Figure 27 Rowan and other rare species return when protected by fences or where the deer numbers have been reduced (Hinterzarten, south-west Germany).

recovery of the forest by means of natural regeneration, including species very sensitive to browsing and, consequently, quite rare. Rowan (*Sorbus aucuparia*) is an illustrative example in this regard (**Figure 27**).

Ecological and silvicultural problems aside, sociological and economic factors have, in a way, contributed to the increased acceptance of natural regeneration and its practical application. Three such factors are:

1. The 'green' movement amongst the public, which favors all procedures promoting natural forms of management.
2. Forestry in Central Europe has reached a phase in its development where there is a trend away from afforestation, towards nature-based forestry. Most forests are being reconstructed, and provide the opportunity for more demanding species to regenerate under the shelter of existing stands.
3. Forestry is suffering from the same problems as all other industries within the primary sector: falling revenues from the production of raw materials and a steady increase in the costs. All forest enterprises have, therefore, been forced to reduce their costs. Natural regeneration is one possible way of achieving this.

See also: **Afforestation**: Stand Establishment, Treatment and Promotion - European Experience. **Ecology**: Natural Disturbance in Forest Environments. **Genetics and Genetic Resources**: Forest Management for Conservation. **Silviculture**: Coppice Silviculture Practiced in Temperate Regions; Natural Regeneration of Tropical Rain Forests. **Sustainable Forest Management**: Overview. **Tree Physiology**: Physiology of Sexual Reproduction in Trees; Physiology of Vegetative Reproduction.

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Forest Rehabilitation

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Introduction

Rehabilitation is a form of reforestation that differs from more traditional approaches because it seeks to achieve outcomes other than just timber production. As well as creating a supply of goods such as timber, many rehabilitation projects aim to achieve functional changes and re-establish the ecological processes that once supported the original forest ecosystems. These changes then increase the supply of ecological services from a forest such as increased topsoil organic matter and fertility, enhanced hillslope stability, or improvements in watershed protection. Most rehabilitation projects try to do this by restoring some, though not necessarily all, of the original biodiversity (unlike ecological restoration which seeks to restore all of the plant and animal communities that were once present in the original forest).

One of the potential advantages of rehabilitation is that it can provide greater benefits for humans living in and around the new forest than most of the more traditional forms of reforestation. This may be through the socioeconomic benefits the forests provide from new goods such as timber, fruit, nuts, or medicinal plants leading to improvements in human livelihoods. Alternatively, it may come from the environmental and cultural benefits generated (**Table 1**). Finding the right balance between improving human well-being and improving the ecological integrity is difficult. This is because there may be more than one stakeholder involved at a particular site and each may have different priorities. Rehabilitation therefore represents a particularly difficult form of silviculture.

Some say it is too difficult – we should simply separate these different objectives and do each on different parts of the landscape. That is, we should continue to carry out intensive commercial production on those parts of a landscape that are suitable and protect or restore biodiversity in other, residual areas less suited for production. This view ignores the fact that the world's landscapes are being simplified and homogenized as agricultural areas have spread and natural forests are lost. Many now question the sustainability of these agricultural landscapes. Indeed, the provision of ecological services from new forests to ensure the sustainability of some agricultural landscapes may be a far more valuable outcome than any goods these forests may supply.

What is needed, therefore, is a more sophisticated array of silvicultural options to match the range of socioeconomic and ecological dilemmas that land managers are facing. This does not mean that traditional forms of reforestation are superseded. Indeed, in many situations they may continue to be the predominant method by which cleared land is reforested. What it does mean, however, is that they should not be seen as the only way in which reforestation is undertaken.

This article reviews some of approaches that have been developed to achieve these purposes. It also considers the problems limiting the application of these and some of the issues involving scaling up from these site level interventions to reforesting at a landscape scale.

Table 1 Goods and services provided by forest rehabilitation

Goods	*Ecological services for*	
	Individual landowner	*Community*
Industrial timbers	Hillslope stabilization	Biodiversity
Firewood	Improved soil fertility	Watershed protection
Fruits	Windbreaks and shelter	Hillslope stabilization
Gums and resins	Aesthetic benefits	Clean water
Animal protein	Cultural benefits	Carbon sequestration
Medicinal plants	Recreational benefits	Aesthetic benefits
Other food crops		Cultural benefits Recreational benefits

A Typology of Rehabilitation

Rehabilitation may take place under two circumstances. One is where deforestation is not complete and where logging or agricultural clearing has left some residual forest. This residual forest may consist entirely of remnants of the original forest or it may also include regrowth that has developed since the disturbing event occurred. The other circumstance is where deforestation has been complete and only grassland or shrublands persists. In either situation the prevailing conditions may prevent natural recovery occurring as quickly as is needed meaning that some form of silvicultural intervention is needed. These two conditions generate alternative silvicultural options. These options are summarized by the typology in **Table 2**. Typologies such as this necessarily disguise the fact that, in practice, these alternatives sometimes merge or overlap.

