10	–	23.4	–	–	131.2	13.1	
15	–	24.8	–	–	215.9	14.4	
20	–	25.1	–	–	295.0	14.8	
22	–	25.2	–	–	322.5	14.7	
Nauclea diderrichii							
5	667	9.0	9.6	4.12	28.27	5.65	Onyekwelu et al. (2003b)
9	587	13.1	15.7	13.86	121.40	13.49	
15	443	15.0	19.0	15.23	156.46	10.43	
24	491	21.1	24.3	23.18	344.37	14.35	
30	496	23.6	29.3	40.08	475.52	15.85	

[a] Height of dominant tree

plantations possess the capacity of producing between 3 and 10 times greater commercial biomass or timber per unit area than natural forests (Pandey 1995; Evans 1999c; Evans and Turnbull 2004). For example, while the maximum mean annual volume increment (MAI) in a natural tropical forest in Nigeria is 5 m^3/ha/year, that of an adjacent *N. diderrichii* (indigenous species) and *G. arborea* (exotic species) plantations were 16.0 and 51.5 m^3/ha/year, respectively (Lowe 1997; Onyekwelu 2001). Some tropical plantation species such as *Eucalyptus* spp., *Acacia mangium*, *G. arborea, Pinus* spp*,* etc., have MAI between 30 and 55 m^3/ha/year (FAO 2001a; Onyekwelu 2001; Evans and Turnbull 2004).

Given proper planning, good management and application of tree breeding, much higher yield is possible. For example, the maximum MAI of genetically improved *Eucalyptus grandis* plantations in Brazil and Cameroon was reported to range between 70 and 89.5 m^3/ha/year (Betancourt 1987; Pandey 1995). However, this high productivity is not applicable to all tropical forest plantation species. Some species (Teak, *Casuarina equisetifolia,* etc.) could have MAI as low as 2–4 m^3/ha/year (Lamprecht 1990; Enters 2000; FAO 2001a). The poor performance is mainly a result of low inputs and poor management, coupled with yield-reducing factors such as illicit removal, fire, pest infestation and disease outbreaks (Enters 2000). Given a good combination of high quality reproductive material, rigorous site selection and application of known technologies, good planting materials adapted to the site, appropriate silvicultural practices and improved protection, the yield of tropical forest plantation species could be increased considerably.

27.13 Thinning

There is a dearth of information in literature on thinning in tropical forest plantations. This can be attributed to two main reasons: (1) extensive forest plantation development in the tropics is a recent phenomenon and thus, time has been insufficient to undertake long-term thinning experiments (Evans and Turnbull 2004), (2) a high percentage of early extensive plantations were established as fuelwood and pulpwood plantations in which thinning programmes were not intended (Onyekwelu et al. 2003a). In addition, the lack of permanent sample plots, coupled with rising deforestation and encroachment into forest plantation stands in the tropics have hindered long-term thinning investigations.

The practice of thinning is one of the important and common basic tools of silviculture administered to improve tree growth rates. It has received increased attention with the advent of intensive forest management. Although unthinned stands usually show the highest stand density (relative mean basal area = 100%), such stands respond to thinning with a significant increase in volume increment. Optimum stand density (optimum basal area) is reached when the annual volume increment is at a maximum. A further reduction of basal area leads to increment losses (Pretzsch 2009). In practice, foresters seek to develop thinning schedules for an optimization of management and productivity.

Thinning involves practices ranging from light removal of small understory trees to heavy removal of dominant overstory trees. By implication, thinning is a controlled process by which inferior trees are progressively eliminated and better ones are encouraged to develop so that only the best candidate trees will remain for final harvest. Thus, it promotes the growth of the best individual trees in a stand by removing damaged, diseased, or deformed trees and concentrating growth on fewer, high-quality trees. Thinning is a complex biotechnical measure that needs careful planning. Before administering thinning, account should be taken of the stand's biological characteristics, e.g., age, density, composition and productivity, as well as site conditions, e.g., topography, climate, soils, rate and character of anthropogenic disturbance and wildfire dynamics (Danilin 2006).

The main objectives of thinning in forest stand include (Evans and Turnbull 2004): (1) to reduce the number of trees in a stand so that the remaining ones will have more space for crown and root development, thereby encouraging stem diameter increment and reach utilizable size sooner, (2) to remove dead, dying, diseased and any other tree that may be a source of infection for or cause damage to the healthy trees, (3) to remove trees of poor stem form, e.g., crooked, forked, roughly or heavily branched trees, etc., so that all future increments are concentrated on trees with good stem form, (4) to favour the most vigorous trees with good stem form which are likely to be part of the final crop and (5) to provide an intermediate financial return from thinning. Other objectives of thinning include: maintaining light level beneath a forest stand to provide vegetation for grazing, reduction of wildfire risk, encouraging ground forest flora, providing poles and posts, increasing recreational and amenity value of the forest, etc.

