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Restoration of Degraded Tropical Forest Landscapes

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The current scale of deforestation in tropical regions and the large areas of degraded lands now present underscore the urgent need for interventions to restore biodiversity, ecological functioning, and the supply of goods and ecological services previously used by poor rural communities. Traditional timber plantations have supplied some goods but have made only minor contributions to fulfilling most of these other objectives. New approaches to reforestation are now emerging, with potential for both overcoming forest degradation and addressing rural poverty.

One of the defining events of the past century was the astonishingly rapid decline in the extent of tropical forests. An estimated 350 million hectares have been deforested, and another 500 million hectares of secondary and primary tropical forests have been degraded (*1*). The damaging consequences of this include the loss of ecological services (such as biodiversity and watershed protection), the loss of many goods (such as timber and nontimber forest products), and the loss of means of existence for forest-dwelling people. These losses have fallen particularly heavily on the rural poor in tropical countries, where the livelihoods of at least 300 million people now depend upon these degraded or secondary forests (*1*).

Until recently there were three major responses to this process of forest degradation. One was to expand networks of protected areas to help protect the remaining biodiversity. In this response, the focus has largely been on making the selection of candidate sites as representative and comprehensive as possible (*2*). A second was to improve agricultural productivity on abandoned lands in order to improve the livelihoods of communities living in these areas. The third approach has been to undertake some form of reforestation. Much of this has been done with the use of industrial monocultures involving a limited number of species from a remarkably small number of genera (particularly *Pinus*, *Eucalyptus*, and *Acacia*). Although many of these plantations have been productive and generated goods such as pulpwood, few provide the variety of goods (e.g., timbers, medicines, and foods) once provided by the original forests to the people living in these areas.

Neither agricultural development nor past forms of reforestation have been sufficient to provide sustainable livelihoods and environmental services over the large areas of degraded land that have developed. Despite the expansion of protected area networks, there has been an overall gradual simplification and homogenization of some of the world's most biologically diverse landscapes. It is unclear just what the long-term consequences of this might be.

In recent years, new forms of reforestation have been tested that may offer additional ways of dealing with degraded tropical forest landscapes. These include improvements in the management of secondary or regrowth forests as well as more complex forms of reforestation where forest cover has been entirely lost [Supporting Online Material (SOM) Text]. There is clear evidence that biodiversity conservation can be enhanced by the careful location of protected areas (*2*). Likewise, improved methods of regrowth management and reforestation should also help restore biodiversity to degraded landscapes (Fig. 1).

Accelerating Natural Recovery

One way of increasing forest cover is to protect and manage the large areas of secondary or regrowth forests now present. Not all degraded lands are completely deforested, and they vary in forest cover, degree of fragmentation, and extent to which biodiversity has been lost. They also vary in their capacity to recover unaided if further disturbances can be prevented. Successional development (or self-repair) can be rapid at sites where forest clearance has occurred relatively recently (years versus decades); where some residual trees, seedling banks, and soil seed stores composed of native species remain; and where intact, biodiversity-rich native forests are still present in the landscape. Well-documented examples where natural regeneration has occurred over very large areas are Puerto Rico (*3*), Tanzania (*4*), Costa Rica (*5*), and Brazil (*6*). Species-rich forests can develop in this way, but such forests often contain only a subset of the original plant or wildlife species (*3*, *7*). Although it is rarely possible to determine the proportions or identities of missing plant species, the most common absentees are the large-fruited plant species because of the absence of appropriate dispersal agents. Foresters have sought to increase the populations of commercially important timber species in such secondary forest by enrichment planting (planting target species under canopy gaps or along cleared strips) (Fig. 2). The same technique might be used to improve biodiversity by adding species that are otherwise unable to colonize and regenerate or are ecologically threatened or vulnerable.

