SUSTAINING TROPICAL FOREST RESOURCES

REFORESTATION OF DEGRADED LANDS

OTA Background Papers are documents containing information that supplements formal OTA assessments or is an outcome of internal exploratory planning and evaluation. The material is usually not of immediate policy interest such as is contained in an OTA Report or Technical Memorandum, nor does it present options for Congress to consider.

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Preface

Deforestation has claimed half of the world's original tropical forest lands. The result has been a decline in the land's inherent productivity, with serious repercussions on human welfare. One solution to this vast problem is reforestation. More specifically, tree planting on degraded lands can help restore land productivity as well as provide wood for building materials, fuel for cooking, and fodder for livestock.

This background paper is designed to provide the U.S. Congress with an overview of some reforestation technologies and their possible beneficial and adverse impacts. It also discusses the constraints and opportunities for the introduction of these technologies in such activities as timber and fuel production, watershed protection, and agroforestry.

This paper is part of OTA's forthcoming assessment *Technologies To Sustain Tropical Forest Resources.* A concurrent background paper, *Sustaining Tropical Forest Resources: U.S. and International Institutions,* will focus on the role of various institutions in developing and implementing technologies to sustain tropical forest resources. These analyses form the main part of OTA's response to the general request of the House Committee on Foreign Affairs and the Senate Committee on Energy and Natural Resources, and supported by the Subcommittee on Insular Affairs of the House Committee on Interior and Insular Affairs and the Subcommittee on Environmental Pollution of the Senate Committee on Environment and Public Works.

This paper was authored by OTA analysts Susan Shen and Alison Hess. OTA also wishes to acknowledge the tropical forest resources advisory panel and executive agency liaisons who reviewed this document and contributed technical information to the OTA staff.

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Highlights

- Approximately 2 billion hectares (5 billion acres) of tropical lands are in various stages of degradation and have, in theory, potential for reforestation.
- Most manmade reforestation is done with imported species. Many native trees, more familiar to local people, have untapped potential for reforestation.
- Tree plantations using only one species are widespread. Little effort is being made to develop technologies for multiple-species reforestation.
- Selection and breeding of superior trees in temperate zones have gradually produced varieties adapted to specific site conditions that give as much as 50 percent yield gains. However, such work is just beginning in the tropics.
- New cloning techniques can produce millions of "supertrees," but they increase the risk of failure because of reduced genetic diversity.
- Organized programs of seed collection, processing, certification, storage, and distribution are needed to develop the seed quality and quantity necessary for large-scale reforestation.
- Bacterial and fungal inoculants can increase tree survival and growth, especially on degraded lands. Many of the needed inoculants are not yet commercially produced.
- Reforestation is most likely to be successful when programs are designed to provide what local people want. In many cases, this means the creation of various kinds of incentives for local participation.
- New technologies have the potential to reduce the costs of reforesting degraded lands; however, better methods are needed to measure important but indirect benefits in order to justify the reforestation investment.

Chapter 1

Introduction and Background

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Introduction and Background

INTRODUCTION

Eleven million hectares (ha) of the world's remaining tropical forests are converted to other land uses or to wasteland each year (33). About half of the Earth's original tropical forest land has thus been altered. Deforestation can be beneficial where cleared tropical land can sustain agriculture. Under available farming technologies, however, many remaining tropical lands cannot sustain agriculture and are soon abandoned or converted to less productive uses. Often, forests cannot regrow naturally on these degraded lands.

Tropical nations* (fig. 1) have about 650 million ha of cropland and nearly 2 billion ha of land in various stages of degradation (33,114). Those regions with rapidly growing populations—Asia, Central America, North Africa, and the heavily populated parts of East and West Africa—need productive land most desperately, yet have the most rapid deforestation and extensive areas of degraded land. In many of these places, firewood has become so scarce that certain foods requiring cooking have been eliminated from the diet. People must use crop residues and dried dung for fuel, which robs the soil of organic matter and nutrients and accelerates erosion. Soil eroded from degraded lands fills riverbeds and reservoirs, increasing the severity of floods and causing water scarcities.

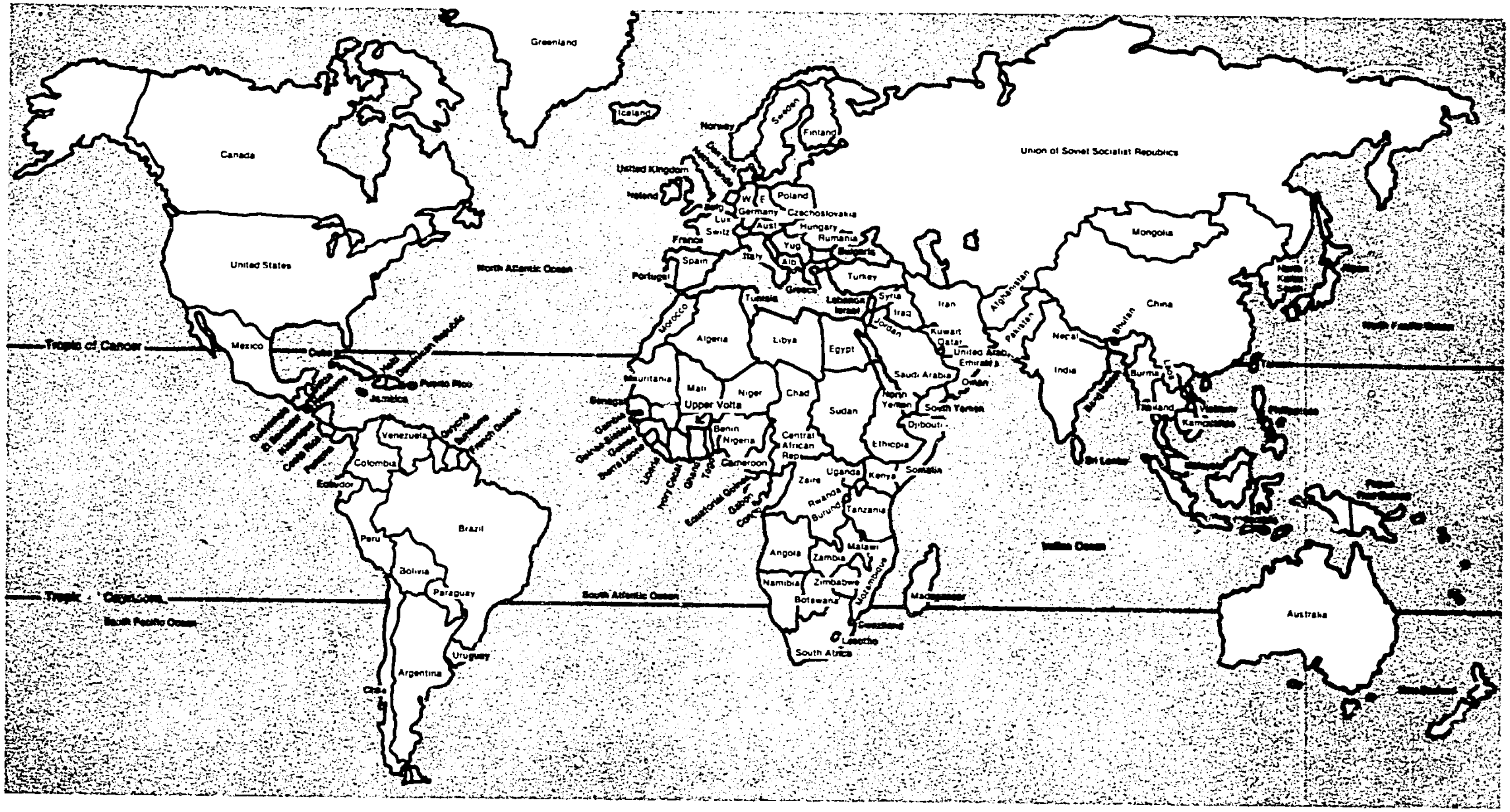
The best solution for stopping this trend of land degradation is to prevent inappropriate land-use practices on forested lands. Where this is not possible, reforestation is one way to improve the productivity of many degraded lands and provide useful products for the people. Trees provide wood, fuel, food, fodder, and other uses. Trees protect soil from the effects of tropical heat, rain, and wind. Soil temperatures are lower under tree canopies, permitting reaccumulation of organic matter that restores soil structure and microbiota and enhances moisture- and nutrient-holding abilities. Bacteria on the roots of some trees produce nitrogen fertilizer, while fungi on tree roots can convert soil minerals to useful forms. In dry areas, trees can help to prevent the rise of saline ground water (92). Where surface soils are dry or infertile, deep tree roots can tap underground reservoirs of nutrients and water and bring them to the surface.

In recent years, reforestation efforts have increased. Of the approximately 11.5 million ha of planted forest in 1980 in the tropical nations, some 40 percent have been planted since 1976 (33). About 60 percent of this was planted for industrial purposes (lumber, veneer, pulpwood, etc.). The other 40 percent was nonindustrial (fuelwood, watershed protection, etc.). While it is not known how much of this planting occurred on degraded land and how much occurred on recently cleared primary forests, it is probable that a large and increasing proportion of the reforestation, especially nonindustrial planting, is occurring on degraded sites (37).

This background paper discusses techniques to reforest tropical lands and gives special emphasis to degraded lands and community-oriented forestry. It does not address methods to manage existing forests, nor does it focus on public policies or institutional mechanisms to sustain tropical forests. Those issues are covered in a forthcoming OTA report, *Technologies To Sustain Tropical Forest Resources*, and in another background paper, *U.S. and International Institutions.*

*In this background paper, tropical lands include all lands located at latitudes south of 23.5° N and north of 23.5° S.

Figure 1.—Tropical Forests and Woodlands, for the Purpose of the Report, Are Located at Latitudes South of 23.5° N and North of 23.5° S, and at Other Frost-Free Localities



BACKGROUND

To understand the constraints on existing reforestation techniques and the potentials of new ones, it is first necessary to define land degradation, briefly describe tropical soils and climates, and discuss the causes of land degradation and benefits of reforestation.

Definition of Degraded Lands

Degradation of tropical land is a physical, chemical, and biological process set in motion by activities that reduce the land's inherent productivity. This process includes accelerated erosion and leaching, decreased soil fertility, diminished natural plant regeneration, disrupted hydrological cycle, and possible salinization, waterlogging, flooding, or increased drought risk, as well as the establishment of weedy plants that displace more desirable plant species. Evidence that the degradation process is advancing includes, for example, a reduction in the water-holding ability of the soil, a decrease in the amount of soil nutrients available to plants, a reduction of the soil's ability to hold nutrients, or soil compaction or surface hardening.

This definition implies a strong interrelationship between inappropriate land-use practices and land degradation. In some places degradation is manifest (e.g., erosion and desertification), whereas in others it is inferred (e.g., declining crop yields).

Tropical Soils and Climates

Although the chemical, physical, and biological processes that occur in the tropics are the same as those elsewhere in the world, the rates often are accelerated. Tropical air, soil, and water temperatures are higher; rainfall is more intense and erratic; and the growing season is longer than in temperate parts of the world. These factors affect tropical forests and their soils. Further, they can place severe constraints on certain land uses. Although detailed soil descriptions are beyond the scope of this report,* a simple but useful breakdown of tropical areas divides it into three types: 1) hot, wet lands, 2) arid/semiarid lands, and 3) mountainous lands.

Most tropical soils on hot, wet lands have significant fertility problems. Year-long high temperatures and high rainfall combine to accelerate the removal of nutrients needed by plants from rock materials and soil mineral particles. The residual minerals tend to be composed mostly of aluminum, silicon, iron, oxygen, and water—a chemical composition so restricted that many food or tree crops will have stunted growth or will not survive. An estimated 2 percent of the soils of hot, wet lands, if cleared of vegetation, will irreversibly harden on drying (119), severely limiting reestablishment of any vegetation (67).

In arid/semiarid lands, soil nutrients needed by many plants become available to plants with sufficient water (16). However, if most of the water evaporates from the soil surface rather than percolating down, dissolved solids or salts can accumulate at or near the land surface in concentrations that many plants will not tolerate (43).

Mountainous lands** are cooler than the other two categories and exist in both wet and dry climates. Because they have steep slopes, their soils are easily eroded. Much of the rainfall in the wetter regions runs off the land surface rather than percolating into the ground. Consequently, soils in mountainous lands are likely to be rocky and thin, except perhaps on the lower slopes (16).

*See Van Wambeke (119) and Fripiat and Herbillon (36) for more detailed information. These are good references on soils of the hot wet tropics. They not only contain the commonly cited information on agriculture, soil names, etc., but also provide discussions of mineralogical and chemical processes.

**Elevated areas throughout the tropics typically from 750 meters and above.

Photo credit: B. C. Stone for the National Academy of Sciences

Severely degraded lands on Guam which were once covered by tropical forests. Erosion has uncovered large expanses of infertile soil

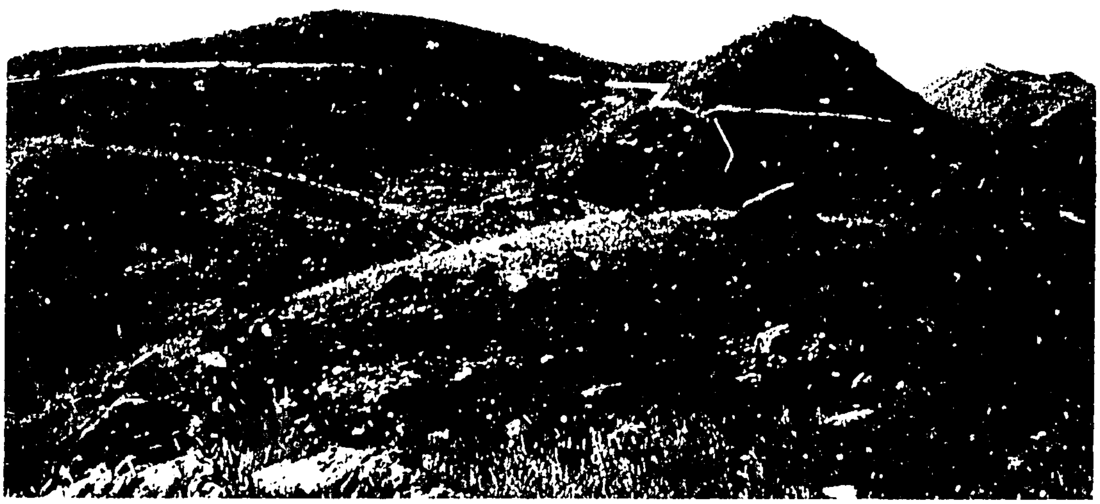


Photo credit: OTA staff

Barren landscapes on islands along the south coast of China reflect deforestation that occurred hundreds of years ago

Scope and Causes of Land Degradation

In much of the open woodlands of arid and semiarid areas, overgrazing and repeated fires have converted the vegetation to a degraded fire climax stage. Consequently, soils become dry and little woody regeneration occurs. Fire-tolerant vegetation—often unpalatable to animals—persists, leading to a desert-like state. Today, there are few undisturbed woodlands or savannas in these regions. An estimated 20.5 million hectares (ha) of tropical arid lands, an area about the size of South Dakota, become desertified every year. To date, an estimated 1.56 billion ha of tropical land have undergone desertification (table 1).