The main benefit of thinning is to increase economic gain, which may be achieved through improving the value of the residual stems (products), offsetting the expense of carrying establishment costs to rotation age, and/or increasing stand utilization. Large trees are more valuable than small ones because the resulting products from large trees have a greater value than those from small trees, particularly ones below sawlog size. Other benefits of thinning being recognized are increase in light and nutrient availability, risk reduction for insect infestations, disease epidemics, and damage from abiotic agents, etc.

27.13.1 Timing of Thinning Operation

The timing of thinning operations in forest plantations, especially the age at which thinning should commence is one of the most important and critical management and silvicultural decision in a rotation. Making an early start will affect stem quality and crown development and trees respond too slowly when stands are thinned too late (Lewis et al. 1976; Nwoboshi 1982; Dean and Baldwin 1993; Morataya et al. 1999). Wrong or poor timing of thinning operation can have profound effect, not only on the current status of the forest (Geoff et al. 2006), but also on future forest conditions. Thinning operations are usually administered between canopy closure and culmination of Mean Annual Increment (MAI) (Strin 1990) and should be determined by management objectives, site quality, stand density, probability of subsequent thinning operations, rotation length, etc. If sawlogs, veneer logs or multiple products are the objective(s) of management, early thinning may be required to increase the proportion of large, high quality, merchantable stems at final harvest, especially in short rotation, high density stand and on good sites with high growth potential. It is recommended that the final thinning be carried out before the peak of MAI.

First thinning can be administered earlier on land with high site quality than land with low site quality. However, the significance of site in administering the first thinning is better understood when considered with stand density. Time of the first thinning, even on the best sites, can be delayed in stands with poor survival and low initial planting density. The first thinning is best administered as soon as the seedlings are well established (i.e., shortly after canopy closure), prior to overcrowding and competition, reduction in diameter growth, heavy mortality and before the live crown ratio is reduced to below 35% of total height. Depending on species and site condition, this is usually between ages of 2 and 5 in tropical forest plantations (Dupuy and Mille 1993; FORMECU 1999), before the trees experience severe intraspecific competition and while they are still small enough to permit thinning with relatively light equipment such as a rotary mower or light chopper. Hughell (1991), Dupuy and Mille (1993), FORMECU (1999) and Morataya et al. (1999) recommended 3–4 years after plantation establishment for the first thinning in Gmelina plantations while Onyekwelu et al. (2003a) recommended 5 years for first thinning in Gmelina stands. Florence (1996) recommended that *E. grandis* plantations should be thinned within 2–4 years of canopy closure. However, care must be taken not to administer first thinning too early, as it may encourage the development of epicormic branches and slow down self-pruning. On the other hand, delayed thinning may result in a decline in release potential, higher risk of windthrow due to the spindly nature of trees and volume lost to natural mortality.

Experience in thinning in forest plantations in Latin American countries has increased in recent years (e.g., Galloway et al. 1996; Morataya et al. 1999; Kanninen et al. 2004). Based on their findings, Morataya et al. (1999) concluded that a delay in thinning (especially first thinning) is not desirable in *Gmelina* and Teak plantations, since both attained the greater portion of their diameter growth during the first 6–8 years. Amakiri and Nwoboshi (1986) showed that thinning reduced nutrient uptake from the soil, their accumulation in the vegetative part as well as the rates of litter decomposition and release of K and N in 25-year old *T. grandis* plantation. In Costa Rican teak plantation, highest individual tree growth was obtained when the plantations were thinned at 60% thinning intensity applied at the age of 4 years, and the two consecutive 25% thinnings at the ages of 8 and 12 years (Kanninen et al. 2004). Thinning had a significant effect on the diameter and height growth of individual trees in both pure and mixed plantations, with the thinned stands having greater diameter and height growth than unthinned ones. However, the unthinned stands generally had higher basal area and volume growth (Piotto et al. 2003). In a 24-year-old plantation of *Acacia koa*, thinning in combination with grass control and P fertilization significantly increased annual diameter increment by 118%; thinning alone did not produce a significant increase in diameter increment (Scowcroft et al. 2007). In a thinning experiment in Nigeria, Lowe (1976) found that 5 years after implementing a moderate and a heavy thinning operation, trees in a 20-year-old plantation reacted positively to thinning in terms of individual tree growth and concluded that thinning reinforced rather than changed the pattern of discriminative growth within the stand, even for the heaviest thinning. Other

Table 27.7 Thinning regimes used in the management of some tropical forest plantation species in various parts of the tropics

