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 to expect that they are genetically well adapted to local biotic and abiotic conditions. For plantation managers, in contrast, mismatches of species, provenances, and genotypes to local site conditions are commonplace. Furthermore, transplanted seedlings often suffer high mortality rates and, if planted poorly, may grow slowly or develop deformed stems even if they do survive. Natural regeneration is also generally less expensive than artificial regeneration, but it is not always 'free.' In any event, where natural regeneration is relied upon, management interventions are generally less drastic than where seeds or seedlings are planted. Lessening the impacts of stand regeneration operations, in addition to saving money, has the advantage of reducing the effects of forest management on biodiversity and ecosystem functioning (e.g., stream sedimentation and nutrient cycling). This is not to say, however, that methods for securing natural regeneration are always gentle. On the contrary, where natural, stand-regenerating disturbances include fires, hurricanes, or other major perturbations, the appropriate regeneration treatments are also likely to be severe.

Successfully regenerating commercial species without causing unnecessary harm to other species or forest processes requires substantial ecological and more specific silvicultural knowledge. For example, the reactions to harvesting and other stand manipulations of commercial species, weeds, and other taxa need to be known. Forest managers thus need to be aware of the intervals between seed crops (e.g., mast year frequencies), the distances to which seeds are dispersed, the probability of seedling establishment and survival, and the relative growth rates of commercial species and the species with which they compete. Due to a variety of factors including destructive harvesting practices, droughts, intense seed predation, herbivory, and the effects of pathogens, natural regeneration may not result in fully stocked stands.

A major challenge for forest managers is developing sufficient understanding of the regeneration mechanisms of the species for which the area is being managed as well as of the other species that influence forest development. Plants regenerate in a variety of ways, both sexually (i.e., by seed), and vegetatively (e.g., from rhizomes or coppicing from cut stumps). Among sexually reproducing species are those that produce seeds that lack dormancy (i.e., they either germinate or die soon after maturing), and others that produce seeds that may remain dormant in the soil for many years. Species that regenerate vegetatively may simply sprout back after being damaged or spread extensively by root sprouts or stem layering. Extensive vegetative expansion is fairly rare among tropical trees, at least those that grow to be large, but is common among other growth forms such as vines, grasses, and ferns. Sprouting of naturally broken or felled trees, in contrast, is commonplace.

Reducing Logging Damage to Advanced Regeneration

The understories of many forests contain substantial populations of seedlings, saplings, and poles of commercial species, which are collectively referred to as 'advanced regeneration,' and subcanopy trees, which are referred to as 'advanced residuals.' Where harvesting is planned to be carried out before completion of a full rotation (i.e., the time required for a germinated seed to grow into a plant of harvestable size), reducing harvesting damage to the future crop trees is critical. Due to limited knowledge about the capacity of most tropical tree species to respond favorably to canopy opening after suffering prolonged suppression, future crop trees should be selected on the basis of stem and crown form, not just by species and stem diameter. In any event, harvesting should be considered to be an intensive silvicultural intervention and not a forest product mining operation.

Promoting Seed Production and Seedling Establishment

Regeneration from seed can fail at any phase of the process of flower production, pollination, seed set, seed dispersal, and seedling establishment. For species that are poorly represented by advanced regeneration or as buried seeds in the soil, retention of seed-producing individuals is generally of the utmost importance. The minimum density of retained seed-bearers is a function of a large number of factors including both propagule and site characteristics. For example, the required density of retained individuals of a dioecious species (i.e., one with separate sexes) that produces large and poorly dispersed seeds is likely greater than for a species with perfect flowers and small, wind-dispersed seeds. The location of seed trees relative to skid trails, felling gaps, and other canopy openings may also be critical. For example, on the Yucatan Peninsula of Mexico, regeneration of *Swietenia macrophylla* is promoted by retention of seed trees upwind from such openings. The timing of harvesting operations can also be critical if the seed-producing trees are cut before their seeds are dispersed. Setting a minimum diameter limit for harvesting that is close to or less than the minimum size at which trees start to reproduce is another obvious cause of regeneration failures. Unfortunately, diameter limits are all too often determined without regard to the biology of the species being harvested.

There is a wide range of harvesting options designed to promote regeneration, ranging from massive clear-cuts to single tree selection, which results in only small gaps in the canopy. In deciding upon the appropriate harvesting system for the forest and species of concern, the silviculturalist needs to determine the minimum canopy opening that promotes the regeneration of the desired species. Where silvicultural treatments other than harvesting are to be applied, the silviculturalist should also know whether mineral soil needs to be exposed to promote seed germination and seedling establishment.

