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Supporting Online Material for

Restoration of Degraded Tropical Forest Landscapes

David Lamb,* Peter D. Erskine, John A. Parrotta

*To whom correspondence should be addressed. E-mail: d.lamb@uq.edu.au

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Science Supporting Online Material
Restoration of Degraded Tropical Forest Landscapes

David Lamb,¹ Peter Erskine,¹ John A. Parrotta²

¹ Rainforest Cooperative Research Center and School of Integrative Biology, University of Queensland, Brisbane, Australia; ² USDA Forest Service, Research & Development, 4th floor, RP-C, 1601 North Kent Street, Arlington, VA 22209, USA.

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(A) Case Studies

Successful forest restoration has taken place at a range of scales throughout the tropical world. Case studies demonstrating this from a number of tropical countries are described below. These vary from largely passive operations with minimal intervention to more expensive and detailed programs where successional development was much more directed. The case studies also reflect the outcome of the interactions between ecological and socio-economic systems.

The source of the information for each case study is referenced immediately after the country name. Some of the species used for forest restoration are listed below each case study, as are some of the main outcomes.

Australia (S1)

Plantation trials of a variety of native high-value timber species have been tested in the wet tropics of Australia. *Araucaria cunninghamii* and *Flindersia brayleyana* are two species that grow well in plantations. In this case study 50-60 year old monoculture plantations of these species have acquired more than 350 species of trees, shrubs, epiphytes and vines in their understories. More species colonized beneath the *Flindersia* (hardwood) canopy than beneath the *Araucaria* (conifer) canopy. The source of propagules was natural rainforest located up to 200 m away. Some of the new colonists have joined the canopy layer of the plantation species transforming the appearance of the plantation from a simple monoculture to a polyculture (Fig. S1). The rate at which colonization has occurred exceeds the rate at which succession normally proceeds on old agricultural fields. This suggests the plantations have acted to catalyze colonization. The extent of colonization varies with distance from intact rainforest with much lower rates occurring in more distant plantations. Most of the plant diaspores are likely to have been dispersed by birds and bats and most have small rather than large diameters. That is, the forest regenerating under the plantation canopy has few of the larger fruited species because there have been no dispersal agents able to carry them. Such dispersal agents may appear in time as the plantation habitat changes and more niches develop.

This catalytic process has created a very diverse new forest with a variety of life forms in a comparatively short time period. However, it raises the issue of what the most appropriate management response might now be. One option might be to simply fell the forest at a commercially appropriate time and replant. This was the original objective of those who established the plantation but it means the new biodiversity will be lost. An alternative might be to manage the forest as a biodiversity reserve and forgo the timber harvest. This represents a change in management objective but could reflect changing community priorities. A third response might be to manage the plantation trees and their new colonists on some kind of a selection system thereby attempting retain biodiversity and also obtain some financial benefit.

Species used: *Araucaria cunninghamii* and *Flindersia brayleyana*

Outcomes: Simple plantations can facilitate successional development if a source of colonists is not too far away. However, managers must be clear about the objectives of reforestation and the nature of the balance between production and biodiversity gain. This balance can change over time as social changes take place and timber markets alter.

Brazil (S2-S4)

A large open-cut bauxite mine at Trombetas in Para' state in central Amazonia is located in an area of relatively undisturbed evergreen equatorial moist forest. A reforestation program has been developed to restore the original forest cover to the greatest extent possible. The operation has treated about 100 ha of mined land per year over last 15 years.

The method used involves several key steps. Firstly, the mined site is leveled and topsoil is replaced to a depth of about 15 cm using topsoil from the site that had been removed and stockpiled (for less than six months) prior to mining. Next, the site is deep-ripped to a depth of 90 cm (one meter between rows). Then trees are planted along alternate rip lines at 2 m spacings (2,500 trees per ha) using direct seeding, stumped saplings or potted seedlings. Some 160 local tree species were tested for their suitability in the program and more than 70 species from the local natural forests are routinely used.