Tree species	Location	Age (years)	Stocking (tree/ha)	Reference(s)
Tectona grandis	Costa Rica	0	1,111	Pérez and Kanninen (2005)
		4	556	
		8	333	
		12	200	
		18	150	
		24	120	
		30	Clear-fell	
Gmelina arborea	Nigeria	0	1,300	Onyekwelu et al. (2003a)
		5	400	
		10	330	
		15	280	
		20	Clear-fell	
Eucalyptus grandis	South Africa	0	1,370	Schönau and Coetzee (1989)
		3–5	750	
		7–9	500	
		11–13	300	
		25–30	Clear-fell	
Nauclea diderrichii		0	1,111	Dupuy and Mille (1993)
		5	400–500	
		9	200–250	
		15	130–170	
		30–40	Clear-fell	
Pinus caribaea var. hondurensis	Queensland Australia	0	746	Evans and Turnbull (2004)
		2–3	700	
		22	500	
		30	300	
Araucaria cunninghamii	Queensland Australia	0	833	Hogg and Nester (1991)
		25	400	
		45–50	Clear-fell	

thinning experiences in tropical forest plantations include: Schönau and Coetzee (1989), Yahya (1993), Medhurst and Beadle (2001), Mabvurira and Pukkala (2002), Medhurst et al. (2003)and Pérez and Kanninen (2005). Based on experience and scenarios, thinning regimes have been recommended for various tropical forest plantation species. These recommendations are summarised in Table 27.7.

27.13.2 Positive Effects of Thinning

Most of the positive effects of thinning are obtained by increasing the amount of growing space available to residual trees. The temporary elimination of competition between individual trees for light, soil moisture and nutrient and the quick response of the trees to take advantage of the additional growing space result in the following main positive effects.

1. Trees in pure and mixed plantations of some tree species (*Terminalia amazonia*, *Vochysia guatemalensis*, *Jacaranda copaia*, *Virola koschnyi*, *Vochysia ferruginea*, *Calophyllum brasiliense* and *Genipa americana*) responded significantly to thinning with increased diameter growth (Piotto et al. 2003). Maximum diameter growth of residual trees is obtained when thinning is conducted early, at the onset of competition between trees. When plantations are thinned too late, there is little or no gain in diameter growth as residual trees respond too slowly to the additional growing space. For example, the diameter increment in *Gmelina arborea* and *Tectona grandis* plantations thinned late, which did not differ significantly with that of unthinned stands (Morataya et al. 1999).
2. Tree growth is strongly correlated with the amount of carbohydrate produced, which is a function of crown size and the ability of the root system to supply water and essential nutrients (Nwoboshi 1982). When trees are released from competition through thinning, their roots quickly respond with rapid lateral extension, thus most of the initial increases in growth following thinning are due mainly to increased moisture and nutrients supply. Also, the additional growing space surrounding a tree after thinning induces active growth of shoots and foliage, which results in outward crown expansion. Morataya et al. (1999) showed that early thinning in Gmelina and Teak plantations in Costa Rica resulted in more average foliage per tree than in unthinned stands.
3. Reduced susceptibility of stands to disease, insect and fire attack due to the removal of diseased and infested trees. Dense stands with slow growth and reduced tree vigour are more subsequently prone to insect and disease attack than healthy trees in well-spaced stands (Nebeker et al. 1985). Uninfested trees are generally larger, with thicker bark, greater crown/bole ratios, larger crowns, and faster growth rates. Good forest management with scheduled thinning has continued to be recognized as a means of maintaining healthy stands and promoting resistance to insect and disease attack (Nebeker et al. 1985).
4. Some genetic improvement may be achieved through thinning (Nebeker et al. 1985). The removal of diseased trees or trees with undesirable characters, e.g., bad growth form, by means of thinning prior to regeneration of the stand, can minimize undesirable traits in the following generation.
5. Other positive effects of thinning include:
   - Improved access for equipment
   - Enhanced wildlife habitat through increased herbaceous ground cover

27.13.3 Negative Effects of Thinning

1. Thinning facilitates the shaded low branches at the base of the live crown of residual trees to receive more light and remain alive longer, thus resulting in larger lower branches, higher live-crown ratio and delayed natural pruning. In addition, large epicormic branches may develop along the stem. While this may be desirable in maintaining rapid growth of individual trees, it adversely affects

wood quality and product value due to the increased size and number of knots in the timber (Geoff et al. 2006; West 2006).

2. Vulnerability of residual trees to wind or rainstorm may increase by increasing turbulence within the stand and allowing more sway of trees (Moore and Maguire 2005). Increased swaying increases the force exerted on the ground, thus increasing the risk of uprooting (Cameron 2002). The gravity of this damage varies with the rooting characteristics of the species. Shallow rooting species are more susceptible than deep rooting species. Also, tree swaying in a thinned stand substantially increases the amount of tension wood that develops in the stem of residual trees (West 2006).
3. There could be felling-related damages in the form of branch breakage, bole wounding, root breakage, bending and breakage of whole trees. The degree of felling-related damage is influenced by method of felling, felling equipment and its configuration, tree species, density, stand age, site climatic conditions (e.g., wind or rainstorm).
4. Reduction of the photosynthetic surface area in a stand, and thus an immediate drop in production per unit area occurs. Since thinning does not raise site production potentials, it does not raise the overall or total production of a stand. When compared to an unthinned stand, the total stand production of a thinned stand is less.