Natural recovery of degraded forest areas is not inevitable, and recovery is difficult where the system has crossed an ecological threshold and reached a new steady state con-

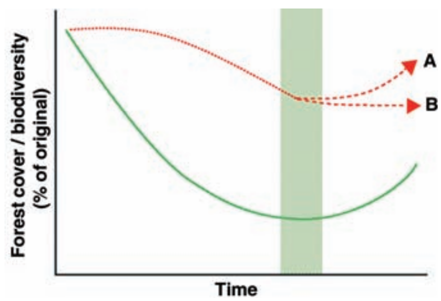

Fig. 1. A conceptual diagram of changes in forest cover in a landscape over time as a consequence of agricultural intensification. Forest cover is shown as a solid line, and the corresponding change in biodiversity is shown as a dotted line. Biodiversity loss occurs as forest cover declines, although the magnitude of this loss depends on the extent and location of the protected area network. When reforestation begins to occur (shaded area), it will increase forest cover, but any corresponding improvement in biodiversity depends on the types of reforestation carried out. Trend A depicts a scenario where secondary forest is protected and where connectivity is enhanced by reforestation using a diverse range of native species; trend B, where reforestation relies solely on extensive monoculture plantations of fast-growing exotic species.

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dition (*8*, *9*). A common example is when degradation leads to topsoil loss and a reduction in soil fertility, complicating recolonization of these sites for many of the original species. Another threshold is commonly crossed when sites become occupied by grasses. This increases the risk of wildfires, particularly in the seasonal tropics, which then reduces woody plant recruitment and favors the further spread of grasslands. There are many examples throughout the tropics of extensive grasslands that persist over time despite being entirely surrounded by forests (*10*). Therefore, even though natural regeneration is potentially the cheapest way of fostering reforestation over large areas, it is also the riskiest option because thresholds may have been crossed or because excluding further disturbances is difficult (*9*).

Plantings and Plantations

Most deliberate efforts to overcome degradation involve tree planting. However, even traditional forms of timber plantation can be risky operations, and, where species selection or early stand management are inappropriate, plantations can fail (*11*, *12*). Planting to generate ecological services as well as goods is even more difficult, because trade-offs must be made between the productivity of desired goods (i.e., timber) and provision of ecological services (i.e., biodiversity) and the techniques to achieve these simultaneous goals are still being developed. Some of the approaches are summarized in Table 1, which also shows their capacity to supply services as well as goods. The choice of approach will depend on the socioeconomic circumstances of the land owner as well as on the ecological situation (soil fertility, extent to which natural forest remnants remain in the landscape, etc.) (*13*).

Restoration plantings. The most ambitious goal is to attempt to reestablish the original forest ecosystem. Although the rules of ecosystem assembly are still debated (*14*), there are some empirical data from several sites showing promising results (*15*–*17*). Two broad approaches have been tested. Each involves a contrasting assembly rule, but each appears to offer promising results under appropriate conditions.

One approach is to use a small number of fast-growing but short-lived tree species (i.e., equivalent to early successional pioneer species) to create a canopy cover. These shade out grasses and weeds, diminish the fire hazard, and facilitate colonization of the site by a wider range of species from nearby intact forest (*1*, *16*). Under certain circumstances, these cover or nurse trees might be established by direct seeding (*18*). The success of this low-diversity planting technique depends on the ability of additional native species to reach the site from nearby intact forest, principally through seed dispersal by frugivorous birds and mammals. In such cases, small-fruited species are generally more likely to colonize than large-fruited species. The approach also runs the risk of facilitating colonization by undesired weed species.

The other approach uses a much greater number of species representative of more mature successional stages and bypasses the natural successional sequence. Plantings are usually at high densities (>2500 trees per ha), and competitive interactions determine the final forest composition (*19*). Species unable to tolerate open planting can be added once canopy closure has occurred, either as seedlings or by direct seeding. Such an approach was used in a forest restoration program after bauxite mining in central Amazonia (SOM Text). In this case, over 160 species representing a range of life forms and successional stages were planted after mining ceased and topsoil replaced (Fig. 3). After 13 years, the new forest, enriched by colonization by species from nearby intact forests, resembled the undisturbed forest in its tree species composition, although structural recovery is still incomplete (*18*). The approach allows key species to be targeted (e.g., large-fruited species) but requires sufficient ecological knowledge to be able to collect seeds and germinate large numbers of seedlings from a wide variety of species.