Desertification occurs in the savanna region of North Africa as well as in the savannas of southern tropical Africa and northeast Brazil. In the Sudan and elsewhere in North Africa, the populations of grazing animals—including goats, sheep, cattle, and camels—number in the millions and their grazing intensity has severely impaired natural regeneration of forests and forage (28). Consequently, people have had to range farther in search of fodder for their animals and wood for cooking and heating (131).

Forest degradation and loss under the rainy and seasonal environments may not be so severe as under the arid and semiarid environments, but the effects on people are similar. There are approximately 156 million ha of tropical moist forest, 181 million ha of forest fallow, and 84 million ha of deforested watersheds available for reforestation (131). When areas cleared by agriculturalists are exposed to abundant rainfall, erosion, and leaching, soil productivity is greatly decreased. After 1 to 5 years, the land typically is abandoned by farmers who move on to other areas. The land then reverts to secondary forest, vines, brush, or grasses of low nutritive value. Land abandonment is caused by decreasing crop yields and increasing weed control problems (57). Normally, these farmers (shifting cultivators) allow fallow periods of 10 to 15 years, thus giving enough time for soils to recuperate some productivity. However, in a growing number of places, increased population pressures lead to shortening of these periods. Food production is then greatly decreased, leading to even stronger pressures to clear more forest. Such effects of acute population pressure are evident in Haiti, El Salvador, and parts of the Philippines and Indonesia (131). Detailed descriptions of tropical agriculture and its effect on soils include: Laudelout (71); Nye and Greenland (88); Jurien and Henry (60); Watters (123); Sanchez (104); Lal and Greenland (69).

Table 1.—Tropical Lands Recently Undergoing Severe Desertification (million hectares)

Region	Total desertified area
Latin America	701.8
Africa	685.0
India and Pakistan	170.0
Total	1,556.8

SOURCE: United Nations, *U.N. Conference on Desertification: Round-Up, Plan of Action and Resolutions* (New York: United Nations, 1978).

Population growth rates in tropical countries are the world's highest. Growing numbers and rising aspirations lead to more than proportional increases in the demand for food, fuel, fodder, and building materials (15). Population growth also requires increased land for urbanization and village expansion, energy production, and transportation (14).

With few exceptions, such as the river valleys of West Africa where river blindness is being eradicated, most of those lands that can sustain stable agriculture probably have been cultivated. Remaining unused lands are those already degraded, or those too infertile for continuous farming without constant infusion of high-cost inputs such as commercial fertilizer. Without these inputs, the land becomes susceptible to degradation, thus reducing the standard of living (49,108).

In recent years, some developing countries have been planning and encouraging movement of people, usually into sparsely occupied virgin tropical forests. Two examples are Brazil's planned colonization of the Amazon Basin via the Transamazon highway and Indonesia's colonization of its outer islands (49,108).

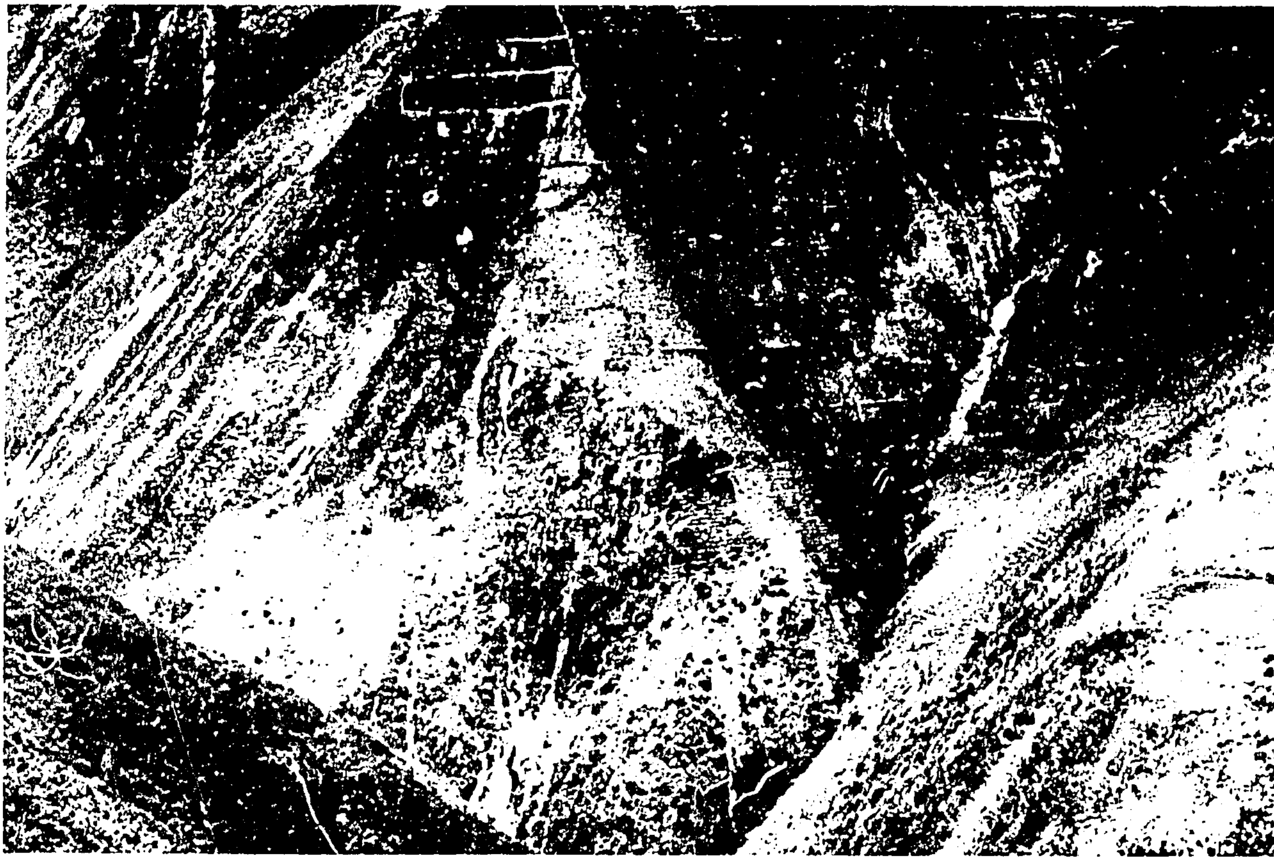


Photo credit: OTA staff

As demands for agricultural land increase, forests on steep slopes in Haiti are cleared. This leads to loss of soil and crops from erosion and overstresses the land base

In both cases, people are moved between regions that are geographically and geologically different and thus they are ill-equipped to cope with the new environment. Consequently, inappropriate land use practices have led to decreased crop yields. Forest clearing exposed the lands to heavy erosion and depleted the soil's nutrient supply, leading to land degradation and to indebtedness and landlessness for the people.

The expansion of lands under cultivation will continue, given the rising pressures. More lands will become degraded and subsequently abandoned. To break this cycle, some of these degraded lands can be reclaimed via reforestation. Tree planting of degraded lands is not a panacea to deforestation or inappropriate land uses. Some degraded lands will be difficult and some may be impossible to reclaim. In addition, reforestation of degraded lands may not be so profitable, in financial terms, as reforestation of rich, fertile lands. However, in many countries, fertile sites are reserved for agricultural activities. Given the dwindling amount of good lands and the increasing demands for forest products, it is necessary to consider all alternatives. Reforestation is an alternative that has the potential to rehabilitate the degraded soils and provide many goods and services for industrial and local needs.

Reclamation Using Trees

For degraded sites it is often advantageous to plant trees because of their ability to use water and nutrients inaccessible to plants with shallow roots and because they supply a multitude of products: wood, fuel, fodder, and others. Moreover, a tree canopy acts as a buffer against the direct impact of raindrops on the soil. The litter and humus layers underlying the forest absorb moisture, allowing water to infiltrate the ground and recharge the ground water supply (92). Trees, by shading the soil, reduce soil temperatures and thus promote accumulation of organic matter and retard possible soil hardening.

The presence or absence of organic matter in any soil is an important factor in the soil's productivity. Soil organic matter is important to soil productivity because it:

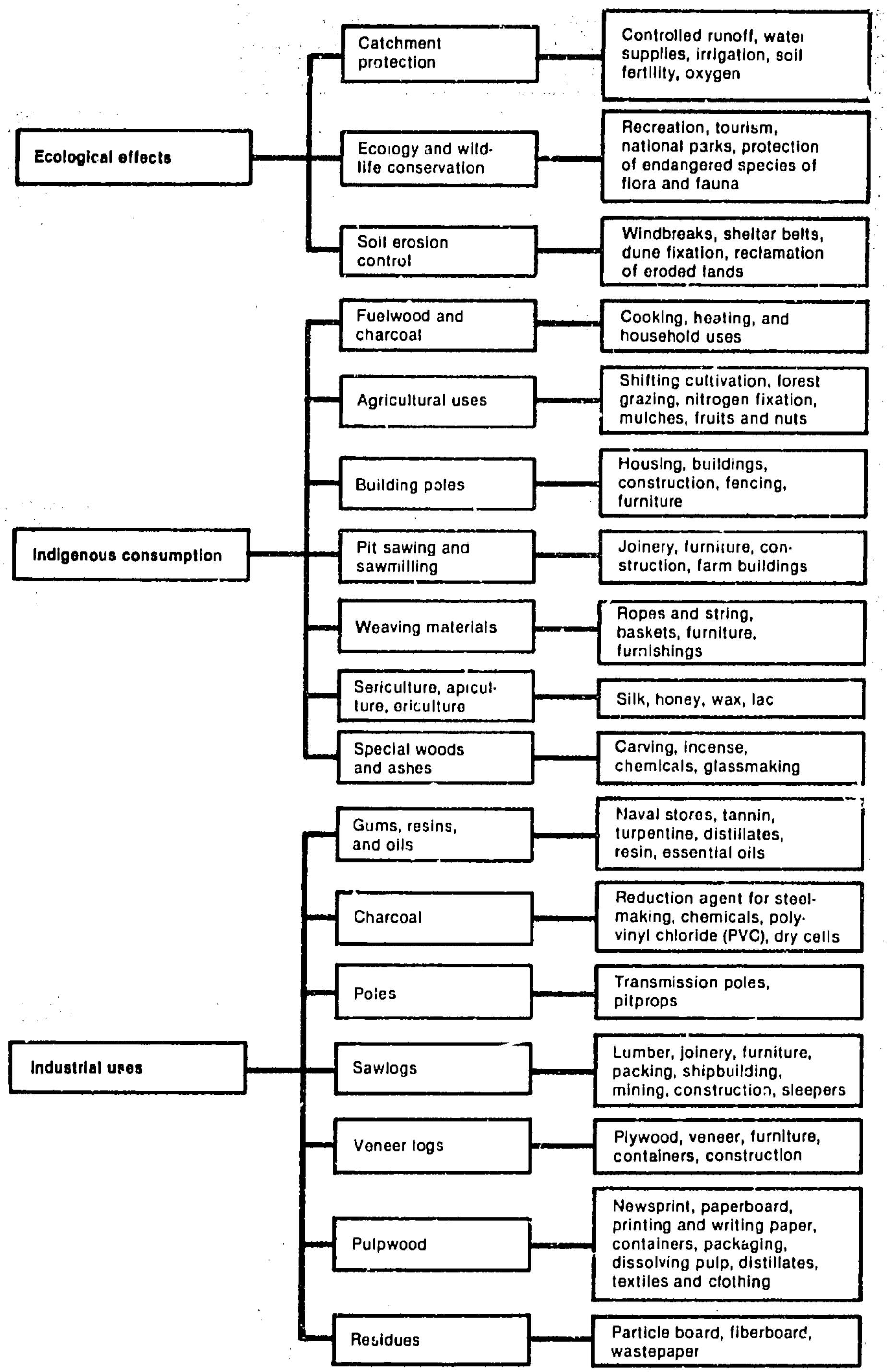
- contributes to the development of soil aggregates, which enhance root development and reduce the energy needed to work the soil;
- increases the air- and water-holding capacity of the soil, which is necessary for plant growth and helps to reduce erosion;
- releases essential plant nutrients as it decays;
- holds nutrients from fertilizer in storage until the plants need them; and
- enhances the abundance and distribution of vital soil biota (90).

Soils under forest cover often have high organic matter content. Land-use practices that jeopardize the soil's organic content therefore can have adverse effects on successfully reforesting degraded lands.

The living network of roots near the surface of forest soils provides mechanical support for steep slopes; this root network is the main contribution to slope strength and prevention of landslides (100). Consequently, trees are particularly valuable for watershed protection and for arresting desertification in areas of moving soils (e.g., sand dunes). Some trees act as soil improvers as well as soil protectors. Leguminous trees and forbs have the capacity to enrich soil with nitrogen. Legume trees have nutrient-rich leaves which can be used as fodder or mulch (80,81).

There are many reasons for planting trees. Provision of goods for household and industrial use (see fig. 2) is equally as important as rehabilitative factors. For local needs, a tree species with several attributes or a mixture of tree species can be planted to obtain multiple benefits —e.g., ability to enrich soil fertility, wood suitable for fuel and poles, and nutritious leaves for fodder.

Figure 2.—The Role of Forests



SOURCE: World Bank, 1978.

Chapter 2

Reforestation Technologies

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Chapter 2
Reforestation Technologies

Reforestation, for the purposes of this paper, refers to the planting of seeds, plants, or parts of plants to establish trees. This definition includes afforestation.* This section of the paper discusses various preplanting considerations, the application of various technologies on different types of degraded lands, and alternative technologies to maintain the newly restored site. Both new and promising technologies, as well as conventional techniques, are described.

Although a discussion of natural regeneration** of forests is outside the scope of this background paper because it requires little human manipulation, it is a technology worthy of further investigation and research. Silvicultural treatments of naturally regenerated forests to encourage and enhance natural reproduction have great potential for preservation of genetic resources and may be less costly than plantations (122). Preliminary studies indicate that productivity of naturally regenerated forest plots can be equal to or greater than the productivity of plantations after 40 years (59). The results suggest that plantations may not have an advantage over natural regeneration in the long term. However, few techniques have been developed to manage native tropical forests, and those few attempts have concentrated mainly on the tropical rain forests and moist deciduous forests (111).

*Planting trees on sites that never bore woody vegetation.
**Wherein trees regrow naturally from seeds or sprouts, without human help.

WHAT TO PLANT

Before a reforestation effort is initiated, a decision must be made as to what to plant. The choice of tree species depends on the site to be reforested. In this case, "site" includes not only the physical environment but also socioeconomic factors—especially the needs of land users. Trees selected to reforest degraded lands must be able to thrive on open lands, compete with aggressive weeds, and withstand stress (e.g., drought, fire, low fertility). It is especially beneficial if the species can add nitrogen to the soil and provide products that serve the needs of local communities.

