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Rejoining Habitat Remnants: Restoring Degraded Rainforest Lands

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In the closing years of the twentieth century, the preservation of the world's declining biological diversity has emerged as a major conservation challenge. Land managers and policy makers in most developing countries have to deal with the immediate problems of rural poverty and an increasing need for food and living space on the one hand, and the demands of the world community to conserve biological diversity on the other. In many Western industrial countries, present levels of social and economic development have been achieved through the capitalization of natural resources, and it is hardly surprising that this is seen as a model for others to follow. The model is appropriate, however, only if one accepts the accompanying environmental costs, and while some less-developed countries are apparently willing to do so, many are concerned about the consequences such development may have for their biological resources (Kahn and McDonald, chap. 2).

The problem of preserving biological diversity is perhaps most acute in landscapes occupied by moist tropical forests, both because of their great biological richness and apparent fragility (but see Lugo 1995) and because they are being subjected to rapid land use changes. Large areas of forested land are being cleared for food production, but failure to recognize the importance of tightly linked forest nutrient cycles in maintaining soil productivity has resulted in declining crop production (Jordan 1993), and as a result many cleared lands are being abandoned in a degraded form. Settlers and indigenous farmers are thus forced to exploit new lands, and consequently there are fewer areas of undisturbed forest available for conservation reserves. In addition, many of the remaining undisturbed areas are now isolated fragments, often unrepresentative of the diversity of ecosystems once present in the landscape.

The tropical conservation problem results from a complex mix of economics, politics, and biology. From a biological viewpoint, the challenge is to develop sustainable land management practices that satisfy the needs of the local human population and contribute to the conservation of biological diversity, while simultaneously developing and maintaining a viable and representative system of nature reserves. In this chapter, we highlight ways of dealing with degraded lands to restore their ecological function, to reduce the effects of fragmentation on native fauna and flora, and in some cases, to produce economic benefits for local communities.

RESTORATION GOALS

Three alternative goals when overcoming land degradation in a previously forested area might be

1. *Restoration,* attempting to restore a forested area to its presumed original condition. This new forest would contain the same complement of species and would have the same general structure as the original forest.
2. *Rehabilitation,* in which mostly native species are used in the new forest, but some exotics are included because they are economically or ecologically necessary to overcome the degradation.
3. *Reclamation,* using only exotic species to overcome degradation. Again, these may be chosen for economic or ecological reasons.

These alternatives are similar in that they all aim to re-create productive and functional forest ecosystems on an otherwise degraded landscape, but they differ in the extent to which they seek to reestablish the original forest biodiversity.

Restoration, as defined above, is obviously the preferred option if preservation of biological diversity is the prime objective. However, it is also likely to be the most expensive option if large areas are to be treated, and its feasibility is debatable for several reasons.

1. The richness of tropical forests makes it impossible to plant or directly seed anything more than a small subset of the plant species once present. Moreover, many forest plants require animal mutualists to reproduce, and ensuring that these animals also recolonize degraded sites is problematic.
2. Biotic composition and relative population sizes of different plant species are rarely known for tropical forests. These difficulties are amplified when a site has been degraded and only remnants are left to indicate the likely original condition.
3. Forest clearing for agriculture commonly results in the most fertile land on gentle topography being cleared first. Forest remnants are therefore often unrepresentative of the original forest types in cleared areas, and while some plant and animal species may be found in both situations, many are likely to have disappeared. Even where representative forest remnants persist on more fertile sites, the size of these remnants is often too small to sustain the original biota or to provide adequate sources of colonists for degraded sites.
4. The widespread presence of weed or pest species makes them difficult to eradicate and can hinder the re-creation of original communities.
5. While it may be possible to approximate the original forest composition at a particular site, finer-scale spatial variation may be impossible to specify (except in general terms) because we lack knowledge of site and habitat requirements for the majority of species. Community composition is also highly dynamic, so that aiming at a preferred species composition is "a game with a moving target whose trajectory cannot be accurately predicted" (Simberloff 1990b, 44).
6. Small differences in factors such as climate or population sizes of planted species at the time of establishment may lead to different outcomes. For example, the presence of a particular mycorrhizal symbiont, or the order in which species enter the new ecosystem, can affect the nature and diversity of the ecosystem (Gilpin 1987a; Grange, Brown, and Sinclair 1993).

Add to these problems the stochastic nature of rainforest succession (e.g., Webb, Tracey, and Williams 1972), and it is clear that true restoration is practically impossible to define precisely, much less implement. This does not mean, however, that a more modest goal of reestablishing a representative species-rich community of plants and animals is not achievable. Whether this community has the same species richness and relative population sizes may not matter. In circumstances in which regional levels of biological diversity are plummeting, even modest levels of "restoration" are worth attempting.

WHERE TO RESTORE?

Studies of island biogeography suggest a generalized relationship between species richness and island area of the form

$$\log S = \log C + Z \log A$$

where S is species richness, A is area, C is a constant giving the number of species when A has a value of 1, and Z is also a constant, usually assuming a value of 0.7 or less (Williamson 1981). The actual value of Z (the slope of the log species-log area relationship) varies with the biota and locality in question. The predicted species loss caused by deforestation, which leads to the creation of forest "islands," may therefore be high or low depending on the factors that influence Z, such as the species' vagility and the hostility of the surrounding habitat (Lugo, Parrotta, and Brown 1993). If Z is low, then restoration of massive areas might be needed to significantly increase regional biodiversity where only fragments of an original forest area remain. Such restoration is expensive and often difficult to achieve for social and political reasons.

The situation may not be as difficult as this simple analysis suggests, however. Most forest remnants are not "islands" in a biologically sterile "sea," and many species are not distributed at random across a landscape, but are concentrated in certain key locations. Small increases in the sizes of these key habitats may allow the persistence of larger populations of certain species.

Potential target areas for forest restoration (table 24.1) include the following.

1. *Habitats of particular species.* Because restoration seeks to prevent further species loss, an obvious focus for activity is the habitats of endangered species, especially local endemics (see Andersen, Thornhill, and Koopowitz, chap. 18). It may be possible to define the habitat requirements of these species and attempt to re-create conditions for their reproduction and expansion, although lack of baseline knowledge of habitat conditions or variation in the distribution and density of target species may make this difficult. Artificially increasing the local population size of an endangered species may be a short-term solution, but its longer-term survival will probably require restoration of more extensive areas of forest.

2. *Streamsides.* Riparian ecosystems are productive and comparatively species-rich. Many species are restricted to these habitats, while others range more widely but still depend on these systems (Remsen and Parker 1983; Crome, Isaacs, and Moore 1995).

Table 24.1 Preferred target areas for forest restoration.