27.13.4 Methods of Thinning

Of the various thinning methods four have been widely accepted: (a) Low thinning (thinning from below), (b) Crown/high thinning (thinning from above), (c) Selection thinning, and (d) Mechanical (systematic) thinning (Fig. 27.4). Thinning methods that do not conform to any of the above are sometimes referred to as “free thinning” (Province of British Columbia 1999). Thinning method influences the diameter distribution of a stand (Fig. 27.4) as well as the subsequent growth of the residual stand because all the trees in the stand are not equally vigorous or able to respond equally to release. Thinning method also affects the revenue derived from the thinning. Methods that remove large trees will often be more profitable than those that remove smaller trees. For even-aged, single-species plantations, tree vigour is closely related to their position in the canopy. The method that results in the greatest growth response and best quality trees may also be the most expensive. Thus, the best choice of thinning method will often represent a compromise between cost and quality. Often a combination of thinning methods is used during a single operation due to the irregularity of the relative crown positions of the trees in most stands.

Details of the different methods and their characteristics are described comprehensively in e.g., Nyland (1996), Smith et al. (1997), Graham et al. (1999) and Evans and Turnbull (2004).

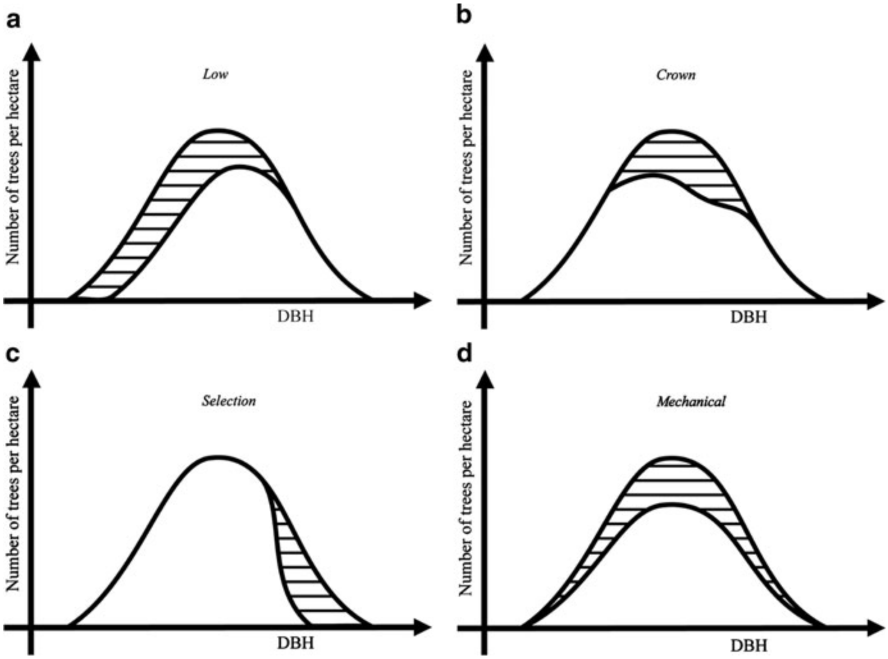

Fig. 27.4 The effect of different methods of thinning on diameter distribution of a forest stand (Evans 1982, Smith et al. 1997 – modified)

27.14 Pruning

Pruning is a silvicultural technique that removes branches in order to improve wood quality. It is often applied in two subsequent steps to different heights of the trunk, first in the so-called “low pruning” (3–4 m high) and second in a “high pruning” (6–8 m high) which takes place at the same time as selective thinning is carried out.

Montagu et al. (2003) comprehensively reviewed the biological and silvicultural basis for producing clear wood from planted eucalypts. Despite the “self-pruning” nature of many eucalypts species, the amount of clear wood able to be produced by untended stands is limited. Pruning increases the proportion of clear wood. The authors suggested that pruning should be undertaken while branches are small and alive. Minimising decay entry by ensuring branches are small when pruned is an important control measure. Pruning in conjunction with thinning can substantially increase the volume of clear wood produced.

27.15 Protection Against Pests and Diseases

Plantation forests should be managed with the objective of keeping them in a healthy, productive condition, one in which pests and disease are kept at low levels and do not interfere with management objectives.

Interestingly, the overall conclusion of a study by Nair (2001) is that while plantations are at greater risk of pest outbreaks than natural forests, plantations of exotic species are at no greater risk than plantations of indigenous tree species, because the exotic status is only one among the many determinants of pest outbreak.

Nair (2007) distinguishes three categories of insect pests associated with plantation tree species: nursery pests, sapling pests and pests of older, established plantations. Focussing on the latter serious pests include defoliators, sap suckers and stem borers. Leaf-feeding insects causing serious damage occur on *Dalbergia sissoo,* Eucalypts*, Falcataria moluccana* and *Tectona grandis*, among others. Nair (2007) mentioned, for example, the case of the caterpillar *Hyblaea puera,* which caused annual defoliation in some teak plantations in Asia that resulted in a 44% loss of the wood volume increment. According to Nair, this pest is becoming increasingly important in exotic teak plantations in Latin America.