The debate whether to use native or exotic tree species, to plant in monocultures or polyculture, and to select single-purpose or multipurpose trees continues. Meanwhile, several factors may influence the selection. Among them are the objectives of reforestation, availability of seeds, and the level of costs (labor, cash, and risk) associated with reforestation alternatives. The primary reason for the kinds of reforestation addressed in this background paper is to restore degraded lands and to produce products—e.g., food, fuel, fodder, or commercial timber—to meet the needs of the people.

Native v. Exotic Species

Most large-scale tropical plantations to produce industrial timber use exotic species.* The most commonly used genera are *Pinus, Eucalyptus, Gmelina, Tectona, Terminalia, Cupressus, Cunninghamia,* and *Araucaria.* Some lesser known genera such as *Cedrela, Triplochiton, Anthocephalus, Aucoumea, Albizia,* and *Agathis* also are gaining popularity. Most of these genera, though indigenous to the tropics, are planted as exotics (37).

Despite objections that exotic species are susceptible to increased disease risk, they have been used exclusively in plantings in the tropics. This may be because there is much experience, information, and research on exotics, especially on *Pinus, Eucalyptus,* and *Tectona.* There are arguments for and against the wide-

*Trees that are not native to a locale.

spread use of exotic species. Proponents cite their initial reduced susceptibility to native insects and diseases as an advantage. However, exotic species may be more susceptible to serious damage if native pathogens and pests adapt to the new hosts, since the exotics are unlikely to have evolved resistance to these organisms.

The use of native species—ones that grow naturally in the local region—in plantations has been largely ignored. The reasons for this vary from lack of familiarity with many tropical tree species to lack of seed supplies, and the sometimes slower growth rates of native species. The latter is a common argument for using exotics over native species (37,131,135). However, while this difference may occur where rainfall is above 1,500 millimeters (mm), growth of exotics and native species usually are similar in the arid and semiarid parts of Africa (126).

Arguments supporting reforestation using native species are varied. First, native species are adapted to the local environment and thus may be less susceptible to stress, serious disease, and pest damage. Local people are more familiar with their native plants and have more uses for them (54). Similarly, the timber of native species is likely to be known to local wood-using industries. Further, use of native trees contributes to the conservation of native flora and fauna (29).

Monoculture v. Polyculture

The use of a single species in forest plantations is known as monoculture. Monoculture plantations may be more susceptible to disease and pest outbreaks. Some diversity can be achieved by alternating species in blocks of land being planted or by alternating different genetic varieties of the same species. This method should prevent pests that develop and multiply in one plantation block from spreading rapidly to other blocks of trees having the same genetic makeup (135).

Multiple species (polyculture) plantations are, in theory, better able to mimic the natural forest, yield a greater variety of products, and are less susceptible to pests than are monocultures. Interplanting legume (nitrogen-fixing) tree species with other commercial tree species may reduce the amount of fertilizer required after successive rotations. In experimental plantations, Indonesians are interplanting *Calliandra* with *Pinus merkusii* and with *Eucalyptus deglupta* to yield firewood for local use. *Calliandra* also shades trees such as *Agathis loranthifolia*, which require shade initially for better growth (83).

Yet little actual experience has been gained dealing with polyculture plantations either at the industrial scale or in village forests (131). Only recently have projects been established where mixtures of species have been planted for a variety of end uses (e.g., GTZ, IDRC, and USAID projects in the Sahel). Areas of mixed plantations are beginning to be established in the social forestry projects of Asia, especially India and Nepal. Even in those projects, information is lacking on the optimum species mixture and spacing. The management of mixtures of tree species for production is biologically complex, especially for more than two species. It becomes even more difficult where multiple products are extracted from multiple species under multiple harvesting regimes. However, perceived benefits of polyculture planting,

Photo credit: COMALCO for NAS

Polyculture: African mahogany (*Khaya* species) planted between *Leucaena leucocephala* trees on highly aluminous soil in Weipa, North Queensland, Australia. *Leucaena* is being tested as a nurse crop for mahogany especially in the context of social forestry, make them worthy of further investigation.

Single-Purpose v. Multipurpose Trees

Forest plantations in the past served industrial purposes and thus grew only one product, such as sawtimber or pulpwood. Now, with an increasing demand for food, fuel, and fodder, plantations are needed to serve a variety of objectives. Thus, the use of multipurpose trees is becoming increasingly important, especially on degraded lands where population pressure is often high. *Acacia albida*, a multipurpose tree, bears leaves at the beginning of the dry season, thus providing shade when most other trees are bare. It also yields edible seed pods at a time when little other fodder is available. The tree enhances soil fertility because it fixes nitrogen and provides leaf mulch, and it can be used as firewood (82). *A. albida* is just one of more than 1,000 species of the genus *Acacia* (84). Other multipurpose trees exist that perform equally well and hold great promise for reforestation. Various lists of these promising species are available (44,79, 80,83,84,85,118,125).

The family *Leguminosae* deserves special attention in the process of selecting trees for reforestation. Legumes are among the first to colonize newly cleared land. *Acacia albida*, mentioned above, is a legume. Its kin, *Acacia mangium*, outperforms other species on degraded lands in Malaysia. Wood of this species has potential for sawtimber, veneer, furniture, firewood, pulp, and particle board. Its leaves can be used as forage for livestock (85). The foliage of species such as *Calliandra* is readily eaten by cattle and goats; its flower provides rich nectar to produce *Calliandra* honey (84). Many other tropical legumes exist whose potentials are unknown.

Photo credit: A. S. Bhat for NAS

Multipurpose trees such as *Sesbania grandiflora* can provide firewood, fodder, food, and green manure and hold promise for reforesting eroded wastelands throughout the tropics

Little is known of the variability in growth and performance of multipurpose tree species. Variation is related to habitat so that each planting site should be tested with genetically different varieties of the same species. Such efforts are under way. The National Academy of Sciences (NAS) is designing and implementing international trials of tree species for the Sahel and of multipurpose tropical tree species for many grantee institutions. Both the International Council for Research in Agroforestry (ICRAF) and the Commonwealth Forestry Institute are cooperating with NAS in preparing manuals for evaluation of multipurpose species. But even when correct species and provenances are known, there is still a major gap in the knowledge of silvicultural techniques for multipurpose tree plantings. Here, little information is available, and no research guide exists. Despite these obstacles, multipurpose trees merit special consideration because of their multiplicity of likely benefits.

Genetic Improvement

Plant breeding has been responsible for about half of the spectacular gains in agricultural crop yields accomplished in the past three decades. The application of genetic science to forestry lags many decades behind agriculture, partly because it takes a longer time to breed trees than agricultural crops. However, tree breeding programs in industrialized nations have already achieved important productivity gains—10 to 20 percent in first generation and 35 to 45 percent in second generation seed orchard progeny—for industrial timber plantations (87). First genetic selections have yielded gains of as much as 50 percent in some energy plantations (97). Tree breeding programs could greatly accelerate genetic improvement of trees, especially tropical trees, and forestry yields from degraded land sites could increase.

Most reforestation projects in the tropics use seeds without testing them to see whether they are genetically appropriate for the project's site conditions. Since most tree species used in reforestation are found over broad geographic ranges, different races within the same species have adapted to different environments. Thus, a species' suitability to a particular site can vary depending on the race used. A well-established technique matching races with sites is called provenance* testing. Seeds of the desired species are collected from various sites (provenances) and tested at the site to be reforested or at a site with a similar environment.

Once the best provenance has been identified, several options are available to obtain planting materials. Seeds from the desired provenance sometimes can be purchased. Alternatively, individual trees from the provenance test can be selected as parent material. Once the best individuals have been identified, they can be used to establish seed orchards or to produce rooted cuttings for planting materials. This ensures that only seeds and seedlings from superior trees are used in the reforestation program. Another technique is to use superior trees from an environment similar to the reforestation site to establish a seed orchard without the provenance testing. If the desired species already grows on the reforestation site and if superior trees have not been eliminated, then it is possible to obtain planting materials adapted to the site from those trees. Where this is feasible, it is probably the fastest and least expensive approach.

These tree improvement and selection techniques have been successful for reforestation on degraded tropical lands. For example, *Eucalyptus grandis* generally does not grow well on the steep, eroding, and phosphorus-deficient soils of Andean slopes in Columbia. By selecting trees from early plantings that did grow well on such sites to establish a seed orchard, an adapted race for the degraded sites has been produced (135).

*Testing populations of the same species to study their performance under a range of site and climatic conditions.

Conventional provenance testing is a major undertaking. For proper statistical analysis, hundreds of trees from each seed source are planted in replicated blocks and grown to maturity. The process generally takes so long that the original seed source may be unavailable by the time results are available. When that happens, the test plots must be developed as seed orchards, further prolonging the process. This usually takes too long to accommodate an individual reforestation program. Many provenance tests do not yield results because of premature termination of the project or departure of the investigator. Therefore, provenance testing must be carried out by established institutions that can maintain long-term programs.

The potential to shorten the time needed for tree improvement is increasing as new techniques are being tested. Tissue culture (discussed in the following section) can rapidly mass-produce clones of chosen individuals from a provenance test. The clones can then be tested for particular microsites or outplanted at the reforestation site. The establishment of international networks of cooperating scientists to collect seeds or planting material and to record environmental data for each parent tree can reduce the number of provenances to be evaluated for each test. Another new technique, where many provenances are planted in one stand (single tree randomized plots), allows the testing of many more provenances without a corresponding increase in budget or personnel. And the propagation of clones ensures that the provenance with the exact genetic materials is used, thus allowing more types to be tested. The U.S. Forest Service, in experiments with *Eucalyptus* in Florida, used single tree randomized plots and cloning to shorten the time for screening of appropriate provenances (38). These techniques have not been used in reforestation of degraded tropical lands. Before that can be done, pilot-scale implementation projects, ones having at least a 10-year timespan for sufficient results to appear, need to be initiated.

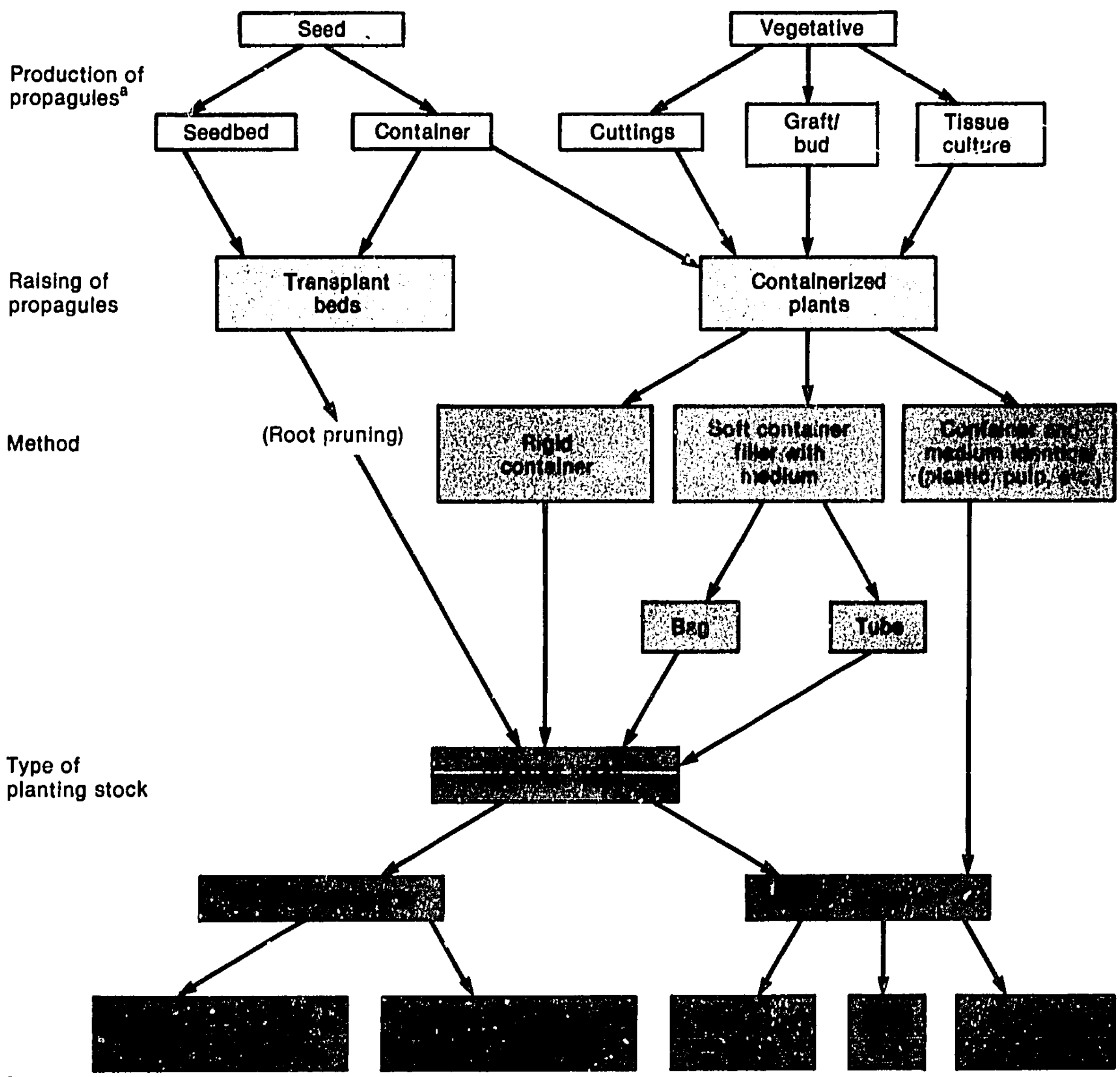
PLANTING MATERIALS

Various techniques are used to propagate trees. Some propagation techniques have been known for centuries (e.g., direct seeding) and are available for implementation; others (e.g., tissue culture) are at various stages of development or are undergoing refinement. (See fig. 3 for schematic chart of production of nursery stock and table 2 matching nursery planting stock with land classifications.)

Seed

To reforest degraded lands, seeds of various species must be available in great quantities. Today, supply falls short of need. The seed supply for species most commonly used in tropical, industrial plantations (pines, eucalyptus, *Gmelina*, teak) is adequate, although some valuable provenances are in short supply and

Figure 3.—Production of Nursery Stock in the Tropics



[a]A structure (e.g., cutting, seed) that propagates a plant.

SOURCE: Evans, 1982.