Within 10 years of establishment most sites have many more tree and shrub species than the number initially planted because of seed stored in the topsoil or colonization from the surrounding forest (see Fig 3B in main text). These new species would have been brought to the site by birds, bats and terrestrial mammals and most were species with small seed. Larger seeded species may be dispersed into the site later when the habitats are more suitable for the appropriate wildlife. If not, they might need to be deliberately re-introduced. Not surprisingly the density of these new colonists was greater at sites near intact forest but dispersal was evident up to 640 m away from old-growth forest.

Several alternative planting designs have been tried including natural regeneration and commercial timber plantations. Comparisons between these different planting designs showed the rate of species accumulation varied depending on treatment with the greatest diversity being measured in the mixed native species treatment (around 130 woody plant species in 0.25 ha) than in sites left to regenerate naturally or planted using mixed plantings of commercial species.

Weeds such as grasses were effectively shaded out by the dense canopy cover of the mixed native species community. There were some concerns that shorter tree longevities in the natural regeneration and tree plantation designs could allow grasses and weeds to persist making these methods more risky but these now seem unfounded. Overall it seems the reforestation program has been extremely successful in facilitating the re-establishment of both plants and animals to the site although more time will be needed until composition and structure begins to resemble the nearby intact forest.

Species used: 70-100 local tree species are routinely used, from a wide range of taxa typically found in surrounding, old-growth lowland rainforest

Outcomes: It is possible to restore tropical forests on severely disturbed sites such as those degraded by mining provided sufficient resources are available. In this case a key requirement was the respreading of topsoil that contained nutrients, seed and mycorrhizae. Although a very large number of species were planted this was still less than the number originally present. However, more are brought in by seed-dispersing wildlife. Enrichment plantings of late-successional species under an establishing early-successional canopy may also accelerate forest biodiversity development. This is particularly the case for tree species bearing large-seeded fruits requiring specialized animal dispersal agents.

Burma (S5)

A forest reserve was established in 1902 on the extinct volcano of Mt Popa in central Burma to protect forest surrounding an important monastery. During the Second World War forest clearing occurred widely and continued after the war due to political unrest and increased population pressure. Trees were cut for fuelwood, poachers set fires to trap bush meat and local residents established banana plantations across the reserve area. In the early 1970's the Forest Department of Burma (FDB) attempted to arrest forest loss by planting over 1000 ha of *Eucalyptus camaldulensis* at a density of 750 trees/ha. In 1981 the United Nations Development Program (UNDP) funded a project to establish around 40 guard posts, erect boundary pillars and employ park rangers to patrol the reserve area. Combined with these forest protection measures the FDB propagated native species (see below) to be planted under the eucalypt forests and on the barren hillslopes. They also raised awareness and provided employment in the local communities and addressed soil and gully erosion through engineering techniques and revegetation measures. The UNDP project provided piped water to the local communities and constructed some tourism infrastructure. The eucalypts used in the early reforestation efforts have slowly been harvested and used as fuelwood, posts and poles by local people. The core forest area of 3,200 ha has now increased to nearly 13,000 ha and natural springs are flowing again. Water supplies to the local villages have increased, eco-tourism developments have improved the livelihoods of local communities and the forest now provides excellent recreational opportunities (Fig. S2).

Species used: *Eucalyptus camaldulensis*, *Cassia siamea*, *Acacia catechu*, *Albizia lebbek*, *Hesperethusa crenulata* and *Michelia champaca*

Outcomes: Reforestation can succeed when it is combined with projects that directly increase services to local communities. Under such circumstances it may not be possible to restore all of

the original biodiversity but it may be possible to re-establish many ecological processes and functions.

Kenya (S6, S7)

Increases in human populations are commonly assumed to inevitably lead to deforestation. However, the situation is often more complicated than this and Kenya provides an example where increasing population has helped reforest part of the countryside. Kenya has a limited area of natural forests and good quality agricultural lands. In the early 1990s it had a population growing at the rate of over three per cent. These circumstances suggest forest degradation would be widespread and Kenya did lose 0.5 per cent of forest cover or 93,000 ha between 1990 and 2000. However an aerial and ground survey in the high agricultural potential areas found a strong correlation between rural population density and planted trees with much higher amounts of woody biomass in areas with high population densities. Further, the rate of planting exceeded the rate of population growth while the extent of native vegetation in the region remained constant (at least between 1986-1992). At a national level the volume of planted trees in farmland was greater than the industrial plantations under government control and the amount of woody biomass was more than the amount in natural forests.