Efforts to establish plantations of the African mahoganies *Khaya anthotheca* and *K. ivorensis* to sustain timber supply have been discouraged by the shoot borer *Hypsipyla robusta* moore. It was hypothesized that there is a shade level at which *Hypsipyla* attack and branching are reduced, but height growth is adequate (Opuni-Frimpong et al. 2008). The authors reported on the growth of these African mahoganies and *Hypsipyla* attack under three different forest canopy shade levels: open, medium shade, and deep shade. *Hypsipyla* attack on *K. anthotheca* was 85%, 11% and 0% attack in the open, medium and deep shade treatments, respectively. However, growth in medium and deep shade was slow, which limited the use of this strategy for controlling *Hypsipyla* attack. In Latin America, attack by *Hypsipyla grandella* Zeller is the main reason for the limited success of plantations of *Cedrela odorata* or *Swietenia macrophylla*, two other prominent and highly valuable representatives of the Meliaceae family. Because there is no viable method of pest control currently available, provenance and progenies of the two species are assessed for genetic variation in susceptibility to pest attack, especially for high foliar proanthocyanidin content, which may provide scope for selection for the ability to tolerate attack (Newton et al. 1999).

Wingfield and Robison (2004) reviewed insect pests and diseases of *Gmelina arborea*. In plantations within the natural range of the species, insects have caused substantial damage. Among these, the defoliator *Calopepla leayana (Chrysomelidae)* appears to be most important. No serious insect pest problems have been recorded where *G. arborea* is grown as an exotic, but some fungal pathogens have been introduced into those areas. Among these, leaf spot caused by *Pseudocercospora ranjita* is most widespread although it has not caused any substantial damage. A serious vascular wilt disease caused by *Ceratocystis* *fimbriata* in Brazil has caused the most significant failure of *G. arborea* in plantations.

The expansion of acacia plantations in Southeast Asia has also increased concern regarding the threats posed by diseases, such as those caused by fungal pathogens (Rimbawanto 2002; Lee 2004). Surveys between 1995 and 1996 resulted in a review of the current knowledge of the pathology of *A. mangium, A. auriculiformis, A. crassicarpa* and *A. aulacocarpa* in tropical areas of Southeast Asia, India and Australia (Old et al. 2000). The five most significant diseases according to the survey are root rot (*Ganoderma* complex), stem canker (e.g., *Lasiodiplodia theobromae*, *Botryosphaeria* spp.), pink disease (*Corticum salmonicolor*), heart rot (wood decay fungi) (Barry 2002; Lee 2002) and phyllode rust (*Atelocauda digitata*).

Old et al. (2003) presented a comprehensive review on Eucalyptus diseases in Southeast Asia. Barber (2004) mentioned Cryphonectria canker, Eucalyptus rust, Mycosphaerella leaf disease and the diseases caused by *Phaeophleospora destructans* and *P. epicoccoides* as major threats for Indonesia's eucalypt plantation forests. Eucalyptus rust is caused by *Puccinia psidii*, which occurs predominately in Latin America, and is a remarkable disease in that the pathogen is not known on eucalypts in their places of origin. It has apparently originated on native Myrtaceae in South America and is highly infective on some *Eucalyptus* spp. planted there. *P. psidii* causes one of the most serious forestry diseases in Brazil and is considered to be the most serious threat to eucalypt plantations worldwide (Coutinho et al. 1998).

A pantropically occurring pathogen is *Phellinus noxius* (Ramsden et al. 2002), which was also recently identified to cause a basal root rot in teak plantations and brown root disease in *Azadirachta excelsa* plantations in Malaysia (Mohd et al. 2005, 2006).

For further information, we recommend consulting region-specific reviews on insect pests and fungal diseases of plantation forests, e.g., for the Asia-Pacific region (Ramsden et al. 2002), Tanzania (Nsolomo and Venn 1994) or Uganda (Nyeko and Nakabonge 2008).

Integrated pest management (IPM) is a framework of decision making and action tools designed to maintain and improve forest health. Pest and disease-monitoring ensures early detection of potential problems. Combined with analysis of the economic, social and ecological impacts of pests, a sound basis on which to decide for or against control is derived. Two basic strategies, prevention or direct suppression, each with a range of tactics, can be applied. Prevention consists of actions taken to make trees and forests less hospitable to the build-up of pests and diseases and/or preventing new introductions. Direct suppression consists of biological, chemical or mechanical tactics designed to reduce pest and disease populations and subsequent losses. IPM systems consist of a combination of monitoring and action tools designed to reduce pest-induced losses. These systems are continuously evolving and are capable of accepting new technologies, as they become available (FAO 2001a, b, c, d).

27.16 Rotation

Rotation length is the total number of years between establishment and final felling that a forest plantation is allowed to grow. It is an important tool for controlling tree size: the longer the rotation, the larger the tree (Evans and Turnbull 2004). Rotation length (age) in forest plantation management is determined by various factors including: species, site quality and environmental conditions, rate of wood and fibre production, desired wood and fibre properties, regeneration method, tending operations, profitability. Profitability is the over-riding factor that determines rotation age. A properly designed forest plantation investment should encompass growth rates and wood properties in an investment equation that marries costs and prices to determine the optimal length of time that the plantation investment should be "held" (FAO 2001b).