Table 2.—Suitability of Various Types of Nursery Planting Stock for Reforestation in the Tropics

	Climatic conditions				
Type of planting site	Lowland rain forest	Montane Rain Forest	Dry/semideciduous forest	Areas of unreliable rainfall	Arid areas
Dense forest	Tall, whole plants or striplings	Tall, whole plants	Potted stock or stumps	Potted stock, stumps, striplings	
Open exploited forest/line planting	Tall, whole plants or striplings	Tall, whole plants	Potted stock or stumps	Potted stock or stumps	
Agricultural land/ eroded land/ taungya systems	Large, bare-rooted plants. Potted stock. Direct sowing	Small, bare-rooted or minipotted stock. Direct sowing	Potted stock. Root-pruned, bare-rooted stock, stumps. Direct sowing	Potted stock. Root pruned, bare-rooted stock, stumps. Direct sowing	Robust-potted stock (sowing)
Clean weeded land	Small, bare-rooted or minipotted stock. Direct sowing	Small, bare-rooted, or minipotted stock. Direct sowing	Potted or root-pruned, bare-rooted stock. Direct sowing	Potted or root-pruned, bare-rooted stock. Direct sowing	Robust-potted stock (sowing)
Areas with risk of bird damage or animal browsing	Large striplings	Large striplings	Large-potted stock or stumps	Large-potted stock or stumps	Robust-potted stock

SOURCE: J. Evans (29).

their natural origins are threatened with genetic impoverishment or extinction. The seed supply for multipurpose, agroforestry species, on the other hand, is small. Organized programs of seed collection, extraction, storage, and distribution are needed to develop the quantity necessary for large-scale reforestation.

Seed storage of tropical tree species is a problem. Tropical species show great variation in their capacity to retain viability under natural conditions. Many large-seeded species have short periods of viability; *Swietenia* seed is viable for only 6 weeks. Other species retain their viability only under certain conditions. Seed of *Araucaria hunsteinii* will die if allowed to dry out. Legume tree seeds must be kept dry and free from insect or rodent damage to retain their viability (29). Seed storage is therefore an important part of reforestation efforts. Many factors influence the longevity of seed in storage. Recently, some progress has been made in this area. Seeds of some tropical plant species can now be stored in liquid nitrogen (3).

Another problem exists regarding the transfer of seeds within a nation and internationally because the records of seed sour e and genetic history are sometimes poor (17,58). Plans to control planting material (e.g., ref. 89) do not yet apply to tropical countries, and tree seed dealers generally sell seeds without adequate information regarding the place where the parent trees were grown. The use of poorly identified seed often has made it impossible to trace the origin of seed which produced a promising stand meriting further trial or one of bad form to be avoided. Full records of all forest seedlots should be made and copies should accompany all seed distributions. Most importantly, every shipment of seed should show how the species was identified, where and when the seed was collected, and specific site and stand information about the seed source (see ref. 29 for a sample certificate of seed origin). Thus, the recipient will know the quality and origin of a seedlot if problems develop later. International attention was drawn to this problem at a meeting sponsored by the Nitrogen-Fixing Tree Association held at Bellagio, Italy, in September 1982. It will also be the focus of a meeting proposed by ICRAF to be held in 1983 (74).

Nursery Planting Stock

Seedlings

Growing seedlings in a forest nursery is the customary way of raising planting stock in the tropics. (See ref. 91 for sample technical manual on nursery practices.) The two most common methods of raising tree seedlings are: 1) in open beds for bare-root planting, and 2) in containers for seedlings to be planted with nursery soil around the roots.

Seedlings, in the past, were raised in open beds and planted in the field bare-rooted. Those seedlings, however, were susceptible to desiccation and survival was poor. Survival improved when seedlings were taken in individual containers from the nursery to planting sites with soil still around the roots. Containerized seedling techniques have evolved from the method of cutting into the nursery bed between each seedling so that a cube of soil remained attached to the roots (Swaziland bed system) to starting seedlings in the containers. The types, sizes, and durability of containers vary greatly. Choice of container usually depends on cost and convenience, but containers often are bulky to transport because of the soil.

The various types of containers can be classified according to their porosity:

- impervious containers—metal, plastic, or other materials;
- semipervious or pervious containers—mostly paper based, not removed at planting; and
- pre-filled containers—individual units of growing medium (29).

The most commonly used container is the impervious type. Although most are plastic bags or metal tubes, local materials can be used. Bamboo, wood veneer, and banana or palm leaves have been used widely in different parts of the world (32). For example, Paper Industry Corp. of the Philippines uses waste veneers from peeling operations. The use of closed-bottom containers, however, can result in root coiling if the seedling is left in the tube too long. This can be avoided with more modern containers that have an open bottom and are suspended above the ground. The roots self-prune when they come to the air below the containers. See table 3 for a comparison of container and bare-rooted methods. Also, see Tinus and McDonald (112), Venator (120), and Tinus (113)

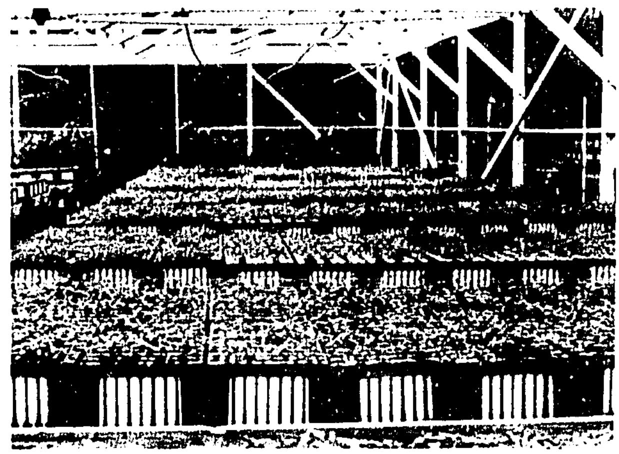


Photo credit: OTA staff

Tree seedling containers in Hawaiian nursery. Roots grow out of a hole in the base of each container, a technique called "air pruning"

for more details on growing seedlings in containers.

Vegetative Propagation

Another technique is vegetative propagation, the reproduction of planting stock without the use of seed. Vegetative propagation has the advantage of hastening production of genetically superior plants and massive reproduction of clones, assuring that the plants will all be of the desired genetic type. It has the disadvantage of higher risks because of lack of genetic diversity. It also requires greater technical expertise. Vegetative propagation is widely used for reproducing crop trees such as rubber, coconut, tea, coffee, cocoa, and oil palm. More detailed trial work is needed to develop efficient operational systems for many tropical forest species.

Methods of vegetative propagation include cuttings, air layering, budding, grafting, and tissue culture (see table 4 for a brief assessment of each of the techniques). Rooted cuttings remain the most popular method. Each year, several million *Eucalyptus* trees are propagated from rooted cuttings in Pointe Noire, Congo, and Aracruz, Brazil (131). *Casuarina junghuhniana* is propagated by cuttings in Thailand and India (83). Once the technique is devel-

Table 3.—Comparison Between Container and Bare-Rooted Methods of Raising Seedlings

	Container system	Bare-rooted system
Materials	Need as many containers as seedlings. Supply of good soil for potting mix	Nursery site with easily worked soil suitable for bed cultivation
Equipment	Container filling tools, soil sieving screen. Tubing shed	Several implements for plowing, leveling, bed formation, seed sowing, undercutting, lifting, etc.
Labor	Labor intensive, not easily mechanized. Much labor needed for container filling, seed sowing, weeding, and container removal at planting. Typically 10 to 20 workers per million seedlings produced	Well suited to mechanization. Most labor intensive components are lifting and packaging, but even these may become mechanized in the future. At Beerburrum, Queensland, 2 to 3 people raised 1.4 million seedlings per year
Transport	Bulky and heavy to transport, costly over long distances	Plants easy to transport over long distances
Silviculture	Excellent survival at planting, except that overgrown plants become pot-bound and suffer serious root deformation and later instability	Good survival depends on careful timing of lifting and planting, to coincide with wet weather, and adequate conditioning of plants. Gives poorer results where climate is unreliable
Supervision	Easier to grow satisfactorily, timing of operations not too critical, but may suffer more from casual neglect of watering, shading, etc.	Requires a high degree of supervision to ensure proper timing and regularity of operations
Protection	Fresh soil in every container reduces chance of buildup of pathogens or soil pests. Diseased seedlings easily isolated and discarded. Weed control tedious	Reuse of same soil may lead to buildup of pathogens or soil pests. Pests and diseases more likely to affect all seedlings in a bed
Cost	High labor intensity tends to produce more costly seedlings. Costs per seedling including overheads are: *A. cunninghamii* in Queensland, using metal tubes U.S. $70 per 1,000 (1978) *Pinus caribaea* in Fiji (small tubes) U.S. $30 per 1,000 (1978) *E. camaldulensis* in Niger U.S. $140 per 1,000 (25) *Albizia falcataria* in the Philippines (short nursery life) U.S. $10 per 1,000 (1978)	*P. caribaea* in Queensland U.S. $20 per 1,000 (1978) *E. camaldulensis* in Niger U.S. $60 per 1,000 (25)
Suitability	All smaller nurseries and especially: 1) for good survival in arid conditions, 2) when many different species are raised, 3) where plants are distributed to the public and post-planting care is likely to be poor—e.g., extension nurseries	1) Large production nurseries raising only a few species for planting and where climate is dependable, 2) raising "stump" plants and as a cheap method for hardy species

SOURCE: J. Evans (29).

oped, the cost of production is low. For example, at Aracruz, Brazil, 230 laborers produce 10 million rooted cuttings annually at a total cost of as little as U.S. $0.10 per plant. For most hardwood species, a team of two to three professionals with a budget of $200,000 should be able to develop a system in 2 to 3 years (131).

Another vegetative propagation method that holds great promise is tissue culture (also called micropropagation). This technique can rapidly produce thousands or even millions of propagules from a single parent; thus, it has great potential for genetic improvement programs. Reforestation requires planting materials with desirable characteristics such as rapid growth, good form, product utility, or adaptation to problem sites (i.e., high acidity, saline soils, etc.), and the use of tissue culture can shorten the time necessary to reproduce a large stock of planting material with the necessary characteristics. A large number of provenances can be tested in a confined space within a limited time period for many of the particular desired characteristics. (See refs. 13 and 98 for more information on tissue culture.)

The technology is well established in tropical agriculture and tropical horticulture (e.g., oil palm), but it is still in the developmental stage for most tree species. The cost of plantlets and the sophistication of the technologies make

Table 4.—Vegetative Propagation Techniques Used With Tree Species

Technique	Description	Advantages	Disadvantages
Grafting and budding	The union of a shoot or branch onto the rootstock of another plant	Propagation of elite selections which do not root readily Maturity/juvenility of the tree is preserved. Mature tissue continues to produce seed	Many trees are graft-incompatible
Cuttings	The induction of root formation on sections of stems, branches, or suckers (the formation of sucker shoots on sections of roots from some species)	Preservation of maturity or juvenility of mother tissue. Mature plant cuttings continue to flower and produce seed Resulting plants can be screened for resistance to soil pests Least labor intense means of vegetative propagation	Cuttings may not survive the time period to root Very difficult with many tree species May require up to 1 year for some trees
Air layering	The induction of root formation on shoots that are still attached to the mother tree		Maturity/juvenility of plants is maintained: shoots from mature tissue plants will continue to produce seed Shoots are nourished by the mother plant
Tissue culture	The sterile culture of small pieces of the mother tree (such as buds, leaf tissues, etc.). Also known as "micropropagation"	Very high volumes of plants can be produced in short periods of time from a small amount of mother plant	Useful when other methods are not feasible Most labor intense method Mature tissues become juvenile so no seed can be produced rapidly Requires use of special facilities Some potential for genetic variation

SOURCE: Plant Research Institute, OTA background paper, 1981.

tissue culture unlikely to replace the use of cuttings for large-scale reforestation in tropical areas. Its nearer term use is likely to be in establishment of "super tree" orchards to produce seeds or cuttings.

Mycorrhizae and *Rhizobium*

Seedling survival and growth rates in the nursery and at the planting site can sometimes be improved by using special kinds of fungi and bacteria. Associations between tree roots and mycorrhizal fungi are essential for healthy growth of most tropical trees. The fungi are active in the transport of nutrients and water to plant roots and, in some cases, are important for the release of nutrient elements from mineral and organic soil particles (76). Populations of mycorrhizae are found naturally in soils, but these can be depressed after long-term clearing and/or topsoil removal, making reestablishment of vegetation on degraded lands difficult. Trials have shown that seedlings inoculated with fungi show improved growth and survival over uninoculated controls (18,21,56,70,77). Some scientists suspect that certain fungi provide plants with resistance to low pH, heavy metal toxicants, high temperatures, and other stresses common to degraded sites.

Methods for reinoculating damaged soils with mycorrhizal fungi include:

- inoculating containerized plants or bare-root nursery stock prior to outplanting,
- pelletizing seed with mycorrhizal inoculum prior to sowing, and
- inoculating soil at the planting site with laboratory produced cultures.

These techniques are being developed, but characteristics of the most widely used technique for inoculum production—pot culture—pose a major constraint to commercial application. The fungus is grown in association with

Photo credit: Weyerhaeuser Co.

Tissue cultured loblolly pine plantlet ready to be transferred from Weyerhaeuser Co.'s laboratory to the soil

roots of living plants in pots of soil or sand in a greenhouse. The soils, infected roots, or fungal spores are then harvested and used as inoculum. Unfortunately, this technique is bulky, clumsy, slow, and susceptible to contamination by pathogens (94).

Photo credit: T. Wood

Ectomycorrhizal fungi on roots of Douglas-fir

Trees of the legume family can grow well on degraded land with low nitrogen content because their roots can be a symbiotic host for *Rhizobium* bacteria which fix nitrogen. *Rhizobium* bacteria, within tree root nodules, produce an enzyme that causes conversion of nitrogen gas (available in the soil but unavailable to the plant as a nutrient) to ammonia. The ammonia, a common fertilizer, is converted to compounds such as amino acids and transported throughout the tree for use in synthesizing plant protein. Thus, some legume leaves, pods, and seeds are highly nutritious as food or fodder, and the leaves are an excellent fertilizer and soil conditioner.

Maximum production of ammonia requires infection of the legume's roots with the right type of *Rhizobium.* Most soils contain *Rhizobium,* but degraded soils probably contain fewer types and lesser amounts of the bacteria. Thus, the appropriate type of *Rhizobium* may not be present at the site of a reforestation effort, or present in enough quantity to infect the tree roots. An association with an inappropriate type of *Rhizobium* may occur, in which case little fertilizer may be produced.

An old inoculation technique is to collect root nodules from a vigorous legume tree, grind them up, and use the product to inoculate other

Photo credit: T. Wood

Nitrogen-fixing nodules formed on the roots of *Acacia pennatula*, a fast-growing tropical woody legume, by *Rhizobium* species

trees of the same species. Because of differing responses to various soil conditions, however, the collected nodules may not contain the appropriate type of *Rhizobium*. Development of other techniques has greatly enhanced the likelihood of the correct association. For example, different types of *Rhizobium* collected from nodules from natural sites are isolated, cultured, and stored. Then various combinations of tree provenances and soil types are tested against the various types of *Rhizobium* to find the most productive combinations. Then, the appropriate *Rhizobium* for a particular reforestation project can be reproduced in culture and sent to the nursery.

Inoculants from cultures are relatively simple to use and cheap, costing only a small fraction of a cent per tree. The inoculant is in powder form and can be applied as a dust or slurry to the tree seed just before planting in the nursery or field. An adhesive such as gum arabic can be used to ensure that inoculum adheres to each seed. Fertilizers such as lime, rock phosphate, and molybdenum can be added to the seed coating to protect the seed and to feed the emerging seedling (48). The inoculant also can be drilled into the soil with the seed at planting. It is possible to inoculate growing trees, but inoculation at the time of planting seems the most efficient method.