Location	Comment
Habitats of particular species	Where populations of particular species have been reduced to critical levels
Streamsides	Often local centers of species richness and important wildlife habitats during drier periods
Degraded lands within existing reserves	To enhance the value of existing conservation areas
Edges of forest remnants	To consolidate boundaries and reduce adverse changes at the edge or within forest fragments
Corridors linking forest remnants	To facilitate species movement between isolated fragments
Islands	Islands are often the only places where exotic pests or predators can be excluded
Within the general degraded land matrix between forest remnants	Wherever it is economically, socially, or politically possible to attempt restoration

Restoration of riparian habitats could allow populations of these latter species to increase and enhance their capacity to colonize other areas. Revegetation of streamside areas also benefits water quality, stabilizes soil surfaces, and reduces erosion.

3. *Degraded areas within and around conservation reserves.* Creation of national parks and nature reserves is often difficult and sometimes controversial (Green, Paine, and McNeely 1991). Costs of managing reserves can also be comparatively high for many tropical countries. It makes sense, therefore, to ensure that degraded areas within these reserves are managed with the aim of optimizing the conservation benefits they provide. The same is true where degraded lands available for restoration are located on the boundaries of nature reserves or forest remnants. In this situation, restoration may aim to consolidate irregular boundaries and reduce the adverse ecological changes that occur at edges and often penetrate some distance into forest remnants (Sisk and Margules 1993; Laurance et al., chap. 32).

4. *Corridors.* Vegetation corridors that link together several forest remnants have been widely discussed as targets for restoration efforts (e.g., Saunders and Hobbs 1991). Corridors may have a particular value in linking remnant areas of forest at different altitudes to facilitate movements of elevational migrants, which are common in the Tropics (Crome 1975). Enabling species to move between remnants may also enhance opportunities for genetic or demographic interchange or facilitate seasonal movements. Much remains to be learned about the most appropriate design for such corridors, such as width, length (and their interaction: Harrison 1992), location, and how edge effects might limit their value. The utility of corridors has been questioned by those who argue that there is little direct evidence that they facilitate species movements in the way that corridor advocates suggest (e.g., Simberloff 1992). Most of the debate has concerned only animal species, and there is currently little field evidence from which to draw definitive conclusions. Irrespective of this debate, it seems likely that corridors beyond a certain minimum width will have value as new habitat even if they have limited utility for increasing animal or plant movement.

5. *Islands.* Degraded island ecosystems may be particularly attractive target areas for

restoration because they are one of the few locations in which pest species can be completely eradicated with a greatly reduced possibility of re-invasion (Downs and Ballantine 1993).

6. *In the matrix between remnants.* Restoration of matrix areas can be used to create new habitat between existing fragments. The size and potential conservation benefit of this habitat will depend on the restoration effort, the landscape pattern of current fragmentation, and the presence of species that can colonize the new habitat. This strategy also offers the advantage of further increasing the biological heterogeneity of the "sea" between remnant forest "islands."

HOW TO RESTORE DEGRADED RAINFOREST LANDS

The first step in any approach to restoration is to alter land use practices responsible for land degradation. In conservation reserves, the management objective is generally to remove human influences to as large an extent as practically possible and assist natural processes that will restore vegetation to a natural condition. In other areas, such as streamsides, corridors, and the general matrix of agricultural areas between remnant vegetation, eliminating human influences is not possible, but destructive patterns of grazing, indiscriminate use of fire, and inappropriate cropping must be altered before systems for reestablishing natural vegetation can be applied.

Four possible methods for restoring natural vegetation are natural regeneration, direct seeding, accelerating natural succession through planting seedlings, and incorporation of restoration goals in timber production programs. These methods will be discussed below, and case studies from Queensland and Puerto Rico will be used to demonstrate the application of the latter two methods.

Natural Regeneration

Restoration through natural regeneration involves protecting the site from further disturbances and allowing natural successional processes to restore a forest community. There are many examples in which natural seed dispersal has led to reforestation of large areas. In the New England region of the United States, forest has reestablished itself over large areas of land cleared for agriculture in the late eighteenth century (Williams 1992). Clearing reached a peak in 1820–1880, when more than 80% of the land was deforested. The present forests are comparatively young, and compositional trends can still be related to past land use (Matlack 1994a). However, the magnitude of the reforestation process in the absence of direct replanting is significant.

Similar patterns of reforestation have occurred in various areas now occupied by rainforest. Jones (1956) reported that large areas of forest in Nigeria appear to have regenerated following extensive agricultural clearing more than two hundred years earlier. Rainforests in Venezuela and Colombia have recovered following widespread wildfires about two hundred fifty years ago (Saldarriaga and West 1986), and there is evidence for natural recovery of rainforests and other tropical forest formations in Puerto Rico during the last fifty years following centuries of intensive agriculture (Birdsey and Weaver 1982).

Recovery times for such natural succession are often very long. Where degradation is severe, limitations to the process may include low availability of propagules (seeds or root stock), seed or seedling predation, loss of dispersal agents, nonavailability of suitable microhabitats for plant establishment, low soil nutrient availability, absence of fungal or bacterial root symbionts that facilitate nutrient uptake, seasonal drought, competition from grasses and ferns, and fire (Uhl and Jordan 1984; Uhl 1987, 1988; Uhl, Buschbacher, and Serrão 1988; Nepstad, Uhl, and Serrão 1991; Parrotta 1992, 1993a; Thébaud and Strasberg, chap. 21). If this approach is consciously applied as a restoration practice, land uses must be restricted to those compatible with restoration objectives.

Direct Seeding

Reestablishment of natural forest can be assisted by broadcast sowing of seed of certain key species that modify the environment and facilitate the reestablishment of other species. This strategy requires some form of weed control and a relatively large supply of seed from appropriate species. Direct seeding has been shown to be more efficient than planting seedlings when establishment rates of greater than 1% of sown seeds can be achieved (C. Van der Woude, pers. comm.). There are many examples of direct seeding being used to revegetate bare soil at mine sites, but few cases in which direct seeding has been used successfully to restore degraded forest lands. Sun, Dickenson, and Bragg (1995) presented results of direct seeding of a rainforest pioneer *(Alphitonia petrei)* in degraded streamside areas in the Wet Tropics of northern Queensland, in combination with herbicide application. In this case, up to 28% of sown seeds became established. If this technique can be tested at a wider variety of sites and proven to be operationally efficient, it may be particularly useful for steep or otherwise inaccessible areas. The difficulty of acquiring seeds of rainforest species in sufficient quantities, however, may limit this option.