There appear to be several reasons for this situation. One is that forest products such as fuelwood and poles were not available to farmers outside their farm area so that best ways for them to acquire these was to grow them themselves. But, perhaps more importantly, farmers have well established tenure of their lands meaning that they have the security of knowing they will benefit from any reforestation activity they undertake.

In some situations much of this reforestation was being undertaken with exotics such as fast-growing eucalypts meaning there was not a direct contribution to national biodiversity conservation. In other cases on-farm hedgerows have considerable diversity of indigenous species (Backe 2001). These forms of reforestation undoubtedly reduced pressure on the remaining natural forests which were therefore able to contribute ecological services. This is not to say that further loss of these forests will not take place. But rather that the rate is likely to be reduced.

Species used: *Eucalyptus* sp. Particularly *E. tereticornis*, *E. saligna* and *E. grandis*, *Grevillea robusta*, wide variety of local species

Outcomes: Reforestation can occur when rural populations are high, provided farmers have security of tenure.

Laos (S8)

In the highlands of central Laos a natural resources management project conducted a direct seeding trial of local tree species across a 30 ha area of the Nam Ngum watershed. The seed of four important species, *Pinus kesiya*, *Keteleeria davidiana*, *Schima wallichii* and *Quercus serrata* was available in large quantities for direct sowing. Small quantities of two other species, the broadleaf *Rhus rhesoides* and a deciduous oak *Quercus griffithii*, were also used in the trial.

Knowledge concerning potential predation and light requirements guided which sowing technique (broadcast, strip sowing with harrowing or pit digging) was used for the different species in the trial. The area receives about 1500mm annual rainfall which falls primarily from May to October, so most the sowing occurred soon after the first rains in May 2001. A team of local women were employed by the project, trained in the different methods of direct seeding and were supervised while they conducted the work. Water buffalo plowed the land to temporarily remove weeds and produced a roughened soil surface where seeds could be sown. Germination of all species was generally higher than predicted and therefore the density of the emerging seedling was often excessive. The emerging seedlings performed at a comparable rate to planted nursery grown seedlings and there was high survival until the end of first dry season. The experimental plots that were plowed and harrowed in the six months preceding sowing were more successful than the plots that were plowed in the previous year. Weeding after sowing was not necessary as the weeds in the area were not very competitive. This trial indicates that careful timing, appropriate species selection, the availability of large quantities of seed and skilled labor enabled direct sowing to be conducted cost effectively in the highland areas of Laos.

Species used: *Pinus kesiya*, *Keteleeria davidiana*, *Schima wallichii*, *Quercus serrata*, *Rhus rhesoides* and *Quercus griffithii*.

Outcomes: Direct seeding can be a cost effective way of re-establishing tropical forest cover under certain circumstances. However, it may only be possible to regenerate a relatively small number of species this way.

Nepal (S9, S10)

In the middle hills of Nepal one of the most successful plantation species is the indigenous chir pine (*Pinus roxburghii*). It occurs naturally at elevations around 1,300 m and is a tough hardy pioneer species. Many of the sites that have potential for restoration are heavily grazed, often eroding grasslands with shallow stony soils. From an ecological point of view chir pine is one of the few species which can survive and grow on these sites. It is also easy to handle in low technology nurseries, making it well suited to use in small village nurseries. Experience has shown that attempts to grow more desirable broadleaf species in large scale plantings on hard sites have largely failed. This is particularly the case in the drier sites, although some success has been achieved in some of the moister areas with species such as utis (*Alnus nepalensis*).

If a plantation area receives protection from grazing, a range of tree and shrub species often regenerate or invade the site soon after establishment, particularly on moister northern aspects. The invading species dramatically increase the biodiversity of the site and add to its productive potential for the village forest users. The ecological role of the chir pine is to act as a pioneer in returning the site to forest which can then be manipulated silviculturally to provide the goods and services needed.