Inoculation of legumes with *Rhizobium* has been practiced in agriculture in industrialized nations for many years. Use of this technique in tropical agriculture is not yet well established, but it is being promoted by several institutions. Unfortunately, the application of this technique in forestry is not well accepted. Inoculants are living organisms that must be transported and stored carefully and used correctly to retain their viability. These requirements can be difficult to achieve, especially at remote tropical sites needing reforestation. Most importantly, inoculants for tropical legume trees commonly are not available because of a lack of production.

These constraints are being overcome slowly. Inoculants for some tropical legume trees, such as *Leucaena* and *Calliandra*, are now available commercially. Research centers, such as Centro Internacional de Agricultural Tropical in Colombia and the Nitrogen Fixation by Tropical Agricultural Legumes project at the University of Hawaii produce inoculants on a pilot scale as a service for researchers and, occasionally, legume growers. While most of the biological nitrogen fixation work at these institutions is on nonwoody agricultural legumes, inoculants for legume trees are gradually being developed and efforts are under way to educate tropical forestry specialists about this technology.

The roots of some nonlegume trees also can be infected by micro-organisms that produce nitrogen fertilizer for the tree. *Casuarina*, planted on tropical degraded lands, is an example of this group of trees. Techniques to culture the micro-organisms that associate with

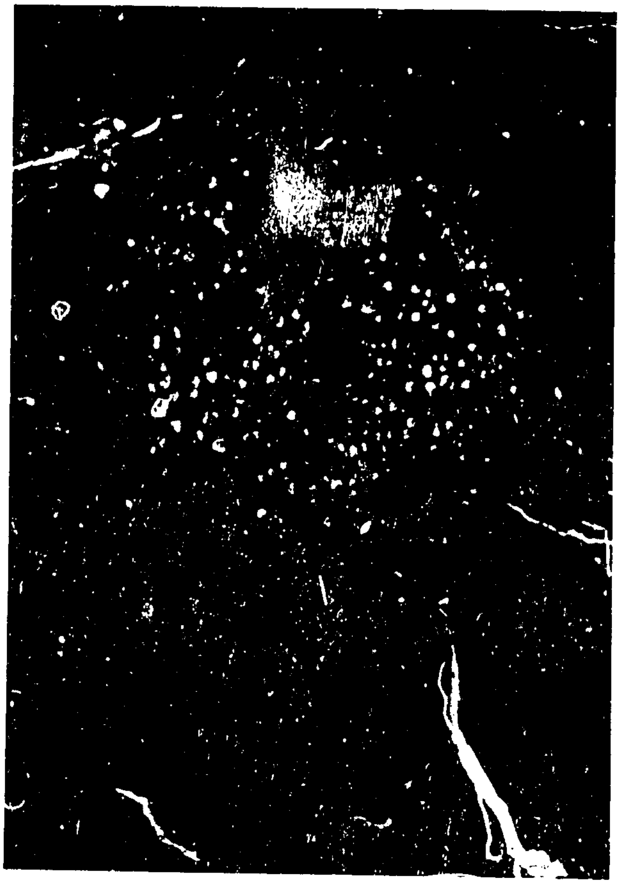


Photo credit: T. Wood

Nitrogen-fixing nodules formed on the roots of red alder *(Alnus rubra)* by an actinomycete in the genus *Frankia*

these nonlegume trees are not yet available. However, the use of ground nodules from already established trees is possible and practical for areas where these trees are native.

Soil Conditioners

Soil conditioners, used to increase soil productivity, are materials other than commercial fertilizers or organic matter that change the properties of soil physically, chemically, or biologically (4). Chemical substances such as Agrosoke and Erosel (plastics) or "super-slurper" (water-holding starch copolymers) are examples. The super-slurper was developed by the U.S. Department of Agriculture to increase seedling survival and growth rates through an ability to absorb, store, and release water to the plant on demand (5). Although it is better known in agriculture, it has shown promise when applied to tree seedlings, and it may have application in tropical forestry, especially in areas where rainfall is limited and sporadic, and where plant desiccation is a problem.

Super-slurper can increase aeration and improve drainage through its expansion capability. It can be used in a variety of ways: mixed into soil or greenhouse media, applied as seed coating, distributed in the hole prior to transplanting, and broadcast over an area to be seeded. The latter, however, is prohibitively expensive because of the amount required and the biodegradable nature of the copolymer. The most promising, economically sound use of super-slurper is its application into the slurry bucket during bare-root planting. This is an effective means of preventing bare root desiccation.

Direct Sowing

Direct sowing means that seed is planted directly at the site. This technique is feasible where seed is plentiful and where mortality of seed and germinating plants is low (101). Thus far, only a few species have been planted this way in the tropics: *Acacia arabica, A. mearnsii, Gmelina arborea* (Senegal/Gambia), *Leucaena leucocephala* (Philippines), *Azadirachta indica* (Nigeria), *Cassia siamea* (Tanzania), and *Pinus caribaea* and *P. oocarpa* (Honduras) (65,78).

The advantage of direct sowing is that no nursery is required and planting costs are low. On the other hand, seedling survival may be low (23) because of weed competition, lack of tending, poor weather, or animal damage. Germination success can be increased by pretreating seed with fungicide, insecticide, and bird and rodent repellents.

Direct sowing can be done either by hand or machine (e.g., tractor or plane). Although the use of aircraft to sow seeds largely is still unproven in the tropics, it shows promise in accelerating reforestation programs through its ability to seed large and remote areas quickly. It is not, however, a replacement for other planting techniques. It is simply another tool

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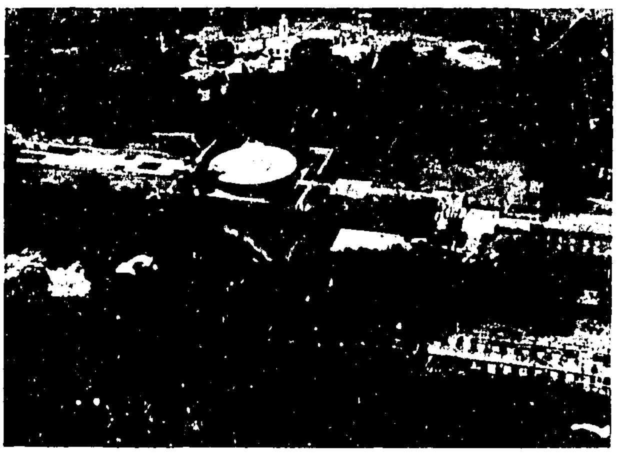


1976

Photo credit: U.S. Army and James Black, Jr. for NAS

Corregidor Island at the entrance of Manila Bay, bomb pocked and denuded in WWII, was air sown with *Leucaena*. It has become the dominant vegetation

to be considered when reforesting remote, rugged sites not easily reached by people or land vehicles.

Aerial seeding for the tropics is at a developmental stage. Only a few sites and species have been tested. (See table 5 for a list of possible candidates for aerial seeding.) The technique entails many logistical problems. Lack of aircraft and logistic, administrative, and communications support are major constraints. The lack of large seed quantities is another constraint. Poor control exists over tree spacings. The seeds used are usually wild or unimproved strains because seeds from genetically selected strains are yet too scarce and expensive to use. On the other hand, the mere fact that there are no capital costs for nurseries nor for the outplanting of seedlings makes aerial seeding attractive.

Transplanting Wildlings and Stumps

Other sources of planting materials exist for reforestation. Natural forest seedlings (wildlings) and root suckers are sometimes transplanted, usually from moist tropical forests, with variable results. Stumps, a nursery stock that has been subjected to drastic pruning of both roots and shoot, can be planted directly into the ground. Stump planting is especially suited for species that have a dominant taproot (32). Examples of species that have been planted as stumps are *Acacia cyanophylla, Azadiracta indica, Cassia siamea, Chlolophora excelsa, Cordia alliodra, Dalbergia sissoo, Gmelina arborea, Tectona grandis,* and *Pterocarpus spp.* (29). During transit, stumps are normally covered with wet sacks or layers of large leaves to prevent desiccation.

Table 5.—Possible Candidates for Aerial Seedings in Developing Countries

Humid tropics	Semiarid areas	Tropical highlands
Acacia auriculiformis	*Acacia albida*	*Acacia mearnsii*
Other *Acacia* spp.	*Acacia nilotica*	*Alnus acuminata*
Albizia falcataria	*Acacia saligna*	*Alnus nepalensis*
Albizia lebbek	*Acacia senegal*	*Alnus rubra*
Other *Albizia* spp.	*Anacardium occidental*	*Callitris* spp.
Anthocephalus chinensis	*Azadirachta indica*	*Eucalyptus globulus*
Avicennia spp. and some other mangroves	*Colophospermum mopane*	*Grevillea robusta*
Calliandra calothyrsus	*Eucalyptus citriodora*	*Inga* spp.
Cassia siamea	*Eucalyptus tereticornis*	*Mimosa scabrella*
Other *Cassia* spp.	*Haloxylon aphyllum*	*Pinus oocarpa*
Casuarina spp.	*Haloxylon persicum*	*Robinia pseudoacacia*
Cecropia spp.	*Pinus halepensis*	
Croton spp.	*Prosopis* spp.	
Derris indica (Pongamia glabra)	*Zizyphus mauritiana*	
Eucalyptus deglupta	*Zizyphus spina-christi*	
Other *Eucalyptus* spp.		
Ficus spp.		
Flindersia brayleyana		
Gliricidia sepium		
Gmelina arborea		
Leucaena leucocephala		
Macaranga spp.		
Maesopsis eminii		
Melaleuca spp.		
Melia azedarach		
Melochia indicia		
Muntingia calabura		
Musanga spp.		
Neoboutnoia spp.		
Pinus caribaea		
Pinus kesiya		
Sesbania grandiflora		
Spathodea campanulata		
Syzygium cumini		
Terminalia catappa		
Trema spp.		

SOURCE: National Academy of Sciences (78).

LAND PREPARATION

Nutrient deficiency, soil compaction, lack of water-holding capacity, and surface hardness are characteristics of degraded lands that influence the success or failure of plant establishment. Because of these problems, many sites need some type of preplanting preparation such as fertilization, clearance of competing weedy vegetation, or loosening of the soil. The degree and type of land preparation depend on several factors: capital and labor available, site and soil conditions, vegetative cover, and species to be planted. For example, *Imperata* grassland may require burning and disking before planting *Eucalyptus*, a tree that requires completely weed-free sites for rapid early growth, whereas direct seeding of *Calliandra* on unprepared sites has been successful (29).

Manual v. Mechanical Clearing

Land preparation can be either done by hand or by machine. On degraded lands with grass or weeds, the land is usually disked. Burning is an efficient method under certain conditions. On gentle slopes or flat degraded lands, the use of tractors is popular. In areas with residual scrubby trees, large tractors with heavy chains between them are used to pull down undesirable trees. Some of the vegetation might be used to make charcoal or be burned. Land clearing methods involving hand or chain saw cutting followed by burning may be better than clearing by heavy equipment. The reasons are: 1) ash has fertilizer value, 2) heavy machinery can cause soil compaction, and 3) bulldozers can displace topsoil (106). On fragile, steep slopes with highly erodible soils, the only suitable method is to manually cut, pile, and/or burn the scrub vegetation (135).

Further advantages of manual methods are that they are less constrained by the rainy season, they require few skills, and the capital cost is relatively low. In addition, manual land preparation provides temporary employment to laborers and causes minimal damage to soil. A disadvantage of manual clearing is the need to recruit, manage, and provide logistics in remote areas for a substantial number of laborers. Mechanical clearing, on the other hand, requires high capital inputs for equipment maintenance; supplies of fuel, oil, and spare parts; and operator training and supervision. Yet in general, mechanical clearance is cheaper than manual clearance (29). The choice between manual and mechanical land preparation must be made on a case-by-case basis, determined by all these considerations.

Soil Improvement

On degraded sites, land preparation is especially important for soil improvement. Plowing suppresses weeds and breaks up soil surface compaction, and ripping breaks up deeper, hardened layers. Contour plowing or using contour barriers of dead vegetation also can reduce soil erosion in areas where vegetation is cleared. Both plowing and ripping are limited to gentle topography. Catch dams, bench terraces, and contour trenches all function to arrest soil movement, thereby improving soil stability and productivity. Ridging in various forms—tie ridging, stepped ridges, small catchments—serve to improve drainage and soil aeration and to retain water on the site (40,128).

The soils of degraded lands commonly are poor in available nutrients; therefore, it may be necessary to add nutrients during land preparation. Several techniques exist to increase soil nutrients, including mulching with organic or inorganic matter, the use of green manure (especially herbaceous legumes), the use of nitrogen-fixing trees, and commercial fertilizers.

Mulching—placing vegetative matter around the base of the tree—suppresses weeds, improves soil moisture conditions, and augments soil organic matter (95). Legume or nonlegume nitrogen-fixing trees can improve soil with their ability to produce nitrogen fertilizer (see sec. on "Nursery Planting Stock"). Foliage dropped by legumes is nitrogen-rich and will augment soil fertility as it decays.

Historically, tropical foresters have relied more on seed provenances and thinning practices than on commercial fertilizers to increase productivity (92). Use of commercial fertilizers for forestry purposes is not likely to become widespread in the tropics given their high cost and the priority given to their use in food production. In most tropical countries, much of the commercial fertilizer must be imported. The cost in foreign exchange combined with uncertainty of plant response limit their application. However, Carton de Colombia has experimented with the application of about 50 grams (g) of fertilizer in planting holes on extremely nutrient poor soils. The results after 3 years have been promising (68). If small amounts of fertilizer can produce significant results, further evaluation is needed to determine the best formulations and amount of nutrients needed per seedling. Research is needed on other deficiencies that limit growing trees.

Some highly weathered tropical soils offer problems when fertilized with essential plant nutrients such as phosphorus and potassium. Phosphorus can become so tightly held by soil minerals that plants can extract little for their benefit, whereas potassium is not held by the soil and is leached away (37,64). The use of the wrong fertilizer, or incorrect amounts of fertilizer, can reduce yields. For instance, application of 100 g of potassium chloride (KCl) per *Pinus caribaea* tree depressed growth and increased mortality on Nigerian savanna sites (61).

Moreover, the use of fertilizer may cause water-associated environmental problems such as increased eutrophication that hampers navigation (52) and may trigger the onset of new health problems. For instance, a large part of the Amazon River Basin has the required environmental conditions for the presence of schistosomiasis, a serious parasitic disease transmitted by freshwater snails. Chemical analyses of waters draining large areas here show a dilute mineral content nearly equivalent to that of distilled water (107,117). The disease is absent probably because the waters contain so little calcium that the snails cannot build shells. The introduction of lime, even in small quantities, into such waters might produce significant environmental changes, including spreading schistosomiasis. Fertilizers can be both beneficial and detrimental, so the impacts of various fertilizer application need to be thoroughly examined before widespread use.