Accelerating Natural Succession by Planting Seedlings

Carefully established plantings of particular tree species can also accelerate natural succession. Once a forest structure is established, the site may become suitable once more for forest-dwelling wildlife. Plant species suited to such restoration programs (table 24.2) include those that can tolerate and ameliorate adverse site conditions and those that act

Table 24.2 Priority species for use in planting programs for forest restoration.

Species type	Comment
Nitrogen-fixing species and those able to improve soil fertility	Such species can reduce the need for costly fertilizer amendments.
Species able to grow rapidly and exclude weeds	These species will help create appropriate microclimatic conditions.
Species attractive to frugivores	These species encourage seed dispersal to the site via frugivores.
Mutualistic species able to sustain wildlife at otherwise stressful times of the year	These species may help maintain wildlife populations.
Poor dispersers (e.g., large fruits)	Such species may not colonize the site otherwise.
Rare or threatened species	Plantings will increase local population sizes.

to accelerate the colonization process by attracting seed-dispersing animals (Lugo 1988b; Lugo et al. 1993; Parrotta 1992, 1993a,b).

The "framework species" method developed in northern Queensland (Goosem and Tucker 1995) uses suites of local tree species that promote more rapid natural succession. It has the greatest potential in areas where substantial forest tracts and remnants still exist. These framework species have a number of important features: individuals can grow in close proximity (i.e., they are "gregarious"); they cast sufficient shade to eliminate grasses and weeds and thus rapidly capture the planted site; and they have small to medium-sized fruits that are attractive to a wide range of avian and mammalian frugivores, the major seed dispersers in local closed forests (Goosem and Young 1989).

Pioneer species constitute 30% of framework species. Pioneers rapidly provide food for frugivores and arboreal folivores (J. W. Winter, pers. comm.), create perches and other forest structures, and through self-thinning and short lifespans, quickly create ground habitats such as fallen logs. Figs (*Ficus* spp.) are also important because they can serve as a major food and perching resource to many local frugivores and some folivores (Crome 1975). Other framework species are from later successional stages but become regular, abundant fruit producers within three to six years after establishment. Species that are unlikely to colonize the site quickly because of large diaspore size, are threatened or endangered, or can provide particular food or habitat for endangered wildlife (e.g., *Flindersia* spp.: Laurance 1990) may also be used.

The planted area should be close enough to nearby forest that the arrival of seed and fruit eaters is likely. In northern Queensland, some fruit pigeons and flocks of gregarious frugivores such as metallic starlings *(Aplonis metallica)* and yellow orioles *(Oriolus flavocinctus)* can easily cross about 500 m of open grassland. Other species may have different tolerances. Whether the primary factor in trees attracting frugivores is fruit reward or perch site is uncertain. McDonnell and Stiles (1983) have shown that increased structural complexity alone can enhance seed deposition in planted areas. Their work suggests that if this applies more widely, framework species might be chosen on the basis of their perching value rather than fruit type. If a complete species complement is to be achieved in the restored area, the planting program will also need to provide for the establishment of species with poor natural dispersal abilities, such as those with heavy seeds that rely on wind dispersal.

Inclusion of Restoration Goals in Timber Production Programs

In much of the Tropics it is rarely possible to plant large areas purely for habitat restoration. However, commercial timber and fuelwood plantations on cleared or degraded forest sites may be utilized to meet conservation goals. Native species with high timber value can be planted in mixtures. Alternatively, monocultures of native species carefully selected to match specific site conditions can be established, yielding a mosaic of different species over a particular landscape. The initial species diversity in either situation will not be as high as in the framework species method described above, but the trade-off is that production benefits allow these methods to be applied over larger areas of degraded landscape. This approach (as will be described further below) may therefore yield higher diversity benefits in the longer term.

Alternatively, plantations of exotic species can be used to suppress grasses and weeds and create appropriate understory microclimatic conditions for natural successional processes to increase local biodiversity (e.g., Mathur and Soni 1983; Mitra and Sheldon 1993; Lugo 1992; Parrotta 1992, 1993a,b).

CASE STUDIES

Restoration Efforts in Northern Queensland, Australia

In Australia, clearing of natural vegetation and subsequent land degradation are major environmental problems that have resulted in extensive destruction and fragmentation of forest and woodland habitats. The Australian Tropics have not escaped such effects. Recognition of these problems has recently resulted in government initiatives aimed at mobilizing community support to restore forest on cleared or degraded areas in northern Queensland. Two such initiatives are the Community Nature Conservation Program (CNCP) and the Community Rainforest Reforestation Program (CRRP).

The Atherton Tableland is a focus for both programs. It is an undulating plateau ranging from 700 to 1,000 m in altitude (17° and 17°35′ S), separated from the coast by a narrow coastal plain and a range of granite massifs up to 1,620 m high (fig. 24.1). Annual rainfall on the Tableland proper ranges from 1,400 mm in the north to 3,600 mm in the south, and is strongly seasonal, with a pronounced dry season from July to November. Average temperatures range from a maximum of 28.5°C in December to a minimum of 10.8°C in July (see Laurance, chap. 6, for a more detailed description of the Atherton Tableland).

Before European settlement, the area was mostly rainforest of varying composition, depending on climate and soil type (Tracey 1982, 1986). Clearing began on richer basaltic soils and quickly extended to other areas, but as with most land clearance in the Tropics, there have been many situations in which soil fertility and crop and pasture production declined rapidly following initial clearing (Maggs and Hewett 1993). Significant areas of rainforest in less accessible areas and on poorer soils remained in government ownership, and much of this was logged with varying intensity and quality of management. Logging in state-owned forests ceased following World Heritage listing of the rainforests in 1988.

Case Study 1: Community Nature Conservation Program

The CNCP aims to promote nature conservation outside protected areas by encouraging local communities to help manage their local environment and by providing support to community groups and individuals involved in the restoration of natural plant communities. The CNCP has developed a specialized habitat restoration nursery and works closely with the community group TREAT (Trees for the Evelyn and Atherton Tablelands) to carry out its objectives. Through voluntary nursery and field work and federal