A wide array of rotation ages are used in tropical plantations (Table 27.8). As low as 3–5 years, rotation is used in the establishment of high density, short rotation plantations, especially energy plantations. Up to 100 years rotation may occur for very high-value timber plantations such as teak. Generally, management inputs under very long rotation regimes have to be very low to be financially viable and the forest may revert to semi-natural status long before it is harvested (FAO 2001b). The length of rotation is closely related to the tree species and the proposed end-use of the plantation products. Generally, the shortest rotation age is found in energy

Table 27.8 Common rotation ages for various tropical forest plantation species in different parts of the world

Tree species	Rotation length (years)		
	Energy plantation	Pulpwood/pole plantation	Timber/veneer plantation
Eucalyptus camaldulensis	4–8	7–15	–
Eucalyptus grandis	5–12	5–15	–
Eucalyptus globulus	3–5	8–19	–
Eucalyptus deglupta	–	10–12	–
Gliricidia sepium	5–8	–	–
Acacia auriculiformis	5–10	–	–
Acacia mangium	5–14	–	–
Gmelina arborea	8–15	8–15	15–25
Pinus caribaea	–	10–20	15–25
Pinus patula	–	12–20	15–30
Leucaena leucocephala	5–8	–	–
Paraserianthes falcataria	9	5–15	–
Tectona grandis	5–10	–	30–70
Araucaria angustifolia and *A. cunninghamii*	10–12	–	40–90
Casuarina equisetifolia	8–15	–	30–50
Swietenia macrophylla	–	–	40–60
Terminalia ivorensis and *T. superba*	–	20–25	30–60
Nauclea diderrichii	–	15	35–40

plantations while the longest rotation is common in timber/veneer log plantations (Table 27.8).

Several types of rotations have been identified by foresters (Fenton 1967), which include:

1. Physical rotations
2. Silvicultural rotations
3. Technical rotations
4. Financial rotations
5. Rotation of maximum volume production

In the tropics, technical rotation and rotation of maximum volume production are most common. Technical rotation yields the most out-turn of a specified size and type to satisfy a particular end-use (Evans and Turnbull 2004). Applying technical rotation requires that a certain limit (usually lower limit) be set and that the trees be harvested when the limit is attained. However, upper limits may sometimes be used. It may sometimes be necessary to extend technical rotation to obtain better product. For example, it is important to allow pruned stands to grow beyond a specified technical rotation so that a worthwhile layer of clear, knot-free wood is laid down.

It has been shown that the culmination age of mean annual increment (MAI) in forest plantation corresponds to the age of maximum volume production. This MAI culmination age can be used as the biological basis for determining rotation age, if the objective of management is timber production (Clutter et al. 1983; Adegbehin et al. 1988a, b; Smith et al. 1997). This rotation is complete when the current annual increment (CAI) of the stand falls to MAI level (Fig. 27.5). It is the rotation of maximum volume production if the stand is felled at this point

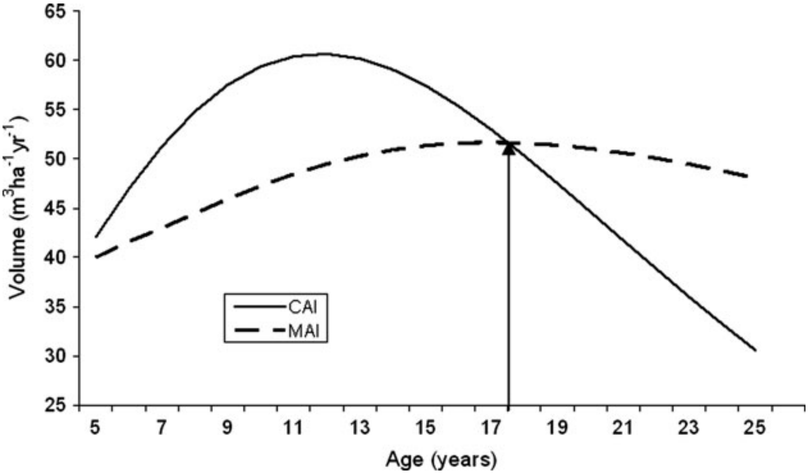

Fig. 27.5 Relationship between current (CAI) and mean annual volume increment (MAI) in Gmelina arborea plantations in Nigeria

(Evans and Turnbull 2004). The rotation age based on the culmination of MAI is attractive because it tends to realize the maximum growth potentials of a species on a particular site. This is because for a given parcel of land, it is the harvest age that will maximize total volume production from a series of rotations. Due to the high yield occasioned by the fast growth rate and early culmination of MAI, rotation age for many tropical forest plantation species are set to coincide with culmination age of MAI, especially for management objectives (e.g., pulpwood) that target maximum volume production. The culmination of MAI has been used to set rotation ages for plantation species such as *Pinus* spp.*, Araucaria cunninghamii, Eucalyptus* spp.*, Tectona grandis*, *Gmelina arborea* and *Nauclea diderrichii* (Sharma 1979; Adegbehin et al. 1988a, b; FORMECU 1999; Onyekwelu et al. 2003b; Evans and Turnbull 2004).