TREE PLANTING

Reforestation of degraded lands is similar to reforestation in general. The main differences are the intensity of site preparation, the selection of tree species, and intensity of maintenance and protection. Well-established technologies for propagating, planting, and tending certain tropical trees and tree crops have been applied in developing countries. These technologies, however, need refinement and adaptation for local site conditions. The management of soils, particularly where continuous tree production is the goal, is of great importance (75, 104). If reforestation of degraded lands is to be profitable and, at the same time, restorative of land quality, more work is needed in selecting high-yielding, fast-growing, soil-enriching, and stress-tolerant species and provenances that produce products desired by the local people or landowners.

Substantial experience and information have been accumulated. Foresters from developing and developed countries alike have had experience with plantations, mostly growing exotic species—some in the tropics, some on degraded lands. Recent references on plantation technologies include Evans (29), ILO (55), FAO (32), Ghosh (40), Wattle Research Institute (124), and Champion and Seth (19).

The following section draws on previous discussions to assess tree planting on specific degraded lands: eroded watersheds, semiarid and arid lands, unproductive grasslands, and saline/alkaline lands.

Repairing Eroding Watersheds

Deforestation of montane regions is one of the most acute and serious ecological problems today (27). Some 10 percent of the world's population live in mountainous areas, while another 40 percent live in the adjacent lowlands. Thus, half of mankind is affected by the tree cover, or lack of it, on mountain watersheds (72). Yet no precise estimates exist of the scale of the problem. Data from FAO and other agencies indicate that some 87 million ha of montane watershed land need reforestation (131).

Maintaining or replacing tree cover on mountain slopes is very important for soil protection (see ch. 1). Trees intercept raindrops, slowing their speed and transforming them into a steady, gentle flow of water down trunks and from leaf tips. The roots foster infiltration of water into the ground to replenish ground water. Removing the protective tree canopy can greatly alter the water regime. This results in floods after heavy downpours as high intensity raindrops compact the soil surface promoting runoff, landslides, and erosion (93).

Efforts to establish tree cover on montane slopes must overcome the erosion and landsliding that may be common to those deforested sites. In areas where erosion is not severe, natural regeneration of vegetation can occur and restricting use of the site may be the most effective and least expensive method to reestab-

Photo credit: U.S. Forest Service

A catch dam, constructed from local materials, is used in the gully to halt further soil erosion

lish tree cover. However, when erosion is acute, primitive dams made of rock, soil, and, if available, tree stems and branches can be constructed in gullies to halt soil movement downslope until trees can be established. Such barriers slow water movement and trap soil. Channels and walls can be constructed to divert water flow from vulnerable areas. Water-spreading techniques can be used to spread runoff water over relatively flat areas, reducing its erosive potential. Control of sheet erosion down a slope can be accomplished by terracing, contour hedges and furrows, and low retaining walls.

Planting sites in montane environments must be prepared by hand to avoid soil damage. Where trees are to be established on degraded watersheds, it is necessary to have tall, well-established seedlings by the end of the first year to avoid being shaded by the ground cover plants. Seedlings raised in containers have better survival and initial growth rates than bare-root seedlings. They can be prepared for site conditions (hardened) in the nursery by repeated root pruning and by regulating watering and amount of direct sunlight (39). However, use of bare-root seedlings often allows larger areas to be planted (96). In remote and inaccessible locations aerial seeding may be more appropriate and should be investigated.

To ensure that watershed protection continues, reforestation programs must integrate the people's needs for food, fodder, and fuel with the need for watershed protection. Species selection should be based on productive as well as restorative characteristics. Fast-growing legume trees and other multipurpose trees can help to meet these criteria, as can agroforestry, where trees are used to support and enhance agriculture. Project planning must also take into account the people living in the lower reaches of the watershed and in other nearby areas. Their demands on the watershed for wood and other products must be either met or supplied from elsewhere for a reforestation program to be assured success.

Reforesting Unproductive Grasslands

Conversion of tropical rainforest into farm or grazing land commonly results in rapid depletion of soil plant nutrients and accelerated soil erosion. In some places, the degradation process leads to takeover by persistent, aggressive weed species of low nutritive value (9). Often the combined problems of low soil fertility and weed infestation become so great that the land is abandoned. Such lands are subject to frequent uncontrolled fires. Whenever the vegetation is burned, erosion becomes very severe, and productivity is reduced further. These lands can contribute to degradation of other sites by causing increased siltation of waterways, floods, and periodic water shortages.

Imperata is the main invader grass species in Southeast Asia and parts of Africa. Known also as cogon and alang-alang, this sharp-edged grass grows a dense network of roots and underground stems, crowding out other species and depriving them of moisture during the dry seasons. Because *Imperata* is an aggressive, rhizomatous grass, burning may induce rapid regeneration. Plowing *Imperata* rhizomes into pieces only encourages it to regenerate into several plants (105).

Imperata occupies some 16 million once-forested ha (one-twelfth of the total land area) in Indonesia (31,62,116). The Indonesian grasslands are expanding by 150,000 ha annually (109) and could eventually cover an area comparable to existing cropland. In the Philippines, *Imperata* covers one-fifth of total land area (41). It has been identified as a problem in Thailand, Malaysia (31), and Papua New Guinea (99). If the percent coverage of Southeast Asia is similar to that of Indonesia, there may be 40 million ha of *Imperata* grasslands in the region.

In Central and South America, the invasion of toxic weeds into cattle ranches cleared from virgin forest is a growing problem. Soil nutrient depletion and weed invasion can cause livestock production to drop to such an extent that ranches have to be abandoned. Comprehensive statistics are lacking, but estimates indicate that some 8 million ha of forest have been cleared for 350 large ranches in the Brazilian Amazon Basin and an unreported area for another 20,000 smaller ranches (115). Yet 85 percent of the ranches in one major area around Paragominas has been abandoned (50).

Special treatment is needed for those areas infested with *Imperata* and for the many abandoned cattle ranches in the Amazon Basin and elsewhere in Latin America. Although the techniques discussed here were developed for lands covered by *Imperata*, the basic principles can be applied to other derived grasslands.

Techniques for Reforesting *Imperata* Grasslands

Tree species selected for reforestation of *Imperata* grasslands should possess the following characteristics to counter those factors that allow grass to dominate:

- easy establishment,
- rapid early growth in poor soil conditions,
- deep rooting,
- dense crown to shade out *Imperata*,
- nitrogen-fixing and soil-improving characteristics, and
- fire resistance (131).

Acacia auriculiformis, *Calliandra calothyrus*, *Gliricidea maculata*, and *Leucaena leucocephala* are species that have been used extensively in Southeast Asia. *Acacia auriculiformis* will grow on the poorest sites, is deep rooting, and has a dense crown (102). Direct seeding of *A. auriculiformis* on *Imperata* grasslands in Malaysia yielded poor results, but large seedlings of this tree can withstand competition from the grass (86). The use of 20 centimeter (cm) tall seedlings raised in nurseries in plastic tubes gave good results (8). Best tree growth results if the grass is cut and burned prior to planting (129). *A. auriculiformis* is susceptible to fire, but this has not been recorded as a cause for failure of reforestation projects (131). It also is a drought-resistant, soil-improving species.

Calliandra calothyrus is a fast-growing, deep-rooted tree with a dense crown. It improves poor soil by nitrogen fixation and high litter production, and it is fire resistant (102). In a trial of direct seeding of *Imperata* grassland that had been burned and plowed, the survival rates after 7 years were:

C. calothyrus	10.4 percent
L. leucocephala	8.3 percent
A. auriculiformis	2.6 percent

Success was not obtained where the site was not first prepared (47). Indonesians use *Calliandra* to reforest land infested with *Imperata cylindrica*, *Eupatorium* species, and *Saccharum* species (83).

Gliricidia maculata grows faster than *C. calothyrus* and can tolerate very poor soils that would be unsuitable for the latter species. It improves soil through nitrogen fixation and litter production. It has the disadvantage, however, of an open crown that allows some growth of weeds such as *Imperata* due to penetration of sunlight (102). *G. maculata* has been used to control the growth of *Imperata* in young rubber plantations (110) and is easily established from cuttings. The establishment of *L. leucocephala* seems difficult by comparison (30).

On upland grass-covered sites, *Leucaena leucocephala* has not grown so rapidly as the trees listed above. The varieties of *Leucaena* available for reforestation are better suited to marginal lowland conditions (sea level to 500 meters (m)) (11). Some varieties grow rapidly to become trees, while others have a shrub form. *Leucaena* canopy is fairly open in the early years after planting; thus, careful tending is necessary to reduce competition from weeds (11). Given early attention, *L. leucocephala* can establish itself firmly. Some of the shrub varieties have rapid and copious seed production, enabling the shrubs to spread down slopes and produce dense cover. *Leucaena,* planted with no other vegetation, may not suffice for erosion control on steep slopes because the leaves tend to fold up at night and when under stress, thus reducing the amount of canopy cover to shield the ground from heavy rain. It is a soil improver with good litter production, nitrogen fixation, and very deep rooting. The latter, together with very rapid resprouting after cutting, indicates potential resistance to grass fires. In addition, dense stands may shade out undergrowth, leaving little grass on the ground to burn, making it useful as a firebreak (81).

In the Philippines, planting has been done simply by burning the grass, opening a furrow with a plow pulled by a water buffalo, and dropping in *Leucaena* seeds. In about 3 years, a thicket of *Leucaena* exists, and the pernicious grass is gone (81).

Photo credit: J. Bisson

Planting bare-root *Leucaena* seedlings on *Imperata*-infested grassland in the Philippines

Arid and Semiarid Lands

Desertification can occur not only in arid and semiarid lands but in certain humid environments as well. In either case, removal of the vegetative cover alters the water regime and reduces the moisture content of the soil, leading eventually to desertlike conditions. An estimated 1.56 billion ha of tropical lands are undergoing severe desertification (114). The problem is particularly acute in Africa and Latin America. Reforestation of these degraded lands is intended to:

- stabilize soils, including sand dunes,
- reduce wind and water erosion,
- improve microclimates, and
- produce fuel, fodder, and other products.

For detailed descriptions of reforestation technologies appropriate for desertified land, see Kaul (63), Goor and Barney (42), Weber (127), Adams et al. (1), Delwaulle (25), and Evans (29). Since water is the main constraint in semiarid and arid lands, reforestation techniques generally entail improving water conditions, which also include choice of tree species, water management, soil stabilization, and protection of trees.

Drought Resistant Species: Many trees and shrubs native to arid and semiarid areas are drought resistant. These drought resistant species can be improved through genetic programs designed to identify, breed, and propagate the most productive of the drought tolerant provenances. Most of the drought resistant species can be reproduced by vegetative propagation (131) and this can be very important for species susceptible to seed-eating insects such as *Prosopis cineraria.*

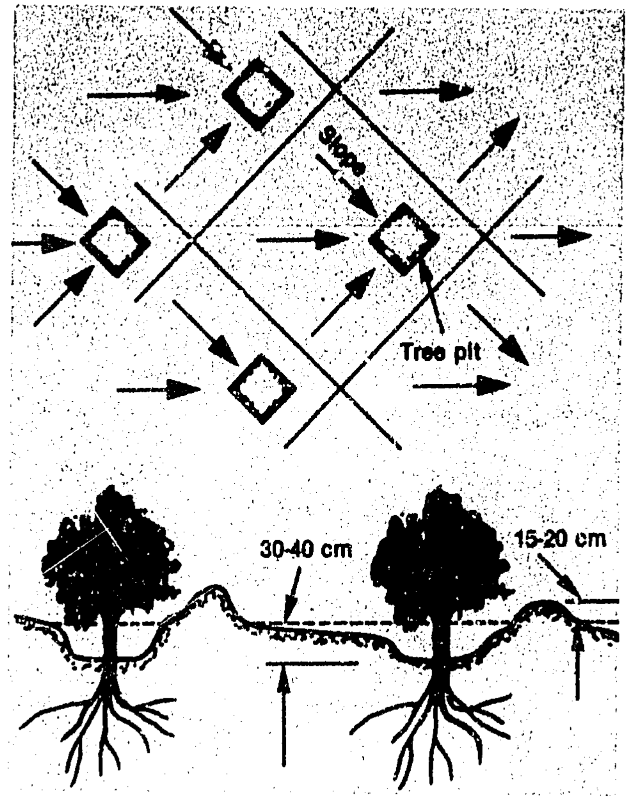
In arid and semiarid areas, nursery-grown seedlings are normally used instead of seeds because seeds may be sought after by small mammals or insects. Good nursery practices are essential. Great care is needed to produce a hardened plant with a well balanced, straight root system. Sometimes, direct sowing of drought resistant species is preferred, especially for the species that have long and fast-growing taproots that may be damaged in a nursery or in transfer to the field.

Other Species: In arid or semiarid regions, the major limiting plant nutrient is likely to be nitrogen. Hence, the use of nitrogen-fixing trees can be extremely valuable. Lists of numerous tree species adapted to these areas and that have proven successful are found in Goor and Barney (42), Weber (127), Adams et al. (1), NAS (79), and Webb et al. (125).

Water Management: Successful reforestation in areas with low rainfall depends on collection and retention of water at the planting site. Water must be directed to the rooting zone of trees and retained there as long as possible. Methods include plowing and ripping the soil surface to increase infiltration, ripping parallel to the slope to retain water, construction of bench terraces on steeper slopes, and funneling moisture onto a smaller area (water harvesting). The latter requires construction of minicatchments that concentrate water into the rooting zones of individual trees. The treatment of soil with mulches of dust, organic matter, plastic, or light-colored stones can reduce evapotranspiration and thus conserve water. Except for mulching and construction of minicatchments, most water-management techniques require the use of tractors and other machinery.

Soil and Sand Stabilization: The destruction of vegetation in arid and semiarid areas makes soil susceptible to wind erosion. Drifting sand encroaches on agricultural land and engulfs settlements (32). However, where the sands can be stabilized, they can often be successfully afforested and become productive.

The principle of dune stabilization is to immobilize the sand long enough for vegetation to become established. The usual practice is either to erect artificial barriers of brushwood or other materials in a grid pattern or to plant sand-binding grasses and trees in a similar pattern. Planting large nursery stock in deep pits may obviate the need for other dune treatments. The use of a mulch or a heavy liquid derived from petroleum or latex as a ground



SOURCE: F. R. Weber for VITA.

Microcatchments are used in reforesting arid lands. Small depressions are constructed around the base of seedling or small tree with the general slope of the surrounding soil surface shaped to move rainfall towards the tree

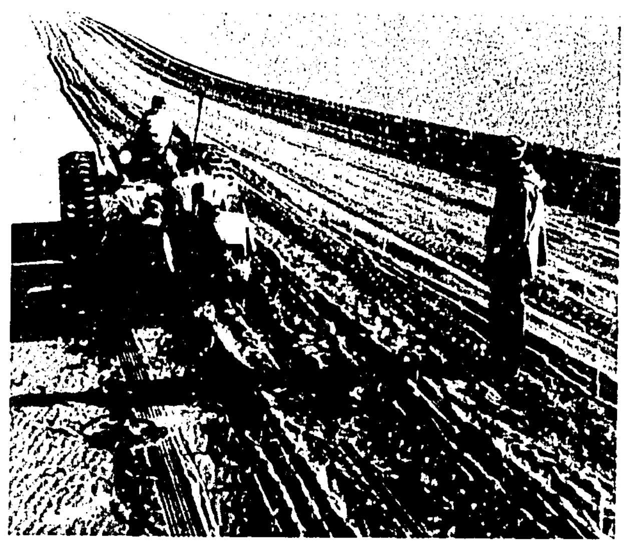


Photo credit: U.S. Agency for International Development

Planting sand-binding grasses to stabilize shifting sand cover has had some success, but is less reliable than traditional methods and has only been used on a pilot scale (90,131).