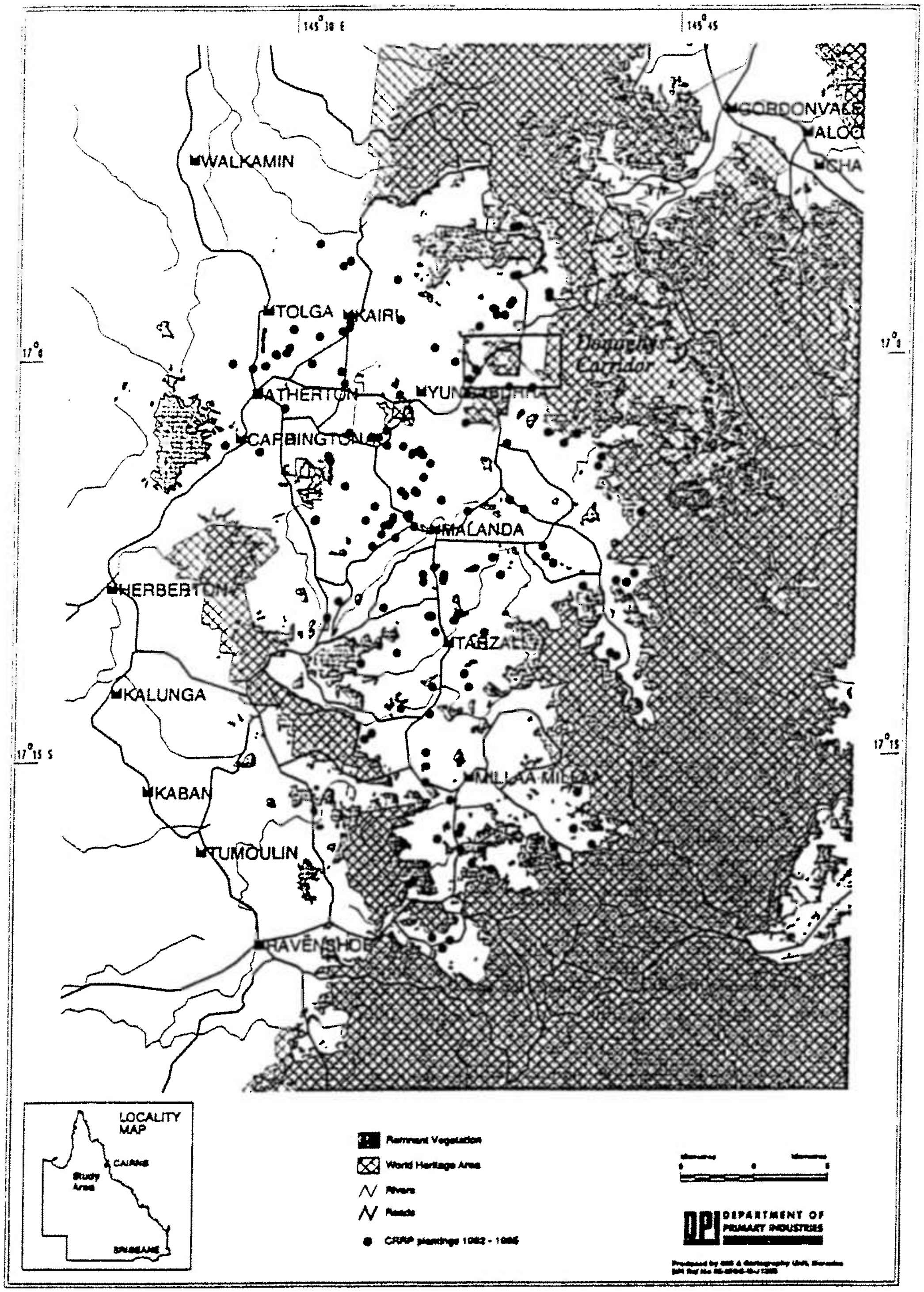

Figure 24.1. Distribution of remaining rainforest in the Atherton Tableland region in northern Queensland. Solid circles indicate location of areas planted under the Community Rainforest Reforestation Program.

and state government support, the CNCP is able to provide free tree seedlings to TREAT members for planting on their properties. Plantings vary from shelterbelts on dairy farms to the repair of riparian zones and expansion of forest remnants. Seedlings are also used by the Queensland Department of Environment and Heritage for restoration projects in and surrounding national parks and other protected areas.

A number of different restoration strategies have been devised for different climatic and edaphic conditions and different scales and intensities of disturbance to natural vegetation. The framework species method described above is commonly used, and specialist legumes such as *Acacia* spp. are used on very degraded soils.

Site preparation involves control of all exotic species prior to planting using knockdown herbicide. All dead material is left to provide mulch cover. Weed control may require two or three herbicide sprayings to exhaust all weeds in the soil seed bank. Plants are randomly established at 1.5 m spacing (about 6,000 stems/ha) during the wet season. This close spacing ensures canopy closure in 12–24 months. An NPK fertilizer is applied at the rate of 100 g per plant at establishment and every month during the wet season thereafter until the trees are two years old. Weeds are excluded by nonresidual herbicide until canopy closure occurs and the area becomes self-maintaining.

Natural colonization following the use of framework species depends on circumstances and time since planting. At one highly degraded site in the coastal lowlands, some 50 plant species (distributed over 45 genera and 31 families) had colonized an area of 200 m^2 by eight years after treatment; these included 36 trees, 3 shrubs, and 11 vine species (Goosem and Tucker 1995). The site was adjacent to an area of riparian rainforest, so dispersal distances were not large.

The framework species method is also being used in the Donaghy's Corridor area (see fig. 24.1) to link a small (500 ha) conservation and recreational reserve, Lake Barrine National Park, with nearby continuous forest. Although the reserve has been isolated for only sixty to eighty years, there have been significant changes to both the small mammal community (Laurance and Laurance 1995) and forest structure (Laurance, chap. 6). A watercourse, Toohey Creek, runs for 2 km over private property between the park and the state forest, and the landowner agreed to revegetation of a linear strip 100 m wide along the creek. Restoration activities began with establishment of fencing and provision of fenced drinking points for cattle. Thirty-eight tree species were selected for planting based on their utility to wildlife and growth rates. Planting began early in 1995 and will be completed over the next three years. Sampling of avian communities, aquatic invertebrates, and mammals is also being undertaken along the corridor route.

Overall, the CNCP has been successful in educating local landowners and community members about ecological processes and the inputs required for successful reestablishment of native rainforest vegetation. It has enabled the development and testing of a number of approaches to forest reestablishment, and its efforts have led to the establishment of about 100 ha of forest in this region. The major limitations of this approach are its expense and the small number of private landowners willing to commit large areas for conservation purposes.

Case Study 2: The Community Rainforest Reforestation Program

Even before logging stopped in Queensland's northern state-owned rainforests, there had been calls for the development of a timber industry based on plantations on private property (Gilmour and Reilly 1970; Tracey 1986). In the 1950s and 1960s, the Queensland government established about 3,000 ha of plantations of native hoop pine *(Araucaria cunninghamii)* and exotic Caribbean pine *(Pinus caribbea)* on land purchased from economically marginal dairy farmers. Various investigations identified substantial areas of land on the Atherton Tableland that had been cleared, but were more suited to catchment protection or production forestry than agriculture (e.g., Gilmour and Reilly 1970). In 1992, federal and state governments agreed to fund the CRRP for four years with the following objectives:

1. Develop a private plantation resource base for a sustainable timber industry in northern Queensland, with a major emphasis on native rainforest species
2. Address problems of land degradation in the Wet Tropics area following extensive inappropriate clearing
3. Provide for improved water quality by establishing vegetative buffers along rivers and streams
4. Train a workforce to support the long-term practice of rainforest plantation establishment (QDPI-Forest Service 1994).