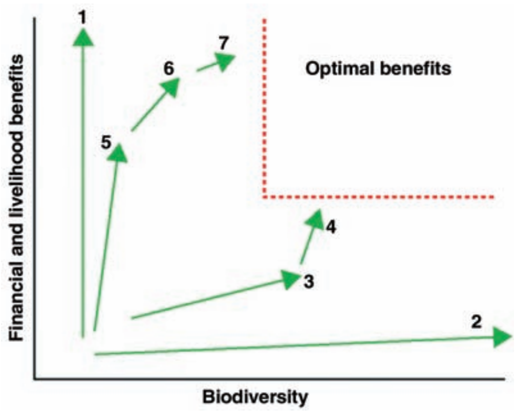

Fig. 2. It is difficult to develop restoration methods at a particular site that optimize financial and livelihood benefits as well as generate improvements in biodiversity (top right corner). Traditional monoculture plantations of exotic species (arrow 1) mostly generate just financial benefits, whereas restoration using methods that maximize diversity and (arrow 2) enhance biodiversity yields few direct financial benefits to landowners, at least in the short term. Protecting forest regrowth (arrow 3) generates improvements in both biodiversity and livelihoods, although the magnitude of the benefits depends on the population density of commercially or socially important species; these can be increased by enrichment of secondary forest with commercially attractive species (arrow 4). Restoration in landscapes where poverty is common necessitates attempting both objectives simultaneously. But, in many situations, it may be necessary to give initial priority to forms of reforestation that improve financial benefits, such as woodlots (arrow 5). In subsequent rotations, this balance might change over time (moving to arrow 6 and later to arrow 7 by using a greater variety of species). There may be greater scope for achieving multiple objectives by using several of these options at different locations within the landscape mosaic.

The key limitation to the use of such restoration plantings is their high cost (*20*). They do not supply significant volumes of commercially useful goods such as timber, and usually there are only limited markets for the ecological services they provide. Hence, restoration plantings are probably an option that can only be used in a relatively small number of situations and rarely in the most severely degraded tropical landscapes, except where the potential environmental benefits or costs of inaction (as in mined land or mangrove restoration) may justify the required investment (SOM Text).

Plantation establishment to provide goods and ecological services. An alternative is to establish plantations that provide goods for which there is a market, such as timbers, but also generate a larger range of ecological services than the more traditional industrial timber plantations. This approach seeks a balance between the financial benefits of industrial timber plantations (which enable large areas to be reforested) and the biodiversity gains possible from carrying out a more complete ecological restoration.

The simplest way this might be done is to use monocultures of native species (particularly those that are fleshy-fruited or have propagules dispersed by forest wildlife) rather than exotics. Although the biodiversity gains are modest, they are more likely to create environmental conditions that are suitable for native fauna than plantations of exotic species. Such trials involving monoculture plantations of high-value native timber species are now under way in many countries (SOM Text). Another approach is to use mixtures of species rather than simply monocultures (*21*). Recent experiments in Costa Rica (*22*, *23*) on commercially attractive native tree species suggest that mixtures in the dry and humid tropics have the potential to offer a number of benefits over monocultures, including production gains and reduced insect damage. Another advantage of mixtures is that they might provide small landowners a form of insurance to protect them from uncertain future markets. However, the design of these mixtures poses several key dilemmas. One question is how many species are needed to maximize these benefits; that is, what is the nature of the relationship between increased diversity and any functional benefits?

Table 1. A summary of some of the different forms of reforestation that might be used when secondary forests are present or when some form of planting is needed. Any combination of these techniques could be used in degraded landscapes depending on ecological circumstances and on the goals of the land managers.

Natural secondary forests	Plantings and plantations: To restore biodiversity	Plantings and plantations: To supply goods and ecological services
Protect and manage natural regrowth: Potentially able to supply a variety of goods and services depending on the age and condition of the forest.	Restoration plantings using small number of short-lived nurse trees: Acquisition of further diversity dependent on colonization from nearby forest remnants. Primary benefit is ecological services although can supply some goods depending on species present.	Tree plantation monoculture of exotic species: An efficient method of timber or food production for (mainly) industrial users; in most circumstances it is less successful in supplying many services.
Protect and manage natural regrowth plus enrichment with key species: Enrichment with commercially, socially, or ecologically useful species can improve the value of these forests to local communities or industry.	Restoration plantings using large number of species from later successional stages: Higher initial diversity that will also be supplemented by colonization from nearby forest remnants. Primary benefit is ecological services although can supply some goods depending on species used.	Tree plantation monoculture of native species: Useful to supply timbers of higher commercial value and other goods such as fruits, nuts etc.; the longer rotations normally used may facilitate an improved supply of ecological services such as watershed protection.
	Direct seeding: The number of species that can be established by direct seeding is limited by seed supply but the establishment cost can be lower. Direct seeding can be used to initiate reforestation in open fields under appropriate conditions but it may be most useful when used to enhance diversity once some tree cover is already present.	Tree plantation used as a nurse crop with underplantings of native species not otherwise able to establish at the site: An initial fast-growing nurse crop supplying commercially useful timbers or other goods can facilitate (e.g., via nitrogen fixation and microclimate alterations) the subsequent establishment of more species-rich forests that supply a wider range of goods and services.
		Tree plantation mixtures of native species: Mixed-species plantations can, potentially, supply a wider range of goods and services than monocultures. Biodiversity gains are greater than in plantation monocultures but are mostly still modest (usually less than five planted species).