Some Residual Natural Forest Still Present at Site

Protect residual forest If a significant stocking of trees remains at the site the most obvious silvicultural

Table 2 A typology of forest rehabilitation approaches

1. Some residual forest still present

- Protect forest and allow natural recovery
- Protect and manage forest to encourage favored species
- Protect forest and enrich with commercially desired species (e.g., timber trees, fruit trees, etc.)

2. No existing forest remains: canopy trees must be replanted

2.1 New plantations with a more or less constant canopy tree composition

- Monoculture of tree species with preference given to native species
- Mosaic of tree monocultures across the landscape using mostly native species
- Tree monoculture with underplantings or inter-row plantings of economically or socially useful agricultural crop plants
- Multispecies tree plantations

2.2 New plantations where the composition of the canopy tree species changes over time (semisuccessional plantings)

- Nurse trees (native or exotic species) used to establish commercial tree species plantations option is to simply protect the site from further disturbances (such as recurrent fires, agricultural clearing, logging, firewood collection, or the harvesting of non-timber forest products) and allow natural successional processes to re-establish the forest. These successional processes might involve regeneration from coppice, seeds, or seedlings already present at the site or from seeds of species dispersed into the site from other nearby forest patches. By providing this protection biodiversity is conserved and forest development occurs without further cost. These species-rich forests are then able to supply a variety of goods and ecological services.

But protection can be difficult. Fire exclusion, for example, can be hard to achieve without a well-established fire suppression organization, particularly if wildfire is unchecked in neighboring lands. Nonetheless, there are many examples of where protection of residual forests has allowed substantial forest recovery over large areas. In time selective harvesting of timber or non-timber species can become possible depending on the density of individuals of these species. The primary advantage of this approach is its low cost while the main disadvantage is that recovery may take some time.

Protect and manage forest to encourage favored species A variant of this first option is to intervene silviculturally to promote the regeneration and growth of some of the more commercially attractive species present within the protected forest. Possible interventions may take the form of weeding or tending to remove competing species or thinning to reduce competition between trees of commercial species or to remove individuals with poor form or vigor. Pruning of these target species may also be commercially advantageous.

Protect and enrich with commercially favored species Heavy logging sometimes leaves a residual forest with only a limited stocking of commercially attractive species although many other species may still be present. Under these circumstances the abundance of seedlings or young trees of the more commercially attractive species (e.g., timber trees, fruit trees, medicinal plants in the understory, etc.) may be low. However, it may be possible to accelerate the recovery process by enriching the forest with these species to improve its commercial (or social) value. In tropical forests this usually requires that seedlings of the commercial species are planted as groups in clearings or in lines cut through the forest. In both cases overhead canopy cover must be minimized to avoid seedlings being suppressed. The density of these introduced seedlings is commonly less than 100 trees per hectare. This means the cost of treatment is much lower than clearing the residual forest and replanting with a monoculture.

Experience with enrichment planting in the tropics has been mixed because weed control is often difficult to maintain. Nonetheless, the technique remains an important option because of the large areas of logged-over forest that have accumulated that are depleted in commercially attractive species.

No Existing Natural Forest Remains at Site: Canopy Trees Must Be Replanted

The advantages of the techniques described above are that they conserve plant biodiversity and the ecological services provided by these biota. But different approaches are needed where deforestation is more complete.

New plantations with a more or less constant canopy tree composition

Plantation monocultures of tree species with preference given to native species Most traditional plantation systems are monocultures. Most also involve fast-growing, exotic species chosen because of the attractiveness of their timber properties and their tolerance of a wide range of site conditions. Most of these species also come as a well-developed silvicultural package with seed from seed orchards, a nursery methodology, and a set of postplanting management prescriptions covering fertilizing, thinning, and pruning. These monocultures are highly suited for intensive production and are the favored approach in most large-scale industrial plantation systems.

Some of these monoculture plantations also provide certain ecological services but their capacity to do so may be limited if the species are shallow-rooted or an understory is absent. Some of these disadvantages can be overcome by establishing leguminous groundcovers for nitrogen fixation or to protect surface soils from erosion.