Landowners are recruited for the CRRP by extension staff through advertisements and at public meetings. After agreeing to participate, landowners are expected to prepare the site for planting and protect planted seedlings from livestock. In 1994–1995 a small fee (A$100/ha) was introduced to help cover costs and ensure landowner commitment. The CRRP provides all seedlings, and they are planted by work crews of supervisors and trainees. Grass and weeds are usually slashed before planting, and the area is disc-plowed or ripped by farm tractor. Newly sprouting vegetation is sprayed with knock-down and pre-emergent herbicide. On steep sites, where machinery cannot operate, the area is sprayed with a knock-down herbicide two or three times.

Species are chosen for particular sites based on the knowledge of local rangers and extension officers, the landowner's goals, and the availability of planting stock. The common planting pattern is a mixture of pioneer and later successional species; for example, a row of eucalypts or other pioneer species and a row of rainforest trees consisting of three to eight species. Spacing is generally 5 m between rows and 2 m along the row (1,000 stems/ha). The wide inter-row spacing allows access by a farm tractor for slashing of grass and weeds. Planting takes place following the onset of monsoon rains and can continue until June, depending on the locality. Survival is monitored, and replanting is undertaken wherever necessary. Ongoing weed control is essential for successful establishment and rapid growth, and trees are kept free of weeds by the use of herbicides for two or three years or until crown closure is reached. Subsequent management of the plantation is the responsibility of the landowner.

In the study area, 139,800 seedlings have so far been planted on seventy-six individual properties, for a total planted area of 206 ha (over 1,500 ha has been planted in the entire

Wet Tropics region). Across the Wet Tropics, 129 different species have been planted, although half of the plantings were of 8 species: *Acacia mangium*, *Agathis robusta*, *Araucaria cunninghamii*, *Elaeocarpus angustifolius*, *Eucalyptus cloeziana*, *E. grandis*, *E. pellita*, and *Flindersia brayleyana*.

Establishment success has been relatively high because of the close attention paid to establishment and maintenance. Early height growth has varied considerably among species and site types. While growth has been relatively good, no one species grew better than others on all site types. This variation suggests that there may be considerable scope for developing a regionally diverse plantation system even if plantation monocultures are planted at particular localities.

Some problems encountered in the program (as compared with a traditional timber plantation or restoration project on government-controlled land) have included (1) getting landowners to carry out required activities in a timely fashion; (2) growing sufficient seedlings of appropriate species when the area of different site types to be planted is not known until a few months prior to planting; and (3) the additional cost associated with maintaining plantations of species with different growth rates. Despite these problems, the CRRP has been very successful in reintroducing a relatively high variety of native species into the Wet Tropics landscape as part of a timber production-oriented initiative. Evidence from older plantation trials in the region suggests that such plantations will eventually acquire a diversity of native species in the understory. The program is helping to demonstrate that mixed-species plantings are valuable for the wider range of goods and services they provide, despite their marginally higher cost (Keenan, Lamb, and Sexton, 1995). The value of these plantations for native fauna, particularly in overcoming problems caused by habitat fragmentation, will be determined through a monitoring program to be implemented over the next few years.

Case Study 3: Coastal Tropical Forest Rehabilitation in Puerto Rico

In Puerto Rico, studies have been conducted during the past decade to test the hypothesis that forest plantations like those described above can surmount barriers to natural regeneration and facilitate the restoration of indigenous forest flora on degraded sites. The study area is the University of Puerto Rico's Toa Baja experimental station on the northern (Atlantic) coast of Puerto Rico (18°27′ N, 66°10′ W). Annual precipitation averages 1,600 mm and is moderately seasonal. Formerly supporting coastal dune forest vegetation, this site has been subject to frequent and often severe disturbances during the past century, including forest clearing, cattle grazing, cultivation, topsoil removal, and periodic fires. The surrounding landscape is presently dominated by residential housing and commercial and industrial facilities. Secondary forest is restricted to roadsides and a 10 ha abandoned wooded pasture adjacent to the southern edge of the study site, which supports about twenty native and naturalized tree species. At the time the experimental plantation was established, the site was dominated by grasses (principally *Panicum maximum* and *Tricholaena repens*), along with some twenty species of herbs and vines; woody plants were absent (Parrotta 1993b).

Natural regeneration of secondary forest tree and shrub species was monitored in experimental plantations and unplanted (though protected) control plots established in 1984 and 1989 (Parrotta 1993a, 1995). The older plantation area includes nine tree plots planted with *Albizia lebbek* at a range of densities and four control plots. The younger plantation area consists of twenty-one plots, three each of the following seven species or species combinations: (1) *Casuarina equisetifolia;* (2) *Eucalyptus robusta;* (3) *Leucaena leucocephala;* (4) *C. equisetifolia* and *E. robusta;* (5) *C. equisetifolia* and *L. leucocephala;* (6) *E. robusta* and *L. leucocephala;* and (7) unplanted, protected controls. All of these species are commercially valuable, and all are exotics. Plots received no irrigation or fertilizer. Planted plots were manually hoed during the first six months to control weed competition, and all plots were protected from disturbances, particularly grazing and fire.

Regeneration studies were initiated at 4.5 years after planting, when plots had closed canopies and well-developed forest floors. In the *A. lebbek* and associated control plots, all woody seedlings of secondary forest species taller than 5 cm were identified, mapped, measured, and tagged in 16 m^2 permanent quadrats. In the plots planted in 1989, all secondary forest species found within each plot were identified and recorded. Understory light conditions and forest floor (litter) depth and dry mass were measured at selected intervals during the study period.

Temporal Patterns of Understory Colonization

In both experiments, ground cover during the first two years was generally very sparse relative to the unplanted controls, but included most grasses and herbaceous species present on the site prior to plantation establishment. Regeneration was not noted within plantation areas until the third year after planting. This was the case despite apparently regular seed inputs by visiting frugivorous bird and bat species, the virtual elimination of understory competition by grasses, and the creation of favorable light, temperature, and humidity conditions from the second year onward. This delay appears to be due to biotic requirements for the breaking of seed dormancy and facilitating germination, rather than constraints of the physical environment. Similar observations of soil fauna and microflora succession in Costa Rican plantations suggest that delays in natural regeneration by native forest species (despite abundant seed rain and suitable physical conditions) may be linked to the rate of development of soil microflora that perform functions required for germination (R. Fisher, pers. comm.).