An example of the change that can take place comes from a series of studies undertaken about 40 km north east of Kathmandu. In this forest there have been three waves of regeneration following planting with chir pine. The first wave developed as coppice from stumps which were remnants of the original forest. The protection from regular cutting and grazing which accompanied pine planting allowed coppice shoots to survive, and these became an early component of the stand

along with the pines. Most of the coppice shoots were *Schima wallichii*, a widespread broadleaf tree which produces high value firewood, construction material and leaves for animal bedding. The second wave consisted of seedling regeneration which germinated about five years after plantation establishment (age was determined from growth ring counts). Like the first wave, the dominant species in this second wave was *S. wallichii*. (*Schima* seeds are small and are probably distributed by birds.) At five years, the plantation would have been quite open and would not have had a closed canopy. However, sufficient amelioration of the site must have occurred to provide a suitable seedbed for *Schima*. A dramatic change in species composition began at about 12 years, when the canopy closed. A third wave of regeneration occurred at this time, and it included a large number of very useful fuel and fodder species. The most notable of the newcomers was *Litsea polyantha* which is highly valued for its leaf fodder. It regenerated at high densities and by plantation age 14 years it covered the forest floor at a density of about 1,600 per ha and with a mean height of 22 cm. Other valuable species which appeared at the same time included *Fraxinus floribunda*, *Cedrela toona*, *Castanopsis indca*, *Prunus cerasoides* and *Michelia champaca*.

Future silvicultural practices, as well as the attitude of the forest users to protecting these valuable species, will determine the fate of these recent additions and whether or not they become dominant components of the stand.

Species used: *Pinus roxburghii* and *Alnus nepalensis*

Outcomes: Restoration can take place over time, often starting with low technology and low cost options, and relying on natural ecological process to provide added biological diversity. However, social controls over cutting and grazing are essential to obtain a diverse species mix.

Puerto Rico (S11)

More than 90 percent of the land area of Puerto Rico had been cleared for agriculture by the start of the 20th century and natural forest was restricted to smaller areas mostly on the steeper mountain areas. A large proportion of the rural population shifted from the country to the cities as agriculture became less profitable after 1940. Many farms were abandoned and were subsequently occupied by secondary forest. Soil fertility had not been lost during farming and, in the absence of fire, natural forest regeneration has been relatively rapid. This has largely developed from new colonists reaching the site rather than from species persisting at the site (e.g. in soil seed banks) during farming. A relatively small group of species commonly formed the initial cover of woody plants at recently abandoned farms. All were species that produced large numbers of seed and were easily dispersed by wind or animals such as birds or bats. Once established, their presence created new habitats and facilitated the colonization of a much wider range of other species. After 35-40 years the tree density, basal area and species richness in the regenerating forest was similar to that in older (>80 years) forests thought to be representative of the original forests on the island. Thus the average basal area in 35-40 year old sites was 30 m² per ha in comparison to 39 m² per ha in the oldest forests and there were 23 species in a 200 m² plot in 35-40 year regrowth and a similar number in the older sites. However, the composition of these regrowth areas was quite different to the older forests and many exotic species were present amongst the colonists. If managers wished to foster the development of a forest containing more native species representative of mature successional stages then some kind of enrichment

planting would be necessary. These species are present across the landscape but their slow rates of dispersal are limiting the extent to which they are represented in the new secondary forests.

Outcomes: Recovery of these forests took place because of demographic changes and not because of deliberate technical interventions. This case study demonstrates that the recovery of forest structure can be rapid if soil fertility is maintained and if intact forest remains nearby. The rate at which the original species diversity recovers, however, may be slow since most of the new colonists are the most easily dispersed species and not the larger-fruited species. These early colonists are only a sub-set of the island flora.