For a number of tropical plantation tree species, the culmination of MAI occurs very early in the life of the stand. For these species, the use of rotation of maximum volume production may not be adequate if very large dimensions logs (e.g., for timber and veneer log) are desired. Consequently, rotation age will have to be extended beyond the age of MAI culmination to the age at which the desired dimension will be obtained. However, the extension of rotation age beyond the culmination age of MAI usually sacrifices volume growth for quality.

27.17 Regeneration of Subsequent Generations

Replanting is the commonest method for regenerating forest plantations in the tropics (FAO 1998). In most cases, plantations are clear-felled and seedlings (or cuttings) of the same or totally new species are reestablished on the same site. However, apart from replanting, forest plantations can be regenerated through other means, among which are regeneration from coppice and natural regeneration through seeds.

27.17.1 Coppice Regeneration and Management

The coppice method of regeneration differs from other methods in that it depends on the shoots re-sprouting from the cut stump of the previous crop. Coppice management is therefore the operation of felling trees and regenerating them through coppices. Coppice management is restricted to tree species that typically sprout vigorously and have sprouts capable of attaining commercial size (Young and Giese 2003). In coppice management, the originally planted trees are felled and the next crop develops from the vigorous shoots (coppice) that sprout from the stumps. To obtain good coppice sprouts, healthy and dominant trees should be used and felling should be conducted during the rainy season and should be low and clean, without tearing of the bark (Venter 1972; Xu et al. 1999; Evans and Turnbull 2004). This is because the quality of the mother tree affects the quality and growth rate of the coppices. The larger the diameter of the coppiced stump, the more the shoots that will grow (McKenna and Woeste 2006). However, there is evidence that shoots developing on old root stocks (after two or three cuttings) exhibit premature aging and earlier culmination of height growth (Evans 1999c). In addition, some stumps die with each coppice cutting and yield declines as site occupancy diminishes (Evans 1999c).

If properly managed, coppices could be used to regenerate tropical forest plantations after harvest at the end of rotation. Coppices could grow faster than planted seedlings. In an experiment with *Eucalyptus urophylla*, Xu et al. (1999) reported that without fertilisation, coppiced trees grew better than replanted trees. Fertilisation did not have a significant effect on the growth rate of coppice trees as against the significant effect of fertilisation of replanted trees. The high growth rate obtained with fertilisation in replanted trees was comparable to that obtained without fertilisation in coppice trees, which suggests that the well-developed root systems of the previous tree helped coppiced trees to take up soil nutrients better than the smaller root systems of the replanted trees. Since several coppices usually develop on a single stump, tending operations is essential, if viable tree products are to be obtained.

Though there is evidence that many tropical forest plantation species have good coppicing ability, coppice management is not popular in the regeneration of tropical forest plantations. Coppice stands are usually managed on short rotations for the production of fuelwood or pulpwood. The use of coppice methods was once popular in Europe but declined in the second half of the twentieth century as oil and gas became cheap (Young and Giese 2003). However, the surge of interest in bioenergy has revived interest in coppice management, especially in Europe, where it is used in the production of high density short rotation energy plantations, thus it is more popular in the regeneration of energy plantation. Coppice management was recommended for second rotation of Eucalyptus plantations unless better genetic material is available for planting. Second rotation of some tropical plantation species (e.g., *Gmelina arborea; Eucalyptus* spp, etc.) has been regenerated through coppice management (Lamb 1968; Suilaman and Lim 1989; Xu et al. 1999). Information on the coppicing ability as well as the growth performances of the coppices of many tropical forest plantation species is lacking, which makes research in this area a necessity.

27.17.2 Natural Regeneration

Profuse regeneration of some important indigenous tree species has been reported in the understory of both monoculture and mixed species plantations (Fahy and Gormally 1998; Wilkie 2002; Lee et al. 2005; Onyekwelu and Fuwape 2008). This regeneration under forest plantation is sometimes comparable to that under natural forest ecosystems. For example, seedlings of *Cola gigantea, Diospyros mespiliformis, Celtis zenkeri, Drypetes* spp*, Hunteria umbellata, Bridellia* spp*, Lophira alata, Ricinodendron heudelotii, etc.* were reported in the understory of

Gmelina arborea monoculture plantations in tropical rainforest ecosystem of Nigeria (Onyekwelu and Fuwape 2008). This is mostly from the seeds buried in the ground prior to forest plantation establishment as well as seeds dispersed from trees in neighbouring natural forests. The implication of the regeneration of indigenous tree species under the canopies of forest plantation is that when current plantations are harvested, the plantation site has the potentials of returning to multi-species ecosystems akin to tropical secondary forests. This kind of regeneration can be adopted if the objective is to gradually revert the plantation site to natural forest site.