After 3 years, there was a rapid increase in both seedling density and species richness, and at 4.5 years, plantation plots collectively supported a fairly rich flora of native and naturalized trees and shrubs (fig. 24.2). While species richness and density of colonizing secondary forest species tended to peak after about 6 years, basal area of colonists continued to increase, and comprised 15–32% of the total stand basal area at 8.7 years. In the *A. lebbek* plantations, naturally colonizing trees had begun to occupy codominant or dominant crown positions after 5 years. In contrast, no woody seedlings were found in either the control plots or the other unplanted, protected grassland.

In the 1989 plots, the overwhelming majority of colonizing species were produced from seeds dispersed by frugivorous birds and bats (fig. 24.3) and derived from parent trees located 50–300 m from the plantation. Only three wind-dispersed species were

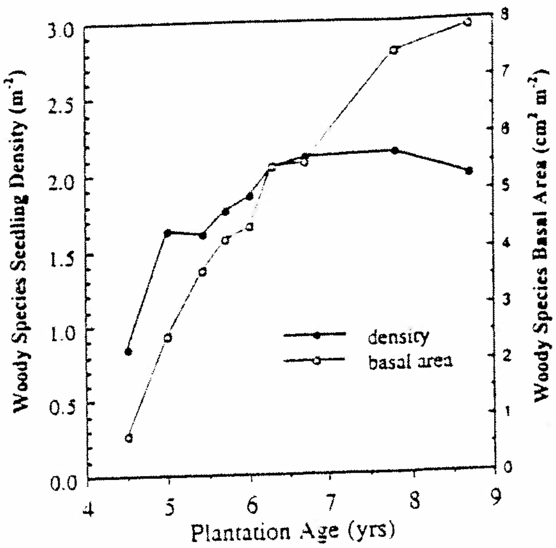

Figure 24.2. Mean density and basal area of colonizing trees and shrubs in *Albizia lebbek* plantation stands at Toa Baja, Puerto Rico. The total numbers of species found in the 192 m^2 areas sampled in each age class were 9, 14, 18, 20, and 19 at 4.5, 5.0, 6.0, 6.7, and 8.7 years of age, respectively.

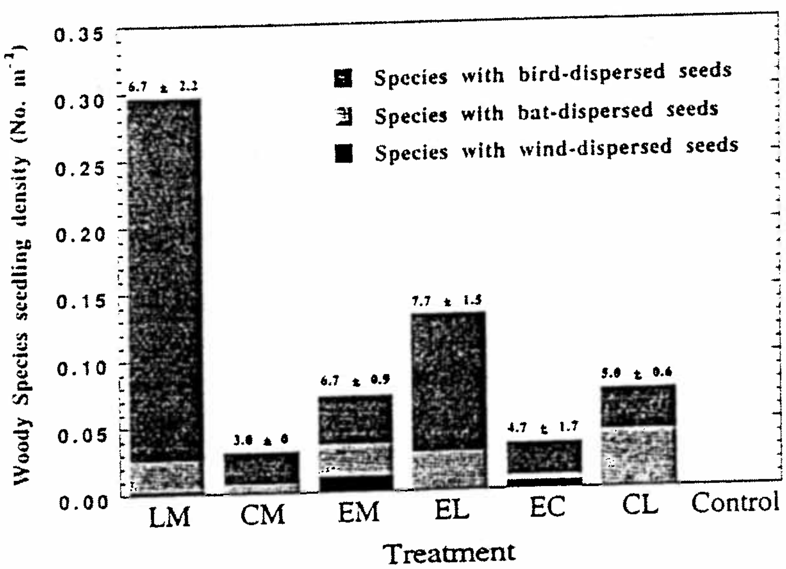

Figure 24.3. Seedling density of understory colonizing tree and shrub species 4.5 years after plantation establishment. Numbers above bars indicate the mean (±SE) number of species for each treatment, based on surveys of three 289 m^2 plots per treatment. LM = *Leucaena leucocephala;* CM = *Casuarina equisetifolia;* EM = *Eucalyptus robusta;* EL = *E. robusta* and *L. leucocephala* (1 : 1); EC = *E. robusta* and *C. equisetifolia* (1 : 1); CL = *C. equisetifolia* and *L. leucocephala* (1 : 1); Control = unplanted, protected grassland.

found in the plantation: *Cedrela odorata, Lonchocarpus latifolius,* and *Spathodea campanulata.* The absence of these colonizing species in control plots, where their seeds also fall, is probably explained by competition with grasses or unsuitable microclimatic conditions (McClanahan and Wolfe 1987, 1993; Nepstad, Uhl, and Serrão 1991; Guevara, Purata, and Van der Maarel 1992; Parrotta 1992, 1993a).

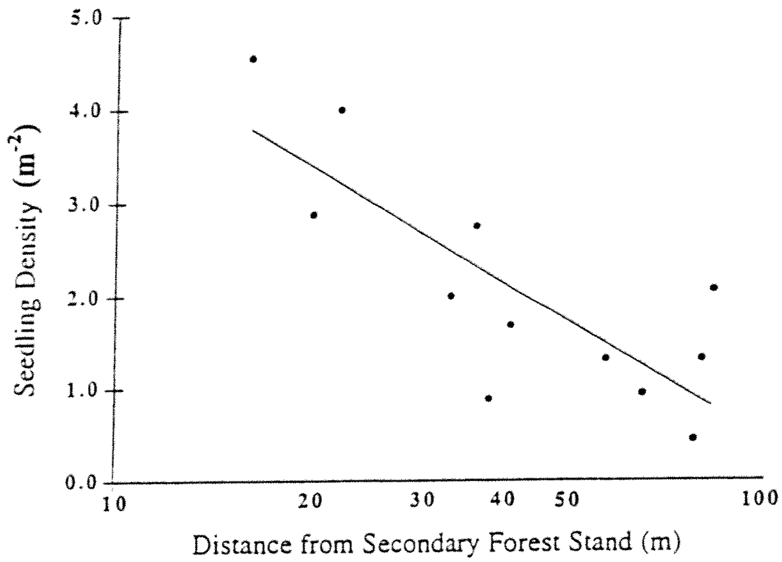

Figure 24.4. Relationship between density of colonizing seedlings and saplings in quadrats under *Albizia lebbek* stands and distance from the nearest secondary forest ($r^2 = .66$, $P < .01$).