Although there is increasing evidence that functions such as production, litter decay, and nutrient cycling can be enhanced as diversity increases (*24*), there is also increasing acceptance that simple taxonomic differences are an incomplete measure of diversity. Responses may depend more on the diversity of functional groups (e.g., nitrogen fixers, slow- or fast-growing canopy trees, and bird-attracting species) or on the diversity of functional responses within these groups rather than simply on the number of tree species used in a plantation (*8*). But our incomplete knowledge of tropical forest flora means it is rarely possible to confidently categorize many species into various functional groups apart from relatively simple categories. Nor, for the same reason, is it yet possible to define species within a particular functional group that might have different functional responses.

A second dilemma facing those wishing to use mixed species plantations is that of identifying species able to form stable mixes (i.e., able to avoid one species outcompeting and excluding others). It is clear that the nature of the diversity-function relation depends on the particular species used and that the sampling effect can alter this relation (*25*). These theoretical problems are matched by some practical ones as well. Unless the market prices of the various species are similar, the overall value of the plantation will be reduced as increasing numbers of lower value species are added.

This means there may be a limit on the use of plantations to foster biodiversity at a particular site, although such plantations often catalyze successional development in the plantation understory (*26*). Trying to strike compromises between conservation and economically valued production may end up generating suboptimal outcomes for each. Nevertheless, mixtures may be useful if they are likely to enhance both ecological resilience and financial resilience of these new systems. The latter would come from the greater diversity of income streams available to the landowner.

Making Reforestation Attractive to Rural Communities

The present scale of land degradation is such that it will only be overcome if large numbers of individual landowners or land managers become involved in reforestation. But, large-scale tree planting or farm forestry is not commonly practiced by rural communities living in degraded landscapes, even though many might practice some form of agroforestry. This may be because most of their land is needed for food production, but it is also because many rural people still have insecure land and tree tenure and are unwilling to invest in an activity from which they may derive little benefit. Reforestation can also be unattractive because the initial costs can be high, whereas the direct financial benefits are delayed in comparison with a variety of other possible land uses the landowner might