Tanzania (S12, S13)

The open woodlands in the Shinyangan region of Tanzania cover a large area and are heavily used by traditional agro-pastoralists. The population of the area is relatively high (42 persons per km²). The region has a rainfall of 600-800 mm but is subject to frequent droughts. In pre-colonial times families and clans developed a system of controlled grazing and enclosures to keep fodder available for their animals during drier periods. These management systems depended on rules maintained by guards and community assemblies. This meant that pasture was preserved and there was a significant pool of biodiversity contained in the woodlands distributed across the landscape. These woodlands contained many resources used by rural communities such as foods and medicinal plants.

This system was changed during the colonial period and in the early years of independence. In the 1920's many woodlands were cleared to eradicate tsetse fly and, later, to establish cash crops such as cotton, tobacco and rice. This accelerated soil erosion and reduced land available to families and clans for grazing. Following the end of the colonial period new government policy changes led to the grouping of communities into villages to make it easier to provide social services to people. However this caused a breakdown of the traditional management systems leading to overgrazing, especially in the vicinity of the new villages. Increased populations also led to greater demands for timber and other forest products such as fruits, nuts and berries which caused over-harvesting in the remaining woodlands that were no longer subject to traditional harvesting regulations.

A policy reversal took place in the 1980's leading to a break up of the government village system and the re-establishment of the traditional management approaches including the re-creation of the system of exclosures. This fostered a massive increase in natural regeneration of woody plants. In 1986 there were 600 ha in exclosures but by 2002 there were 250,000 ha. Traditional community management systems are being redeveloped and supported by government agencies. The government has also begun granting more permanent forms of land tenure.

It is impossible to know if all the former species have regenerated at the degraded sites. However, there is no doubt that significant reforestation has taken place, new habitats have been created and that biological diversity has increased. For example, some surveys have found up to 23 tree species in an area of only 0.5 ha. What is clear is that the forest regeneration has produced significant benefits for the human populations. Productive pastures are being re-established and the tree regeneration is helping to reduce erosion as well as provide new resources such as forage and browse for livestock, foods and medicines and timber.

Species used: *Acacia crassicarpa*, *Leucaena pallida*, *Senna siamea*, *Sesbania sesban* and *Moringa oleifera*

Outcomes: Even degraded lands can sometimes retain considerable amounts of biodiversity. Under the right conditions, this can regenerate and allow ecosystem recovery. Restoration was accomplished by a change in government policy and did not require large financial investments. The policy change included allowing land ownership to return to traditional owners and the restoration of traditional management practices.

Vietnam (S14)

Forests north of the Hai Van Mountain Pass between Da Nang and Hue in Central Vietnam were partially destroyed during the war of the 1960's and 1970s. In the following decades the remaining native forest was illegally harvested and forest fires were deliberately set, such that much of the area became dominated by the grass *Imperata cylindrica*. The regular fires and loss of forest cover lead to extensive soil erosion across the mountain pass (annual rainfall >3000mm). These changes probably represented a regime change from which natural recovery would have been difficult. The Vietnamese Forest Protection Department (FPD) determined that this area should be reforested to reduce the grass fuel load and arrest soil erosion. Since 1986 the FPD has enforced strict protection of the forest area and planted nearly 1400 ha of *Acacia auriculiformis* at densities between 1650-3300 trees/ha in areas dominated by grasslands. These stocking densities meant that a closed forest canopy developed after 3 to 6 years and grass was shaded out. Following the success of these plantings there was interest in ensuring that the forest had a suitable level of biodiversity for its status as national special-use forest. In 1993 the FPD therefore embarked on a series of trials planting native tree species under the canopy of the *A. auriculiformis* forest. They grew native tree seedlings for two years before planting them at a density of 400-500 stems/ha under the acacia forest which had been thinned to 800 trees/ha. Understorey vegetation was cleared regularly for several years before the acacias were thinned down to 300-400 trees/ha. There were eleven native species which were particularly promising under the FPD's general management regime (the best of which were *Aquilaria crassna*, *Hopea odorata* and *Parashorea stellata*) while another six species required specific habitats to become established successfully (ie. *Syzygium sp.* was suitable for riparian areas). The result of this program has been the creation of a new forest containing a diverse range of mostly native species (Fig. S3). In time it is likely that further species will arrive as colonists from remnant forests elsewhere in the district. These forest restoration activities were initiated by national government funding but more than seventy-five percent of the reforestation and monitoring costs came from selling *A. auriculiformis* thinnings. Local communities have benefited from the forest restoration through a decrease in fires and soil erosion, an increase in watershed protection and the creation of a regular wood supply.