Factors Influencing Understory Colonization

The major factors influencing colonization of the plantation understories were distance from seed source, light environment, and overstory species composition. Understory seedling densities and species distributions showed considerable variation with location within the *A. lebbek* plantations. There was a significant ($P < .01$) negative correlation between seedling density (for all colonizing species) and distance from the nearest possible seed source (fig. 24.4), suggesting that proximity to seed sources is an important factor controlling the rate of secondary forest species establishment in plantations (see Thebaud and Strasberg, chap. 21). The relative importance of seed sources external to the plantation would be expected to diminish over time, however, as individuals established within the plantation become reproductively mature, although external seed sources would continue to be important for increasing floristic diversity. Several species, such as *Bourreria succulenta, Citharexylum fruticosum, Cordia polycephala,* and *Schinus terebinthifolius* began flowering and fruiting in the *A. lebbek* plantations by year 5 or 6.

To quantify the light environment at each site, light measurements were made over several days between 1000 and 1300 hours at ten to twenty points. These results were averaged to provide a light value for each site. Measurements were carried out using a hand-held light meter at a height of 1 m. Among *A. lebbek* plantation quadrats, average light intensities at 5.5 years ranged from 2% to 29% of those in the open, and these variations were negatively correlated with the density of colonizing secondary forest species (fig. 24.5). A similar trend was observed in the younger plots. It is unlikely that light intensity had any direct influence on seed germination or subsequent survival, as most species that became established in the plantations can also do so in full sunlight. However, quadrats with higher understory light levels tended to occur on sites with coarser, sandy soils low in organic matter. These sites had lower tree growth and leaf area, and were more likely to be dominated by grasses than were quadrats with lower light intensities. Thus, the relative scarcity of seedlings in the more open quadrats could be due to a combination of increased root competition with herbaceous flora (principally grasses), less favorable soil moisture conditions affected by soil texture and organic matter content, and lower soil nutrient availability (Parrotta 1993a).

Overstory composition appears to exert a strong influence on understory species richness and colonization rates (see fig. 24.3). *L. leucocephala* appears to provide the most favorable conditions for understory colonization by secondary forest species, followed by *E. robusta*. *C. equisetifolia* supported relatively little new regeneration. In mixed-species treatments, understory species richness and seedling densities were generally intermediate between the values from plots of single species (Parrotta 1995). Significant negative correlations ($P < .05$) were found between understory species richness and forest floor depth, and between seedling density, forest floor depth, and dry mass (fig. 24.6). Fewer species and lower densities occurred in the understories of plots with the greatest forest floor depth (i.e., those with *C. equisetifolia* comprising 50–100% of the overstory), indicating that increased litter accumulation acts as a progressively more severe barrier to regeneration by small-seeded (bird-dispersed) woody species.

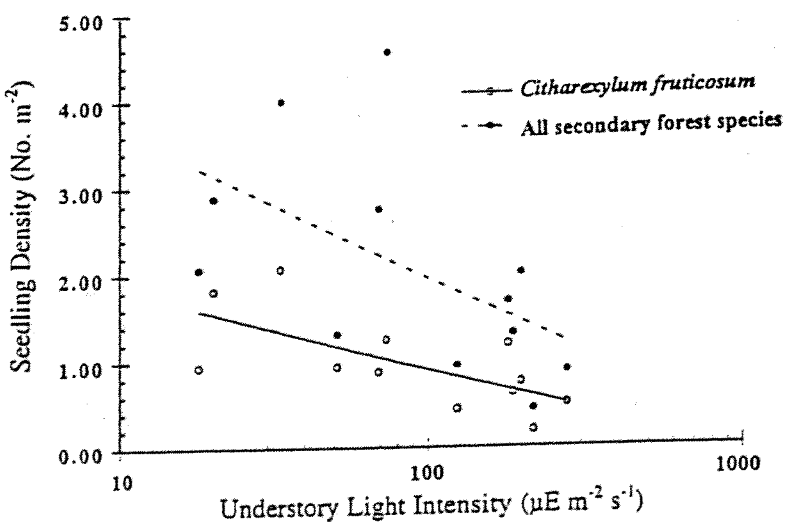

Figure 24.5. Relationship between seedling density and understory light intensity in quadrats in 6.7-year-old *Albizia lebbek* plantations. The understory plants are dominated by *Citharexylum fruticosum* (r^2 = .48, $P < .05$; all secondary forest species: r^2 = .31, $P < .10$). Correlation coefficients and significance levels are for regressions of the general form: $Y = A - B \log_{10} X$.

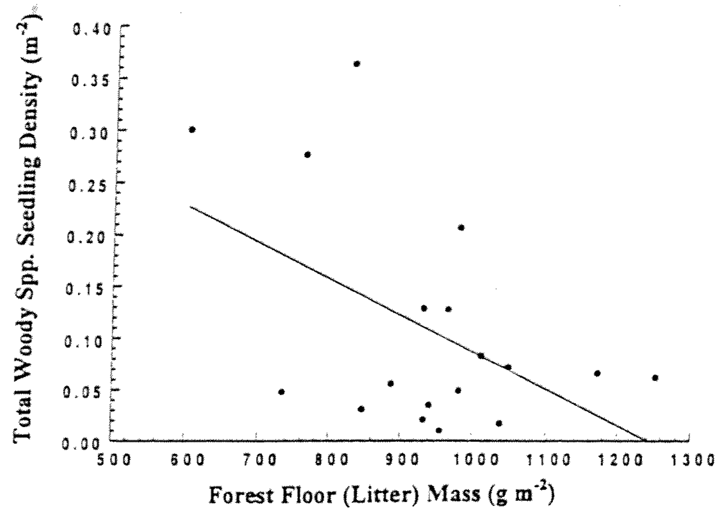

Figure 24.6. Relationship between seedling density of colonizing tree and shrub species and litter mass in single- and mixed-species plantations of *Casuarina equisetifolia, Eucalyptus robusta*, and *Leucaena leucocephala* at 4.5 years of age (r^2 = .26, $P < .05$).

DISCUSSION

Three different approaches to the restoration of forest habitats in tropical landscapes were described in the case studies. In case study 1, a variety of species with desirable characteristics for accelerating successional processes (termed "framework species") were planted at high stocking rates with intensive follow-up maintenance, purely for habitat restoration. Case study 2 also involved planting and intensive maintenance, but used a subset of native plants with potential commercial uses. Case study 3 showed that the difference in the two approaches may not be as great as it might initially appear.

Each approach has certain advantages and disadvantages. The framework species method of case study 1 is the most amenable to reestablishing poorly dispersed, rare, or endangered species by including these in the planting mix. The costs of seedling production and labor are high, however, and are not balanced by any potential commercial benefits. Use of this method may thus be restricted to relatively small areas of landscape, except in societies with the financial resources or community motivation to apply it over large areas.