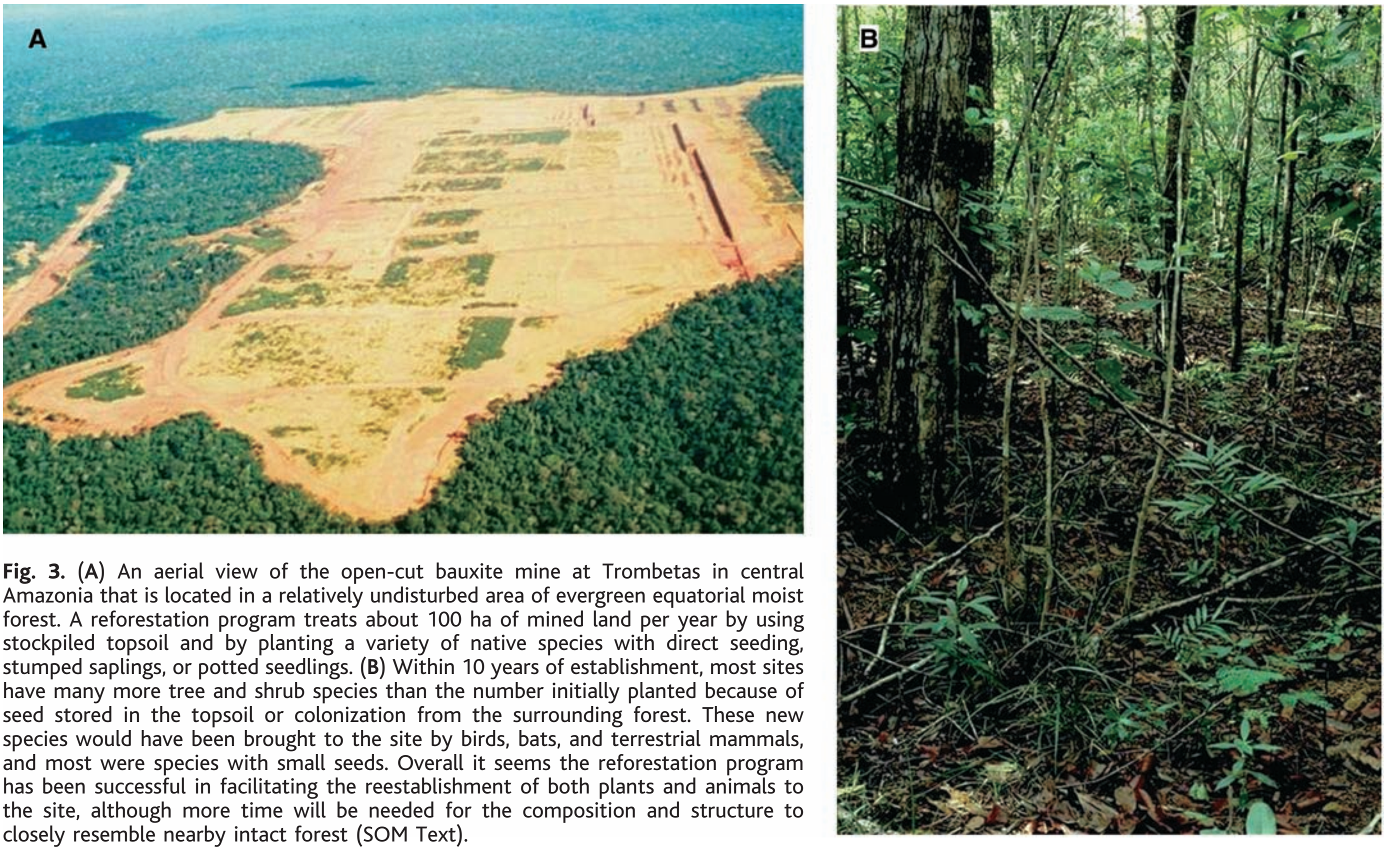

Fig. 3. (**A**) An aerial view of the open-cut bauxite mine at Trombetas in central Amazonia that is located in a relatively undisturbed area of evergreen equatorial moist forest. A reforestation program treats about 100 ha of mined land per year by using stockpiled topsoil and by planting a variety of native species with direct seeding, stumped saplings, or potted seedlings. (**B**) 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. These new species would have been brought to the site by birds, bats, and terrestrial mammals, and most were species with small seeds. Overall it seems the reforestation program has been successful in facilitating the reestablishment of both plants and animals to the site, although more time will be needed for the composition and structure to closely resemble nearby intact forest (SOM Text).

adopt (i.e., reforestation can have high opportunity costs). Even when tree planting is undertaken, most landowners have often found it easier to use fast-growing exotic tree species than native species, about which there is much less ecological or silvicultural knowledge.

There are several ways by which reforestation might be made more attractive to landowners. One is to develop appropriate institutional, legal, and policy settings (e.g., providing secure land tenure, elimination of "perverse" incentives that favor deforestation and forest degradation, and facilitating marketing of forest goods) and to provide financial loans or inducements to make reforestation attractive.

Another is to provide more information and technical assistance to landowners or communities about the species suitable for planting, their silvicultural requirements, and their market values. In many cases, the market prices of timber from slower growing native species are significantly higher than those for fast-growing exotics, and these prices are increasing as supplies from natural forests decline (*27*). As the supplies of low-value timbers from large industrial plantations flood the international markets, the market niche for these high-quality timbers may be a safer and more valuable target for smallholders. Experience to date suggests that smallholders who plant native tree species often prefer to use more than one species because they are interested in producing a variety of goods (*13*).

A third way to make reforestation attractive is to develop silvicultural systems by which plantations can be underplanted with crops that mature more quickly than trees, building on traditional and modern knowledge of agroforestry systems. These might be shade-tolerant agricultural cash crops (e.g., coffee, cocoa, and cardamom) or nontimber forest products such as rattans or medicinal plants (*28*). Again, there is often a significant local market for these species as supplies previously obtained from natural forests decline.