The goal of reforestation on shifting sand dunes is to establish firm rooting by the plant. Only those plants that thrive on fluctuating moisture and nutrient supply and germinate with little water seem to succeed. A planting method consists of mixing together seeds of several species and sowing them at three different depths in a trench—near the surface, slightly deeper, and at about 8 cm from the bottom. During a good rainfall season, the seedlings on the bottom may be killed by waterlogging while the top ones survive, but during a light rainfall season, the top two lines may die because of desiccation while the bottom ones survive (39).

Complete Protection: The exclusion of browsing animals in many regions—even in areas with shifting sand—will result in recovery of the natural herbaceous and woody plant cover. Sometimes natural regeneration can occur despite centuries of land degradation. Since local people in arid and semiarid lands usually depend heavily on livestock, a solution is to provide an alternative source of fodder by planting fast-growing hedges that provide nutritious foliage and have the ability to resprout. The problem is often to convince the herders to pen the cattle and cut and carry fodder from the hedges.

The primary causes of desertification are simple to list, but they are linked together in a complex web that makes the effects of the whole greater than the sum of the individual parts. Thus, the success of any reforestation program, particularly in the semiarid and arid lands, will depend on more than mere technical development. The cooperation of local people is needed to ensure protection, proper care, and thus survival of the trees. To get this cooperation, the needs of the people as they perceive them must be paramount when designing the reforestation project.

Mine Spoils: A Special Case

Mine spoils occupy little total area in the tropics, but they can be an important local rehabilitation problem where land is scarce. The treatment of mine spoils is analogous to that of desertified lands, although the presence of toxic chemicals may provide an additional problem. Reforestation of such wastelands is usually difficult, but techniques are available to prepare the sites successful for tree growth. In general, it may be necessary to:

- reshape the site to minimize erosion;
- cover it with soil;
- neutralize strongly acidic sites with lime;
- buffer it with peat, humus, or other materials to reduce toxicity;
- loosen the soil for better aeration; and/or
- fertilize the site (32).

Site condition will have great influence on the choice of species and the likely social or economic results of the reforestation effort. Costs of reforesting mine spoils are usually high, but as part of a mining operation they are affordable. One such project, Baobab Farms in Kenya, has converted an entire devastated limestone quarry into an economically productive agroforestry plantation (12).

The list of trees suitable for planting at mine spoils is limited, as not many trees can tolerate the extreme soil conditions. Species that can rapidly add humus and nitrogen to the soil are highly desirable. For example, *Casuarina* trees have been used to reclaim mined spoils in Thailand, Papua New Guinea, and the Dominican Republic (84).

Saline/Alkaline Lands

Saline soils contain sufficient soluble salts (e.g., NaCl) to harm plant growth by preventing uptake of soil moisture. Water within the plant actually moves outward to the saline soil to dilute the salt solution. Therefore, even where the saline soil is wet the plant will experience drought stress. Alkaline soils may or may not contain soluble salts (e.g., Na_2CO_3). The major drawback to use of alkaline soils is that soil minerals retain so much sodium on their surfaces that plant growth and soil structure are adversely affected. The kind of salt also affects the platy soil clay minerals. Where soil structure is good, the platy clay minerals are arranged in random fashion. Sodium, however, tends to reduce the random orientation of clay minerals, in some cases allowing them to rearrange in parallel layers as in a deck of cards. This orientation reduces pore spaces and thus soil permeability. Tillage problems in soils having this clay mineral arrangement are common; such soils do not break up easily.

Overall, approximately 121 million ha of saline/alkaline desert soils exist in the tropics: 36 million ha in India and Pakistan; 31 million ha in Africa; and 54 million ha in South America (35). Each year approximately 500,000 more hectares of excessively irrigated lands become saline or alkaline as a result of inadequate drainage or use of irrigation water that is too salty. Capillary action draws moisture to the irrigated soil surface where it evaporates, leaving salts in or on the topsoil. In some cases, salts can be leached from upland soils and bedrock, raising runoff salinity from deforested slopes and adversely affecting agricultural soil in lowland areas of the watersheds by causing temporary or lasting waterlogging and consequent salinization (10). Even the continuous additions to the soil of salt from sea breezes can have negative effects (16). Other factors that contribute to formation of saline and alkaline soils include the presence of impervious subsoil layers, a dry climate, saucer-shaped topography, and use of brackish irrigation water (39).

Techniques for Afforesting Saline and Alkaline Lands

Reforestation of saline and alkaline lands can have a number of beneficial effects on the physical, chemical, and biological soil properties:

- soil surface shading by trees reduces surface evaporation and, consequently, the upward movement of ground water and deposition of salts in upper soil layers;
- the penetration of roots opens up the soil, improving permeability and facilitating leaching of deposited salts;
- soil structure and microbiology are further improved by incorporation of organic matter deposited on the surface as litter; and
- increased transpiration from vegetative cover can reduce waterlogging by lowering the water table in areas where it is too high.

Successful reforestation of salt-affected lands depends on the following:

1. Careful analysis of soil chemistry and structure. Soluble salt concentration and pH should be among the first measurements to be made. (In practice, selection of planting material often proceeds without even this fundamental information.)
2. Correct choice of planting and soil enrichment techniques to match soil characteristics:
   - In many cases, trees must be planted in deep pits to get maximum survival rates.
   - Planting on bund ridges (dikes) has been successful in some cases as such microsites are better drained, which promotes leaching of toxic salts.
   - Establishment of trees in alkaline soils often requires addition of soil amendments and fertilizers, such as 5 kilograms (kg) of gypsum per pit to replace exchangeable soil sodium with calcium, and application of nitrogen and phosphorus fertilizers and/or green manure.
   - In saline soils with pH less than 8.5, it is possible to secure good tree establishment without replacing the soil, and even the gypsum may not be required.
   - Trees should be planted in alkaline soils immediately after the start of the rainy season. For saline soils, planting should follow two or three heavy showers that leach out salts (22).
   - For most tree species irrigation should use freshwater only. Weeding also is necessary in the first 3 years (22).

- Seedlings should be of a proper size for maximum survival—e.g., over 1 meter (m) for *Eucalyptus* hybrids, and over 0.45 m for *Acacia nilotica* and *Prosopis juliflora.*

3. Selection of species suitable for particular site characteristics. Table 6 lists species that grow well in saline and/or alkaline conditions. The table also shows some important economic uses for some species. Yields and quality of produce, of course, cannot be guaranteed in such extreme conditions. In the State of Haryana, India, *Prosopis juliflora* and *Acacia nilotica* are grown together on severely deteriorated sites having sporadic tree/shrub cover. *P. juliflora* is grown on barren regions, and *A. nilotica* can produce high yields of fuelwood and fodder. Proper seed selection and plantation management can result in trees with good form rather than low, spreading shrubs.

Table 6.—A Selection of Tree Species Tolerant of Saline and Alkaline Conditions[†]

Species	Saline tolerance	Alkaline tolerance	Uses	Country
Acacia nilotica[a]	Up to 0.3% SSC	Up to pH 9	Fw/Fd/Ta/G	India
A. saligna	Saline soils	Alkaline soils	Fw/SC/SB/Fd/G	—
A. tortilis	—	Alkaline soils	Fw/T/Fd/SC	—
Albizia lebbek	Saline soils (moderate soils)	—	Fw/T/Sh/Fd/SC	India
Azadirachta indica	Sites free of salt intop 60 cm. Up to 0.45% SSC subsoil	Up to pH 9.8	Fw/T/O/SB/Sh/SC/Ta/PC	India
Butea monosperma	As *A. indica*	As *A. indica*	—	India
Casuarina equisetifolia[a]	Coastal sites, sandy areas	—	Fw/T/SC/Sh/PW/SB/Ta	China/India
Dalbergia sissoo	A *A. indica*	As *A. indica*	—	India
Eucalyptus hybrid[a]	Up to 0.3% SSC	Up to pH 9	—	India
E. camaldulensis[a]	EC 12 to 17 mmhos/cm in top 30 cm	pH 7 to 8.2	Fw/T/SB/B/PW	Israel
E. gomphocephala	Saline soils	—	Fw/T/SC/Sh/SB	Kuwait
E. microtheca	Saline soils	Alkaline soils	Fw/T/SB	Sudan
E. obtusa	Saline soils	—	—	Kuwait
E. occidentalis	Saline soils	—	Fw/T/Sh	—
E. tereticornis	Saline soils	—	—	Sudan
Gleditsia triacanthos	Saline soils	—	Fw/Fd	—
Haloxylon ammodendron	Saline soils	—	—	—
Leucaena leucocephala (K8 and Fiji varieties)	Saline soils	—	Fw/Fd/SC	India
Pongamia pinnata	As *A. indica*	As *A. indica*	—	India
Prosopis juliflora[a]	0.54% SSC (up to 1% SSC)	pH 9.5 (up to pH 10)	Fw/Fd/SC	India
Prosopis pallida	Coastal sites	—	Fw/Fd/B	Hawaii
Prosopis tamarugo[a]	Highly saline tolerant	—	Fw/Fd/SC	Chile
Tamarix aphylla[a]	Saline soils	—	Fw/T/SC/SB	U.S.S.R.
T. manifera	Saline soils	—	—	U.S.S.R.
T. ramosissima	Saline soils	—	—	U.S.S.R.
T. tetranda	Saline soils	—	—	U.S.S.R.
Terminalia arjuna	As *A. indica*	As *A. indica*	—	India

NOTE: Salinity tolerance is expressed either in terms of percent soluble salt content (SSC) or electrolytic conductivity (EC) in units of mmhos/cm. The country listing denotes the country in which the relevant trials were made. It is not an exclusive listing.

[a]Denotes species of particular importance for reclamation of saline/alkaline lands.

Key to Economic Uses: B—bee forage; Fd—fodder; Fw—fuelwood; G—gum; O—oil; PC—pest control; PW—pulpwood; SB—shelterbelts; SC—soil conservation; T—timber, of whatever quality; and Ta—tannin.

[†]Mangroves are not included.

SOURCE: Yadav (134); Goor and Barney (42); and NAS (79).

PROTECTION AND MAINTENANCE OF TREES

Reforestation does not stop after the trees have been planted. To be successful, reforestation efforts require protection of young trees for years. Proper care and maintenance of the planted site are essential to ensure survival of trees to maturity. Once grown, there is the problem of monitoring timber harvests and of systematic replanting. To pay workers to plant trees is not difficult, but to provide incentives for people to keep them alive is. Primary causes of reforestation failure, other than inappropriate technologies, are uncontrolled grazing and fires, competition from weeds, and uncontrolled cutting for fuel, fodder, and lumber.

Protection From Livestock Damage

Livestock grazing is a common cause of reforestation failure, especially in the semiarid and arid tropics. Direct protection through fencing or guards tends to be very expensive. Other, less costly, methods include planting unpalatable trees (e.g., *Cassia samea*) or thorny trees (e.g., *Parkinsonia*) as barriers around the plantation. The use of living fences is becoming a more widespread practice because they provide a number of auxiliary benefits including shade, fodder, windbreak effect, fuel, and wildlife habitat.

Photo credit: G. Budowski for NAS

Diphyse robinioides used as living fence posts in Costa Rica. The fence provides protection and shade for animals. Its foliage can be continuously harvested for forage, firewood, or green manure

Another alternative includes subsidizing farmers with livestock feed or with cash to purchase feed during the period when trees are most susceptible to animal damage. Once the trees are firmly established, controlled access to the planted area is allowed for controlled tree pruning for fodder. Grazing underneath the tree canopy can be beneficial as a means of weeding. However, livestock grazing on recently reforested watersheds can be harmful because animals compact the thin topsoil, thus leading to poor tree growth and increased runoff. The use of game repellent, tested in the United States against deer, has promise. Similar tests must be conducted for goats and sheep.

Weed Control

Weeding is an important aspect of plantation establishment. Weeds compete directly with seedlings for light, soil nutrients, and water. They can smother and eventually kill young trees by shading and growth habits. They also increase fire hazards and shelter harmful animals (29).

There are three main methods of weeding—manual, mechanical, and chemical. The manual method is the most common and straightforward and requires little skill or capital. It can be done on all sites, in almost all weather conditions, and with all species. Mechanical weeding methods may be used in large plantation projects, but generally they are not considered profitable in the tropics. In many tropical countries, chemical weed control techniques have been tested and found successful, but because of safety and cost problems they seldom become the main means of weed control (2).

Local Participation

Where the shortage of firewood for cooking and heating is acute, wood theft probably will occur. No straightforward solution exists for theft when hunger and cold are the driving forces. This reflects a prevailing social problem that must be dealt with in any reforestation scheme. The problem is particularly acute in Africa where women and children must travel for many hours to gather wood for cooking (26).

Whatever the type and location of tree planting, cooperation of local people is essential for establishment and sustained use of newly planted trees (7). Tree planting programs are most successful when local communities are involved and when the people perceive clearly that success is in their self-interest. Because most trees do not yield much benefit for several years, the technical options offered must demonstrate explicit benefits to the people. Long-term financial benefit/cost analyses are not meaningful to poor people, while social benefits are not easily understood or valued by project managers. On the other hand, people certainly understand the concepts of scarcity and risk and may respond to incentives. In local communities, support can be generated through demonstration plantings, commercial plantings by entrepreneurs with larger land holdings, education of community leaders, extension and training programs working directly with farmers or laborers, and direct financial assistance or provision of substitutes (131).

Village woodlots provide an alternative to cutting in larger areas reforested for other purposes. Subsidizing charcoal or kerosene is also an option until reforested areas can be harvested on a sustainable basis for fuel. In any case, incentives must be created to encourage people to care and maintain the reforested area until the benefits can be reaped. For example, a village woodlot project in the State of Gujarat, India, which involved planting trees on degraded communal grazing lands, was able to meet the need of the people by allowing grass for fodder to be cut and carried to livestock during the second year of tree growth. This approach enabled the people to continue feeding their livestock and simultaneously care for and maintain the reforested area (6). Often people will quickly recognize that this method produces much more fodder than when animals were allowed to graze freely.

Another incentive is to guarantee provision of inputs, credit, and technical assistance when required. Where land tenure is a problem, measures could be formulated to offset the risk to participants caused by the lack of secure ownership of the trees—e.g., giving title to the land, short-term licenses, or improved financial incentives.