Species used: *Acacia auriculiformis* followed by *Aquilaria crassna*, *Hopea odorata*, *Parashorea stellata*, *Syzygium sp.*

Outcomes: Exotic species such as *Acacia spp.* can have a role in restoring native forests and fostering habitat diversity at badly degraded sites. A two-step process such as this not only facilitates the establishment of native species to sites they would not otherwise tolerate but also generates sufficient income to pay for most of the establishment costs.

(2) Monocultures of indigenous timber trees

A selection of publications dealing with reforestation using indigenous tree species in Malaysia (*S15, 16*), Australia (*S17*), Costa Rica (*S18-20*), Vietnam (*S21*) and south-east Asia (*S22*) have emerged in the last few decades. The growth rates of these species are often much less than some of the more common exotic species and many have specific site requirements. On the other hand, many command rather higher market prices than exotic species. The most common constraints on their wider use are the difficulty of obtaining and storing seed and the lack of silvicultural knowledge.

(3) Institutional arrangements for reforestation

Planning reforestation at a landscape scale is difficult. There can be many stakeholders with an interest in a particular landscape and only some of these may be resident. These stakeholders may have legal land tenure or de facto tenure and will differ in their economic and political power. Not surprisingly there may be a number of competing land use objectives with certain stakeholders having more interest in some parts of the landscape than others. There is also likely to be a difference in the extent to which stakeholders are willing or able to share the costs of restoration as well as the benefits. The most appropriate institutional arrangements will depend on local circumstances and on the size of the area being restored. Restoration in small areas can often be carried out using existing local organizations where traditional structures are in place and decision-making can be flexible. Restoration across larger areas may involve the development of more complex policy settings or financial arrangements and can be much less flexible. In such cases it may take time for decisions to be implemented. An example of the difficulties of implementing large-scale reforestation programs is the current national reforestation program in Vietnam (*S23*). This aims to reforest five million hectares within a period of 10 years and faces difficulties in balancing land allocations for food production and for reforestation. Such difficulties need not always occur and large areas of reforestation have taken place in Tanzania as a consequence of some relatively simple policy changes concerning land tenure (see Tanzania Case Study; *S12-S13*).

(D) Figures



Fig. S1. *Flindersia brayleyana* (A) and *Araucaria cunninghamii* (B) plantations which have been colonized by a range of rainforest species.



Fig. S2. Restored forests of Mt Popa Forest Reserve in Burma (Myanmar). Note that the light colored foliage in the center of figure are remaining *Eucalyptus camaldulensis* trees.



Fig. S3. The forest of Hai Van Mountain Pass in Central Vietnam in 2004 following reforestation with *Acacia auriculiformis* and a variety of native species. *A. auriculiformis* was used to create a favorable environment for the establishment of native tree species and are gradually harvested to pay for ongoing reforestation works.

(E) Table S1. A selection of URLs of international organizations interested in tropical forest restoration (URLs correct 7th of July, 2005)

International organizations interested in tropical forest restoration	Webpage
Program on Forests (Profor)	http://www.profor.info/
Center for International Forestry Research (CIFOR)	http://www.cifor.cgiar.org/rehab/default.asp
World Wide Fund for Nature (WWF)	http://www.panda.org/about_wwf/what_we_do/forests/our_solutions/restoration/
The World Conservation Union (IUCN)	http://www.iucn.org/themes/fcp/experience_lessons/flr.htm
International Tropical Timber Organization (ITTO)	http://www.itto.or.jp/live/index.jsp
Global Partnership in Forest Landscape Restoration	http://www.unep-wcmc.org/forest/restoration/globalpartnership/
Forest Restoration Information Service	http://www.unep-wcmc.org/index.html?http://www.unep-wcmc.org/forest/restoration/~main
Society for Ecological Restoration International (SERI)	http://www.ser.org

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