Monocultures of indigenous tree species can offer some advantages over those provided by monocultures of exotic species provided they can still grow at what might have become a rather degraded site. Although they might still make only a minor contribution to regional biodiversity protection compared with, say, a regrowth forest they are still likely to be more attractive to at least some wildlife than plantations of exotic species. This attractiveness may be enhanced by the structural complexity inherent in the different age classes that develop as plantation establishment continues over time. And although native species often grow more slowly than the more common exotic species, they may also have higher market values. This means that timber volume increments may be lower but net value increments may be higher.

Mosaic of tree monocultures across the landscape using mostly native species Additional landscape heterogeneity can be created if a mosaic of monocultures is created across a region using different native species in each plantation wherever this is ecologically possible. In this case, species are matched carefully with their optimal sites. For example, species preferring moist sites are planted in valley floor positions while more hardy species are established on hills or ridges. In this case the silvicultural advantages of monocultures are maintained while landscape diversity is enhanced. Overall productivity may also be enhanced in this way by matching species to their preferred sites. On the other hand, this requires detailed knowledge of the species and their site relationships.

Tree monoculture with inter-row plantings or underplantings of agricultural crops The primary disadvantage of tree crops is the length of the period before any economic benefit is obtained. Rotation lengths for many tree species exceed 30 years. Some landowners or stakeholders need a return before such a time span in order to encourage them to undertake reforestation. One way this might be achieved is by underplanting the tree species with short-lived agricultural crops or medicinal plants. The well-known 'taungya' system that was developed during the colonial period in Burma is just one example of this approach. In this case the crop plants are planted between the rows of trees thereby helping to exclude weeds. Cropping is continued until tree canopy closure occurs and is then abandoned.

This tree-plus-crop combination is commonly referred to as agroforestry and there is a huge number of variants. In some cases, such as the taungya system, the crop is short-lived. In other cases the crop is a more or less permanent component of the plantation system. Many of these systems use only a single species of tree but other agroforestry systems use more than one tree species. The commercial advantages of the system are clear provided the crop species can tolerate their subcanopy position. The system also has some ecological advantages since the more complex canopy structures are likely to provide better ecological services such as watershed protection and wildlife habitats than simple monocultures.

Multispecies tree plantations Plantations involving more than one tree species are more complex silvicultural systems requiring more sophisticated management operations but offering some potential advantages over monocultures. These include the possibility of enhanced productivity, improved nutrition, reduced insect or disease and greater financial security from the spreading of risk (see **Table 3**).

These potential advantages do not invariably occur in every mixture and randomly created mixtures are likely to fail. Great care is needed to ensure that only complementary species are used. Complementary species may be those that minimize competition with their neighbors. Thus they may have differing phenologies (so that their demands on site resources are at different times than their neighbors) or differing root depths (so that roots take resources from different soil horizons). Likewise they may have differing canopy architectures (so that crown and foliar competition is minimized) or differing nutritional requirements (so that resource competition is minimized). Nutritional gains can also occur when nitrogen fixers such as *Acacia* or *Albizzia* are mixed with non nitrogen fixers.

Most mixtures contain only modest numbers of species but these can be planted in various configurations such as in alternate rows of particular species or at random. Alternate rows offer the advantage that a faster-growing species might be removed earlier than a slower-growing species without causing much damage to the residual trees. Random plantings of the trees in the mixture offer the advantage of a more intimate mingling of the species enabling the advantages of complementarity to be more fully expressed.

Table 3 Potential benefits of using more than one species in a plantation

Potential benefit	*Reason*
Competition between trees reduced	Competitors have differing growth phenologies and use site resources at different times
	Competitors have different root or canopy architectures that partition spatially distributed resources and use them differentially
Tree nutrition is enhanced	One of species is a nitrogen fixer that adds N to soil
	Nutrient decomposition and cycling is faster with more than one litter type
Reduced insect or disease problems	Target species for insects are hidden in space; host plants for particular diseases are more widely distributed
Financial outcome is improved	Provides insurance and spreads risk of markets changing during rotation period

Adapted with permission from Lamb D and Gilmour DA (2003) *Rehabilitation and Restoration of Degraded Forest.* Gland, Switzerland: IUCN.

Mixtures obviously have higher levels of plant biodiversity than plantation monocultures although the extent of any biodiversity gain depends on the number of species included in the mixture. In most cases this will still be modest compared with that in a natural forest. But mixtures are also likely to have a greater structural complexity than any monoculture meaning they are likely to be more attractive to some wildlife species. Any gain in species richness is likely to benefit the restoration of key ecological processes and ecological services. The key disadvantage of mixed species plantations is obviously in their greater silvicultural complexity and need for more intensive management.