Case study 3 demonstrates that the moderating influence of commercial tree plantations on the understory environment can facilitate reestablishment of native species, potentially increasing biodiversity as well as providing commercial benefits. This method may allow restoration of much larger areas of degraded land. A number of key questions remain unresolved, however. Does the gain in biodiversity reduce the commercial success of the plantation? Does the developing understory inhibit the growth of overstory trees, or is the overstory effectively free of competitive effects once canopy closure is achieved?

Finally, how much biological diversity can be retained when the commercial crop trees are harvested and the area is replanted?

The conservation benefits of such an approach will ultimately depend on the management system used. Where native species with timber value become reestablished in exotic plantations, these may, over time, become the dominant species in the plantations, or they may be incorporated into the production system along with the originally planted species. Choice of plantation species may also strongly influence natural recruitment of native species through factors such as the amount of litter accumulated on the plantation floor.

The use of native species in a timber production program (case study 2) is a flexible alternative that can be directed more or less toward nature conservation depending on the interests of the landowner and the socioeconomic circumstances at the time of harvesting. More complex plantation forestry of this type may become important where societies require a wider range of outputs (Kanowski and Savill 1992; Lamb and Tomlinson 1994). The disadvantages of this approach are that the potential conservation values and timber production benefits are largely unknown, in part because of our limited understanding of the growth rates and wood quality of native species grown in plantation systems.

Biological Factors Affecting the Design of Restoration Strategies

In all three case studies, the process of further species recruitment depends on the design and management of the planting program. Relevant considerations include the location of plantings in relation to primary and secondary forest stands, tree species selection, and planting density (Parrotta 1993a, 1995).

Proximity to seed-bearing trees and the habitat requirements of seed-dispersing birds and bats are key factors influencing development of floristic diversity in restoration plantings or plantations. The importance of perching or roosting sites for seed inputs into open habitats such as grasslands and mined lands has been demonstrated in several recent studies (Guevara, Purata, and Van der Maarel 1986; McClanahan and Wolfe 1987, 1993; Guevara et al. 1992). Where distances to intact forest remnants are large, more complex and creative strategies may be required to maximize the potential for successional processes. "Archipelagoes" of replanted "islands," containing species of particular utility to seed-dispersing wildlife (e.g., framework species; see above), could be created within a "sea" of commercial timber plantations or other kinds of land use. The choice of timber plantation species would influence the recruitment rate of native plants, but the presence of patches of attractant species could facilitate the regeneration process where the distance to potential seed sources is large.

Planting density is important because recruitment of secondary forest species depends on seed inputs, the maintenance of sufficient canopy cover to reduce weed and grass competition, and sufficient habitat diversity for birds and other seed dispersers. If early economic returns are required, harvests should be designed to ensure at least partial canopy closure until the colonizing forest species assume a more dominant structural role within the system.

Socioeconomic Factors Affecting the Design of Restoration Strategies

Sociological context is key to any restoration program (see Viana, Tabanez, and Batista, chap. 23). Land degradation usually has its roots in a particular socioeconomic condition, and policies to address this condition must be implemented to prevent further degradation. Scientists and conservationists often assume that the benefits of restoration are self-evident, but they may not always be apparent to local communities, particularly if they have been gaining some economic benefit from degradative former land uses (Fortmann and Bruce 1988; Gilmour and Fisher 1991; Morrison and Bass 1992). It is therefore advantageous to involve the local community in any restoration program, and this has been a key feature of case studies 1 and 2. This involvement has led to far more effective restoration than if only institutional resources were employed. Involving local people, however, may shift the major objective of a project from optimizing biological diversity to finding a balance between biodiversity and economic production. Where rates of forest loss and land degradation are not being matched by restoration efforts, such a compromise should be willingly accepted.

Perhaps a more difficult issue is whether plantations established for timber production can be diverted to conservation purposes. This will obviously depend on the original reason for plantation establishment. Managers of industrial plantations that required a large capital investment (e.g., a pulp mill) are generally committed to intensive management to satisfy investment criteria and are often not in a position to reduce timber outputs, lengthen rotations, or change harvesting systems to allow a diversity of species to persist during the production cycle. Even in a landscape committed to intensive fiber production, however, there are usually inaccessible areas, streamside zones, naturally poor soils, and other land types that could be used to provide for conservation of regional diversity. Land use systems can also be modified to provide for structural, genetic, and species diversity while managing for fiber production (Bunnell 1990; Franklin 1993).

While there are no universally applicable techniques for tropical forest rehabilitation and restoration, we feel that the case studies presented here illustrate practical approaches worthy of consideration in restoration projects. Further ecological and silvicultural research is necessary to refine these methods and demonstrate their benefits for biological conservation. Research needs include the identification of key barriers to natural forest succession at specific sites; the definition of site conditions under which alternative restoration methods can yield favorable results; assessment of the value of plantations as corridors to facilitate genetic interchange; further investigation of methods for accelerating succession in particular directions; and the development of planting designs and stand management practices that will result in productive, species-rich secondary forests on severely degraded lands.

GENERAL IMPLICATIONS

1. Restoration implies an attempt to reestablish original forest communities in a landscape. This is a difficult task in the Tropics because of the exceptional species richness of tropical forests and our generally poor understanding of their composition and dynamics.

2. There are large areas of degraded forest lands in the Tropics in need of restoration. Large-scale restoration is unlikely to occur, however, because of economic, social, and political constraints. Under these conditions, priority should be placed on restoration of *(a)* the habitats of endangered species, *(b)* corridors linking vegetation remnants along rivers and streams, and *(c)* areas within and around existing conservation reserves. Restored areas need not necessarily be large if they are carefully planned to facilitate movement and genetic exchange between subpopulations of wildlife and plants.
3. All restoration efforts require the prevention of further clearing, grazing, or burning. Re-vegetation can then occur naturally or be facilitated by planting. The choice of planted species is crucial. Where restoration is being attempted, the planted species should be "framework species" that attract seed dispersers (birds or bats), which in turn bring other plant species into the area.
4. Where socioeconomic factors preclude restoration, commercial considerations will determine the species used in plantations. These considerations need not preclude some enhancement of the landscape's biodiversity, because careful matching of species to specific sites may yield a mosaic of different plantation monocultures. Moreover, inaccessible areas, streamsides, and other small conservation areas can be planted with a range of native species to create greater landscape diversity. Alternatively, mixed-species plantations can be established.
5. Natural dispersal and regeneration is likely to enhance the biodiversity of the understory in both mixed-species plantations and mosaics of monocultures. Because this process could facilitate increased biological diversity over large areas of tropical landscapes, researchers and plantation managers should work together to devise methods to achieve and maintain the biological potential of timber plantations.

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