Also, many plantation species exhibit profuse natural regeneration (Evans and Turnbull 2004) from the seeds of the species after natural seed fall. *Cordia alliodora* is reported to exhibit profuse natural regeneration throughout Central America (Evans and Turnbull 2004). In Nigeria, naturally regenerated seedlings (also called wildlings) of *Gmelina arborea, Tectona grandis* and *Nauclea diderrichii* are used to augment seedling requirements and to replace planting failures. These seedlings have not been found to be genetically inferior (in terms of growth and yield) to seedlings raised in the nursery. For *Gmelina arborea*, naturally regenerated seedlings are mostly found at the edge of the plantation (Onyekwelu 2001). Although this regeneration system is not commonly used in industrial plantation establishment in the tropics, it has potentials that should be explored. The use of this regeneration method can present a cheaper means of plantation establishment and reestablishment.

27.18 Plantations and People

To meet the growing demands for wood in developing nations, there will have to be intensification of management of industrial plantations, combined with substantial increase in their productivity, and a greater reliance on wood produced by rural populations for their own use and for industry (Turnbull 1999; Mead 2005).

This review focuses on aspects of tree cultivation such as species choice, domestication and tree improvement, site selection and preparation, seed procurement and plant propagation (incl. biotechnology), nutrient management, management of pests and diseases, thinning, etc. However, social dimensions of silviculture, especially with regard to forest plantations, are rarely discussed. Endo (2003) argues that how trees are planted and managed and how a forest plantation project is organised have a long-term effect on people. However, as forest plantations become more widely established, the impacts of forestry programmes on people become substantial and need attention. According to Endo (2003) an important goal may be, “how to make a forestry project more people-friendly while maintaining or improving the project’s competitiveness.”

In developed countries there is growing concern not only on the sustainability of wood production but also on the environmental and social impacts of plantations in a regional and local context (e.g., Sawyer 1993; Kanowski 1997; Turnbull 1999).

For instance, social conflicts with local people have caused some unsuccessful timber plantation developments in Indonesia (Nawir and Santoso 2005) and elsewhere. Charnley (2005) reviewed cases which indicated that Intensively Managed Industrial Roundwood Plantations (IMPIRs) often bring about land ownership concentration, loss of customary rights of resource access, rural displacement, and socioeconomic decline in neighbouring communities. Often IMPIRs do not appear to provide enough quality jobs to stimulate community development, and rarely benefit people who are already politically and economically marginalized.

Successful beneficial partnership is based on commercial feasibility, equitable agreements, appropriate benefit and cost sharing and a shared understanding of co-management and participatory approaches. Essential for the debate are the questions of what forest practices are acceptable and appropriate on a given piece of land in a particular social context, and who decides. Decision makers concerned with plantation establishment and management should take into account their advantages to local people, and give local residents a voice in the decision-making process, which will help to reduce community resistance to industrial plantations and does not contribute to the decline of rural communities and indigenous cultures (Charnley 2005; Nielson and Evans 2009).

27.19 Conclusions

Forest plantations are established for a variety of reasons and vary in composition and structure, as well as in intensity of management. They are relatively simple production systems, usually even-aged monocultures, mostly managed to optimize the yield of wood from a site, protect or reclaim an environment and provide benefits and/or amenities that are important to the community.

It should be possible to grow most of the wood humans need in managed plantations, and hence eliminate the need to log wild forests (Sedjo 1999). Those wild forests are sinks of carbon and sources and resources of biodiversity. By establishment of plantation forests for the purpose of carbon sequestration, nations could be compliant with the Kyoto Protocol (Sedjo 1999). So plantations can offer a viable means of both conserving natural forests and reducing the amount of CO_2 in the atmosphere. The objective of managing plantations in an economic, ecological and socially responsible way has led to the formulation of criteria and indicators as well as guidelines for sustainable plantation forestry (e.g., Muhtaman et al. 2000; FAO 2006). Certification as an instrument for safeguarding was put into practice but sometimes criticized for being ineffective.

Successful plantation forestry will continue to depend on effective research, development and management, and on innovation and technological advances (Kanowski 1997). The appropriate form of technology will vary with social, environmental and economic circumstances. Kanowski (1997) postulates that the sustainability of plantation forestry will be enhanced, and the benefits of investments most fully realised, where plantation purpose and practice are embedded within the broader social and economic contexts: *In realising the considerable potential of plantation forestry to benefit society, one of the principal challenges to plantation forest owners, managers and scientists is to progress from a narrow focus, which Shiva (1993) has characterised as "monocultures of the mind", to a broader appreciation of plantation purpose and practice. We are well placed to do so, by building on the considerable body of experience and information we have gained relevant to plantation and other forms of forestry in many environments. It is in doing so that we shall sustain plantation forestry in the next century, and maximise its benefits.* As Evans (2009a, b) concludes concerning planted forests as a whole: *Planted forests are not a panacea but are a sustainable way of meeting the world's timber requirement from less than 7% of the world's forest area or a mere 2% of land.* Planted forests of the tropics are making a major and increasingly significant contribution.

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