New plantations where the composition of the canopy tree species changes over time (semisuccessional plantings)

Nurse trees used to establish plantation tree species Some commercially attractive plantation tree species need an overstory canopy of 'nurse' trees to become established. Once they are established this nurse tree cover can be removed. Thus some temperate tree species need protection from frosts when young. Similarly, some tropical tree species are sensitive to full sunlight when at the seedling stage. Nurse crops such as these are also needed for some agricultural crops (e.g., *Erythrina*, *Cordia*, or *Leuceaena* are often used to provide shelter over coffee or cacoa). A forestry example is the requirement by some of the Dipterocarpaceae of Southeast Asia for a temporary overstory cover. Nurse crops can also benefit certain tree species by reducing insect damage, presumably by altering some element of the microclimate affecting the insect. For example, red cedar (Meliaceae) has been found to have greater survival rates when planted below an established cover than when planted in the open. Likewise nurse trees may act to improve soil conditions allowing more valuable species to be established at the site.

These nurse trees facilitate the development and growth of the target species and add to the biological complexity of the new forest. However, they also pose a series of silvicultural dilemmas. These include the question of how tall the nurse trees must be when the target species is planted and how much cover must they provide? How long should this cover be provided before it begins to reduce the growth rates of the commercially attractive species? If the nurse species are short-lived they may disappear around the time when their disadvantages begin to outweigh their advantages. Otherwise they may need to be removed by poisoning or girdling.

While the focus of this silvicultural sequence is the commercial plantation species the added biological and structural complexity of the new forest ensures it has some ecological advantages over simple monocultures as well.

Underplant beneath earlier plantation monoculture A variation on the nurse tree model is when circumstances require that an existing monoculture plantation of one species (perhaps an exotic), be replaced by another (perhaps a native species). This may be because the timber value of the original species has declined or because the environmental or ecological benefits of the current plantation are insufficient and need improvement. In such a situation the best option may be to simply clear the original forest and replant with the preferred species. But in some situations it might be preferable to underplant below the original canopy or plant in strips or corridors cleared through the original plantation and manage a more gradual transition. The choice will obviously depend on the shade tolerances of the various species being added to the site as well as the longevity and current market value of the initial plantation species. The new species might be more valuable timber, nut, or fruit trees or they might simply have greater ecological and conservational value.

The advantage of such an approach is that it avoids rapid changes in wildlife habitat and potentially large soil and nutrient losses caused by erosion after clearing. There is also scope for some financial gain from the harvesting process. The disadvantage is that the shade tolerances of the new species and hence the amount of canopy opening needed must be clearly understood to avoid a lengthy period of trial and error during the transition.

Understory development encouraged beneath tree plantation Many plantations located near intact natural forest can gradually acquire an understory of native species because of natural colonization. The rate at which this occurs will depend on the attributes of the plantation species as well as those of the potential colonists and on the dispersal distances involved. In the tropics greater diversity appears to occur beneath broadleaved plantation trees than beneath conifers. Within the time period of a typical plantation rotation, a very species-rich understory can develop, especially in moist tropical regions. In some cases these colonists can grow up and join the canopy layer.

This phenomenon represents both an opportunity as well as a dilemma. The opportunity is that great biological diversity can be acquired for little cash outlay. This means there may be a significant gain in a variety of ecological services such as watershed protection and nutrient cycling and the restoration of many ecological processes. The dilemma is that there may be an indirect cost in the form of increased competition facing the original plantation trees that will slow their growth. The trade-off will necessarily depend on circumstances. If the site is one where enhanced biodiversity is an advantage then it may be appropriate to tolerate a reduction in timber increment caused by increased competition. On the other hand, if production is the predominant objective then careful management of this competition will be needed.

There are four possible alternative management regimes. One is to harvest the plantation as initially envisaged and to treat the enhanced biodiversity as a temporary benefit that will re-establish again when the second rotation of the plantation is re-established. A second is to regard this biodiversity as now being more socially beneficial than any timber harvest and to not fell the trees as was originally planned. A third is to fell the plantation trees at the end of the rotation as originally planned but to try to protect as much of the new biodiversity as possible while doing this. Subsequently, the primary management objective would then become one of fostering and enhancing this biodiversity rather than re-establishing the plantation timber trees. The final option might be to simply manage the plantation species, together with the new timber species that have joined the canopy, as an uneven-aged forest and to manage this on a selection system. This would recognize that some of the new colonists might have also commercial or social values as food or medicinal plants.