Lastly, reforestation might be more attractive to landowners if they are paid for the ecological services provided to those who benefit from reforestation but who share neither the costs nor risks. Examples of payments for ecological services provided by plantations include water, carbon, and biodiversity (*29*). Such payments could make reforestation quite an attractive land use. Although this market has undergone significant growth in the past decade, fundamental relations between forest composition/structure and their functional characteristics, i.e., their "yields" of ecological services, are still poorly understood. This contributes to the uncertainty of the market value of these services. Further, the legal frameworks to allow trading are yet to be established in most tropical countries, and many of these markets are likely to have high transaction costs. This is particularly the case in landscapes containing many smallholders (*29*). This means that some services (e.g., carbon sequestration) might be most easily provided by large industrial plantations rather than by many small farmers. Such a market might then displace smaller farmers and thus generate significant social costs.

Forest Landscape Restoration

Most degraded tropical landscapes are a mosaic of land uses and may include patches of intact residual forest and productive agricultural lands as well as degraded lands. It is rarely possible to reforest the whole landscape, especially if it is also occupied by many small farms. Under these circumstances, forest restoration is usually done by concentrating on particular sites. These might be riparian areas, buffer zones around residual forest patches, corridors between forest areas, eroding areas on steep hills, etc. However, the effectiveness of conserving biodiversity and restoring key ecological functions that operate at landscape scales (e.g., stabilizing hillslopes and hydrological processes) depends on these separately restored sites complementing others in the landscape mosaic. Individual decisions made by many small landholders are unlikely to achieve this optimal outcome. This then prompts questions such as which parts of the landscape should be reforested first, what type of reforestation should be carried out in particular locations, and what proportion of the landscape should be reforested to achieve particular objectives.

The significance of these questions is that redesigning landscape mosaics may offer greater opportunities than can be achieved at a single site for conserving biodiversity while also improving ecological functioning. That is, the trade-off between conservation and improvements in human well-being may be easier to achieve at a landscape level than at a site level (Fig. 2).

Some progress is being made to answer these questions to achieve certain biodiversity or functional outcomes. However, this still leaves the rather more difficult task for landscape restorationists of achieving these outcomes while also balancing the goals of the many stakeholders who have an interest in the landscape. Not only will these stakeholders differ in the extent to which they can or are willing to share the costs and benefits of any restoration program, but they will also differ in the size of their landholdings and in their economic and political power. In the immediate future, an opportunistic but targeted response by land management authorities aimed at key resources such as water or soil conservation may be all that is possible. In the longer term, it will be necessary to create appropriate conditions for the participation of all relevant stakeholders in the planning and implementation of restoration initiatives.

Outlook

The current rate of deforestation in tropical regions constitutes a major global biodiversity crisis. This loss of biodiversity is significant, but so too are the poverty levels of people who rely on these forests and degraded lands for their livelihoods. Both issues need to be addressed.

Conserving and actively managing the large areas of secondary forest that are now present is one way of doing this. Many rural communities are able to carry this out once appropriate government policies have been developed (*4*, *13*). But natural recovery is not always possible, and there are a variety of newer reforestation methodologies becoming available for areas that are currently deforested. A number of these have the potential to enhance biodiversity, improve ecological functioning, and improve human livelihoods. Ways must now be found of ensuring that these new land uses are made attractive to farmers and that site-specific methodologies are developed for farmers in a particular region to use.

Many hold the view that the elimination of poverty is closely linked to the conservation of biodiversity (*30*). Forest restoration for biodiversity is then a device to improve ecosystem functioning, ecological and economic resilience, and hence human livelihoods. However, the high amounts of rural poverty in some places makes it difficult to target all of these goals immediately; many smallholders may be unable or unwilling to do anything other than try to improve their immediate financial circumstances by improving agricultural productivity. But several trends suggest there may be increasing opportunities in the future to integrate agriculture and tree growing. One is the drift of populations from country to cities, which appears to be widespread in many tropical countries. Another is the likely improvements in the markets for high-quality timbers and other goods and services as supplies from natural forests decline (*27*). If more land becomes available and markets for forest products and services improve, there will be even more scope for making restoration and conservation contribute to poverty reduction.

The biggest challenge, however, will be moving restoration from a site-based activity to a landscape activity. It is at the landscape level that restoration can be used to complement the existing protected area network, and it is at the landscape level that biodiversity restoration and production (and hence poverty alleviation) can be most easily made complementary.

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Supporting Online Material

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SOM Text
Figs. S1 to S3
Table S1
References

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