Trees that can provide locally valued products are highly valued (54). Poor people do not perceive and rarely receive benefits from industrial plantations. Apart from temporary employment and some stimulation of local economies, most benefits of commercial reforestation programs go to the central government and the private companies involved. Even though forestry may offer a worker higher pay than agriculture, work may be temporary, and labor frequently is not available when needed. During the critical planting and weeding season, for example, many laborers wish to work their own lands. Again, forestry competes with agriculture. When given the choice, farmers will usually opt for the latter. Therefore, an important incentive to get individual landowners to plant trees is the possibility of growing enough food, fuel, and fodder to meet individual requirements with some left over for sale.

If reforestation is done only to reestablish trees on a degraded site, in the long run the same forces that initially led to deforestation and degradation will continue. Experience has shown that local participation in tree planting can have positive and long lasting effects on the land and the people. Agroforestry, community forestry, and social forestry systems are alternatives that seem to ensure the long-term sustainability of the restored land by designing reforestation efforts so that the people who live on the site are principal beneficiaries.

REFORESTATION USING COMBINATIONS OF TREES WITH AGRICULTURAL CROPS

Tree planting, by itself, addresses the biophysical processes of land degradation but not the socioeconomic causes of degradation. Increasing demands for basic human needs and inappropriate systems for producing them are the root causes of most land degradation. Therefore, the most sustainable resource use systems will be those that produce a combination of food, fuel, fodder, and construction materials. The use of multipurpose trees is one method of achieving this kind of productivity; the combination of such trees with annual crops or animals is another. The latter method is now widely referred to as agroforestry. It encompasses all practices that combine forestry, agriculture, and livestock raising. The interplanting of annual crops with trees in reforestation technology systems may yield the following results:

- stabilization of shifting cultivators by providing alternative activities;
- early returns from the use or sale of valuable agricultural crops to offset the costs of removing unwanted vegetation and replanting with desired species;
- benefits to farmers from increased soil protection and reduced weeding; and

Photo credit: G. Budowski for NAS

Agroforestry: Three stratum coffee plantation. Coffee is planted in the shade of *Erythrina poeppigiana* (leguminous tree) with *Cordia alliodora* (timber tree) towering above

- opportunity for self-sufficiency in agriculture and wood products for the individual small-plot landholder.

Agroforestry as a science is only in its infancy. Much more information is needed on the interaction of trees and agricultural crops. Active studies are being conducted at ICRAF, CATIE, and the Forest Research Institute in Dehra Dun, India.

Many agroforestry systems exist in which trees, livestock, and agricultural crops are used in combination, theoretically in perpetuity. For detailed discussions of various agroforestry systems, see FAO (34), Vergara (121), Grainger (44), de las Salas (24), King (66), Chandler and Spurgeon (20), and Wilkin (130). Discussion in this paper is limited to just one of these agroforestry systems called "taungya." Its principal objective is to plant crops with trees used for wood production. Taungya entails leasing forest land to peasant farmers who clear the land, plant crops among the trees, and after an agreed period move on to clear new lands. Although this method has been criticized as a way for colonialists to acquire labor, it does have applicability in some modern reforestation schemes.

Taungya is a well-established agroforestry practice. It can be used to achieve several objectives: to prepare land for tree planting, plant agricultural crops among trees, facilitate weeding, and ensure that suitable soil protection measures are taken. Taungya can, with small changes in rotation length of food and fiber crop and spacing regimes, accommodate a considerably increased food production and population (73).

The full potential of agroforestry systems such as taungya has not yet been tapped. However, the greatest promise of agroforestry is the potential of addressing some key ecological problems of the land and socioeconomic problems confronting the people.

Chapter 3

Constraints and Opportunities

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Chapter 3

Constraints and Opportunities

TECHNOLOGICAL CONSTRAINTS

Currently available technologies can be directly applied to reforestation of degraded lands. For almost any type of land, someone, somewhere, has grown trees. However, important technical constraints exist that must be overcome to expedite reforestation. Some of these constraints are:

- shortage of planting stock;
- inadequate attention to collecting, testing, and distributing high quality seeds and clones;
- lack of information and research; and
- lack of trained staff.

In addition, because it is economically infeasible to reforest the broad expanse of degraded tropical land using conventional technologies, the technologies need to be redesigned to require less organization, less infrastructure, and less capital investment. Only then can there be rapid and widespread reforestation.

One major technical constraint to reforestation is the shortage of planting stock. The seed supply is generally adequate for species commonly used in tropical industrial plantations (pines, eucalyptus, *Gmelina*, teak), although some valuable provenances are in short supply and their natural origins are threatened with genetic impoverishment or extinction. On the other hand, seeds for most of the multipurpose and nitrogen-fixing tree species are available only in small quantities and are often of poor quality. The seed supply problem can be alleviated through the use of vegetative propagation such as rooted cuttings or tissue culture. These techniques have great potential to accelerate the process of matching provenances to specific site conditions and to reproduce those provenances on a massive scale. Caution is advised because these techniques greatly reduce the genetic base and thus can increase the forest's susceptibility to outbreaks of pests and disease.

Even though more seeds are needed, care should be taken in their collection. No mechanism exists today to control the quality of tree seeds traded. Most tree seed dealers do not supply adequate information on the origin of the seed and this results in the use of genetic types that are poorly matched to site conditions. Planting the wrong seeds may cause a reforestation project to fail. Similarly, it may be difficult to trace the origin of those seeds that do produce well to get more planting material. Seed certification procedures have been established for agricultural seeds and to a much lesser extent for tree seeds in Europe (89), Canada, and the United States. These are valuable aids for controlling genetic history and seed quality, but they are extremely difficult to negotiate and control, particularly internationally.

Another constraint on reforestation is the lack of relevant and timely information and research. Without accurate data, it is impossible to understand how and why land became degraded or to plan the proper scale and action needed. Although the data base is improving because of the Global Environment Monitoring System (GEMS) sponsored by FAO and UNEP, it will require continuous refining and updating. Information is unavailable on silviculture of various tropical tree species (especially species with many uses), on species and provenances suited for specific sites, on management of mixed-species plantations, and on the best follow-on maintenance and protection.

Even when information on appropriate species and technologies is available, it often is not disseminated effectively to scientists, technicians, and decisionmakers. This is partly because of a dearth of published material and insufficient information transfer within countries. Another constraint on information flow is the lack of an institution with a mandate to coordinate reforestation research, development, and implementation on degraded tropical lands. Thus, foresters are often unaware of what is being done elsewhere in their own country, in other projects or administrative districts, or by various research agencies. Furthermore, they are often unaware of previous work in their own region. Duplication, redundancy, and waste of precious time occur.

Finally, in most tropical countries there is a lack of sufficient numbers of trained staff at professional and technical levels for direct operational forestry research or for extension work. The reasons are many:

- forestry ranks low in public recognition;
- financial rewards are poor in comparison with other professions, since most tropical forestry jobs are in the government sector, which is poorly rewarded in comparison with the private sector;
- competition among ministries, between ministries and industry, and among national and international agencies, and the emphasis on post-graduate qualifications for promotion have led to a "brain drain" from the local government agencies.

Yet even when staff numbers and training are adequate, their efficiency can be impaired by poor project management and poor logistical and technical support (126). Further:

- government officials generally are unwilling to serve in rural areas where the need is greatest; presumably this will continue until the market is saturated with trained personnel.

TECHNOLOGICAL OPPORTUNITIES

Opportunities exist to overcome these technological constraints, including:

- developing international systems for seed source identification, collection, production, and distribution;
- supporting programs on tree improvement, propagation of *Rhizobia* and mycorrhizae, mixed species plantations, and other related subjects;
- supporting efforts to disseminate research information globally, regionally, and in-country;
- including research and dissemination of information as components of reforestation programs; and
- creating incentives for developing country people to enter forestry, such as changing the reward systems in forestry institutions.

Lack of sufficient and appropriate planting materials can be alleviated by developing international systems to identify seed origin, certify quality, and collect seeds in commercial quantities; protect natural stands to conserve germ plasm; and establish seed orchards from which seeds can be made available internationally. Support for tree improvement activities will encourage self-sufficiency in seed production and allow genetic improvement to serve local needs.

Genetic improvement can give gains of 10 to 30 percent in yield in the first few generations (131), and generations can be as short as 2 to 3 years for some tropical trees. Clonal propagation has great potential, particularly where seed is in short supply and where certain site-specific genetic characteristics are desired. Techniques for mass production of cuttings can be developed locally by private nurseries, universities, or research institutions (including forest departments). Additional research may be required, particularly for fast growing tropical species with short rotations. Financial support for techniques such as tissue culture may prove beneficial in the long run because its greatest value may be in gene conservation. Given the potential to increase survivorship and yield with inoculation of seedlings with *Rhizobium* or mycorrhizae (as described in ch. 2), additional support could be given to collect, identify, culture, test, and mass propagate productive strains of those bacteria and fungi.

Research on interactions between agricultural crops and trees has begun in many parts of the world. However, very little research is being conducted on mixing species of trees. It is a practice that is seldom used and poorly understood. Support could be given to initiate more research in this area. The research should aim at both the biological interactions of tree mixtures and at management systems to follow when one species begins to dominate another.

Inadequate information gathering and dissemination lead to inefficient expenditure of funds. The publication of information on local reforestation and research in internationally available journals could help to prevent constantly "reinventing the wheel." Providing published literature to operational and research personnel, especially at the field level, could enhance the likelihood of the most appropriate, up-to-date, and low-cost reforestation technologies being applied to the degraded land. Results of local research and management experience can be published locally at low cost in the form of departmental technical notes and bulletins. Efforts should be made to ensure that staff members receive relevant materials, read them, and, where appropriate, use them. Distributing information internationally is more complicated and expensive. The Commonwealth Forestry Bureau (CFB) maintains all of its forestry research information in Lockheed Dialog, a computer-based information retrieval system in California, but too few institutions in tropical countries have access to necessary computer terminals or money to use this service. Mail service and reprints are also expensive. Donor institutions might help by financing an international information service to provide microfiches containing each month's CFB abstracts to developing countries. Thus, field staff could be kept up to date on current literature and the latest advances in reforestation.

Improvements in information dissemination can be linked to a well-coordinated research effort based on some systematic, scientific approach eliminating unnecessary duplication and waste. In some cases assistance may be needed from established research institutions to design research programs and to help train research staff to interpret and implement results. Donor institutions can help, for example, by providing appropriate equipment. Twinning of research institutions in developed and developing nations is one vehicle to provide this kind of support. (See ref. 132 for more information.) However, other methods to coordinate funding for research need to be formulated.

Providing additional staff, like reforesting additional hectares, requires increased government expenditures, and, where necessary, financial or technical support from donor institutions. Staff recruitment and maintenance depend on a rewarding career structure with sufficient financial inducement. In many countries provision of additional staff could be provided at little extra cost by restructuring forest agencies to reduce unnecessary duplication and complex hierarchies (131).

Forestry extension is becoming increasingly important as planners recognize that project success depends largely on active participation of local people. Incentives must be developed to entice more foresters to live and work in the field to provide necessary support to local people. Unfortunately, most existing forest services are not structured to provide forestry extension services, nor is staff trained in extension and communication skills (6). Therefore, major changes are in order for forestry administration, staffing, and training—changes also designed to acknowledge that forestry extension needs to work with local women who, in many countries, perform the tasks of planting and caring for crops including trees (53).

OTHER CONSIDERATIONS

Forestry is low in priority in many tropical countries. Forest plantations have not competed well against other land uses because the economic returns are often spread over a long time and short-term profits are low compared to those of alternative investments. This is often in conflict with government priorities for projects with quick returns (for which leaders receive more political credit) and with bankers who use conventional discounting methods and have little interest in moderate returns in 30 years. In addition, the lack of comprehensive forestry or land use policies has prevented forestry investment and development. But firm policy guidelines from the governments can produce significant results. For example, fiscal tax incentives for private reforestation established by the Brazilian Government have led to an increase in the rate of reforestation in Brazil (103). By giving tax breaks to landowners who reforest their lands, the Brazilian Government has given recognition to the importance of reforestation.

Reforestation projects may not receive adequate funding and support because benefit/cost analysis can show unfavorable results when it fails to include both direct and indirect costs and benefits. Adequate analysis also requires comprehensive data on costs, benefits, and man- or machine-times and productivities, yet much of this information is unknown at the project planning stage. Price estimates often are unreliable and do not account for inflation. Information on labor requirements is usually missing as well. Moreover, in forestry, yields are difficult to predict because of the long-term nature of the enterprise, climate and management uncertainty, and, more importantly, a lack of accurate information on site/species interactions. New technologies, such as tissue culture to accelerate vegetative propagation and bacterial inoculation to increase seedling survival, are reducing the costs of reforesting degraded lands. Yet methods are not developed to measure the important but indirect benefits to justify investment in reforestation.

Many nonmarket costs and benefits must be included in economic analysis, especially for reforestation projects where the indirect benefits may be more significant than direct benefits. But benefits such as improved environmental quality are often the most difficult variables to quantify. Economists are grappling with this problem. International development banks tend to treat many nonmarket considerations in a qualitative fashion rather than trying to develop artificial values for them (45). However, unless treated carefully, simply listing nonquantified variables may serve to remove them from consideration. Therefore, given the large uncertainties in selecting the best method for reforestation of a degraded site, it may be advisable to try out in practice several approaches until the uncertainties have been sufficiently reduced (51).

Most experts find that major constraints to reforestation of degraded tropical lands are economic, institutional, and social rather than technical. A technical package, once accepted by funding institutions and the host-country government, may solve certain problems, but many obstacles to its acceptance remain. Experts must remember that "forestry is not, in essence, about trees. It is about people. It is only about trees so far as they serve the needs of the people" (46). Successful reforestation requires sufficient funds, strong political will, massive popular support, and cooperation among all involved parties.

Appendixes

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Appendix A

Commissioned Papers and Authors

Technologies and Technology Systems for Reforestation of Degraded Tropical Lands

P. J. Wood, J. Burley, and A. Grainger
Commonwealth Forestry Institute,
Oxford, England

Technologies for Reforestation of Degraded Lands in the Tropics

C. M. Gallegos, C. B. Davey, R. L. Kellison,
P. A. Sanchez, and B. J. Zobel
Universities for International Forestry
(UNIFOR)
Syracuse, New York

Afforestation and Management of Tropical Wastelands in India

R. C. Ghosh
Calcutta, India

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Appendix B

Acronyms

AID — Agency for International Development
CATIE — Centro Agronomico Tropical de Investigacion y Enseñanza
CEQ — Council on Environmental Quality
CFI — Commonwealth Forestry Institute
CIAT — Centro Internacional de Agricultural Tropical
FAO — Food and Agriculture Organization of the United Nations
GEMS — Global Environment Monitoring System
GTZ — German Agency for Technical Cooperation (Deutsche Gesellschaft füer Technische Zusammenarbeit)
ICRAF — International Council for Research in Agroforestry
IDRC — International Development Research Center
ILO — International Labor Organization
NAS — National Academy of Sciences
NFTA — Nitrogen Fixing Tree Association
NifTAL — Nitrogen Fixation by Tropical Agricultural Legumes Project
NRC — National Research Council
PICOP — Paper Industry Corporation of the Philippines
UNEP — U.N. Environment Program
UNESCO — U.N. Educational, Scientific, and Cultural Organization

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