This catalytic role of plantations does not occur everywhere and sometimes the only species that colonize beneath the plantation species are exotic weeds. But provided it is carefully managed, the phenomenon is a cheap means by which monoculture plantations can generate a wider range of ecological services.

Problems in Using These Approaches

This variety of potential alternatives might seem to imply that all are equally available. Unfortunately this is not the case and there are two main reasons. One concerns the biology of native species. Much less is usually known about the ecology or silviculture of most native tree species than is known, for example, about the more common industrial forestry species. This means that species–site relationships and nutritional requirements are uncertain and the competitive abilities or tolerances of these species are mostly unknown. This makes it difficult to develop good mosaics of monocultures or design multispecies plantations using complementary species mixes. A second, even more difficult issue is that of managing the trade-off between production and ecological integrity or authenticity. Different stakeholders will strike different balances because they have differing objectives. This means that reaching a desired balance will probably always involve some degree of trial and error until the basic silviculture and ecology of the several species being used is understood.

The Social–Economic Context for Reforestation

Forest rehabilitation to provide goods and ecological services is more commonly undertaken by farmers and communities rather than by industrial enterprises. This is because of the differing objectives usually being sought by these several groups. But farmers, like industrial enterprises, need some certainty that they will indeed be the ultimate beneficiaries of any reforestation that they undertake. This means that land tenure is a crucial matter. No person is likely to invest time or money in a long-term activity like forestry unless there is some certainty over land ownership or future access. Nor are they likely to protect the young forest from fires or grazing animals unless they can see it to be in their own interest. The irony here, of course, is that many of the most degraded landscapes are also those where rural people's traditional land ownership claims are unrecognized by central governments.

Because ecological services are often distributed far beyond the immediate vicinity of any particular reforestation site there is also the issue of whether these distant beneficiaries of rehabilitation should also contribute to its cost. For example, should a landowner with land affected by salinity contribute to the cost of trees planted in the watershed upstream of his property? These trees will help lower the water table and reduce his salinity problem but will also reduce the area of agricultural land available to his neighbor. If rehabilitation is to be undertaken on a large scale then some way must be found to fund the restoration of these services on degraded lands for the wider public benefit. The current debate over whether the carbon sequestered by tree plantations might be traded in a special market illustrates one approach to this problem.

A related problem is that each forest manager usually makes decisions on a site basis but that many ecological processes operate at a landscape scale. Different land managers will have different goals and therefore use different agricultural and silvicultural approaches. But agricultural sustainability across the landscape as a whole will require collective action by all land managers if optimal outcomes are to be achieved. This will require what might be called forest landscape restoration. Such a landscape may have croplands, patches of remnant forest, and perhaps several of the approaches outlined above. There are few localities where this has been successfully achieved.

See also: **Biological Impacts of Deforestation and Fragmentation**. **Forest Management for Conservation**. **Plant Diversity in Forests**. **Silviculture**: Natural Stand Regeneration; Reclamation of Mining Lands; Sustainability of Forest Plantations. **Sustainable Forest Management**.

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Treatments in Tropical Silviculture

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Introduction

Silviculture can be defined as the art and science of controlling the composition, structure, and dynamics of forests. Although the traditional focus of silviculture was on timber production, modern silviculturalists are expected to respond to society's often conflicting demands about forests. Sustained yield of timber is still a common goal, but non-timber forest products (NTFPs) such as medicinal plants and wildlife sometime receive as much or more attention from some important forest stakeholders. Forests providing these products and the jobs and revenues they yield are also expected to serve as recreation areas, watersheds, and effective moderators of local and global climates. Foresters are expected to manage forests for these goods and services in ways that avoid losses of genetic, species-level, and landscape-level diversities; sometimes they are expected to manage without apparent disruption of the pristine nature of old-growth forest. With so broad an agenda, the relevant question seems to become what isn't silviculture rather than what is?

This article has a somewhat traditional focus on plants and plant products, how they grow, and how forests can be silviculturally treated so as to increase production of the desired species. Although reference is made to different silvicultural systems that have been utilized in the tropics, the emphasis is on the ecological reasons behind these different methods for increasing the stocking and growth of commercial species and the conditions under which they are likely to be successful.

Treatments to Improve Stocking

General Approach

Securing adequate natural regeneration for future harvests is a central but often hard-won goal for forest managers. Despite the popular perception of forest management as necessarily involving tree planting in tropical forests, natural regeneration has a number of advantages over artificial regeneration (e.g., hand or machine planting of seeds or seedlings). One of these advantages is that because the seed sources for natural regeneration are individuals that successfully reproduced in the stand, it is reasonable