Seeds may be produced in abundance but regeneration nevertheless fail if seed dispersers are absent or limited in abundance due to over-hunting. Although many of the best-known timber trees in the tropics have wind-dispersed seeds, many other timber-producing species, as well as most understory trees and virtually all palms, shrubs, and herbs, produce seeds that require the services of mammals, birds, reptiles, or even fish for their dispersal. Seeds that are not dispersed mostly fall under the parent plant where they suffer greatly from competition, seed and seedling predation, and the impacts of pathogens.

Pre- and postdispersal seed predation can greatly reduce the numbers of seeds available for germination. In some cases, mammals and birds (e.g., parrots and doves) eat large numbers of immature seeds. Similarly, many insects (e.g., some beetles and flies) lay their eggs on flowers or young fruits; the larvae hatch and bore inside where they are nourished at the expense of developing seeds. Many mature seeds are in a sense sacrificed to animals that serve as both dispersers and seed predators. Squirrels and other rodents that scatter-hoard seeds for future consumption are a familiar example of this dual function; the seeds they fail to recover are the most likely to survive and contribute to the next generation.

Dispersed seeds that escape predation may nevertheless fail to germinate or establish as seedlings if the environmental conditions of the places to which they are dispersed are not suitable. For example, seeds that are stimulated to germinate by high red : far red ratios of light will fail to germinate if they land in the forest understory. More commonly, seedling establishment fails because the seedling root fails to find a reliable source of water. Seedlings from small seeds that germinate on top of leaf litter are particularly prone to desiccation. In deep shade, when the reserves of carbohydrates stored in seeds are exhausted, seedlings die if they are not able to photosynthesize enough to balance their respiratory carbon losses. Herbivory and damage from fallen branches and trampling also result in the death of many seedlings, as do nutrient deficiencies, but desiccation and carbon imbalances (often associated with fungal infection) apparently kill the majority of seedlings.

It perhaps goes without saying that most seeds and seedlings fail to survive to maturity, but detailed and long-term studies of population biology are often required to determine whether apparent 'bottlenecks' at the seed or seedling phases actually threaten population maintenance. Nevertheless, silviculturalists need to be careful to avoid inadvertently jeopardizing sustainability by creating conditions favorable to weeds, seed predators, herbivores, and pathogens, or that are unfavorable to pollinators or seed dispersal agents. In some cases, seedling establishment can be enhanced by removing surface litter and near-ground competition with controlled burns, or exposing mineral soil by mechanical scarification with a tractor-drawn plow. Such intensive site preparation treatments are more commonly used in plantations than in managed natural forests, but they should not be disregarded as silvicultural options.

Although traditional forest-dwelling people have successfully enriched forest with useful species for millenia, industrial-scale 'enrichment planting' has generally proven to be a problematic and costly way to increase the stocking of commercial tree species. Despite numerous expensive failures, enrichment planting of nursery-grown seedlings along lines cleared through the forest or in felling gaps continues to be tried in many forests, particularly where uncontrolled logging has left severely depleted stands. While poor planting technique is sometimes the problem, most seedlings die because they do not receive the postplanting tending operations needed to assure their survival. More successful, from a silvicultural perspective, has been a regeneration system referred to by its Burmese name, 'taungya,' in which commercial tree species are planted among food crops plants by farmers who do the necessary weeding. This system was discredited where it was originally used by colonial foresters because once the planted trees were established, the farmers were displaced and their agricultural practices were criminalized. Given the recent substantial devolution of forest management responsibilities back to rural communities from central governments in many tropical countries, some aspects of 'taungya' might prove useful for forest regeneration where the farmers own the land.

Particularly in seasonally dry forests and woodlands, many tree species can be managed for trees that sprout from stumps (i.e., coppicing) or from trees cut off above the reach of browsing animals (i.e., pollarding). Coppice stems of better quality typically emerge from low stools (i.e., stumps), but even the best coppices seldom yield large logs. Nevertheless, coppicing is an excellent way to produce small-dimension timber, poles, firewood, and fiber. Pollarding, in slight contrast, is generally used to provide seasonal shade over crops in agroforestry systems, to produce forage for animals, and for firewood production.

Treatments to Improve Growth

General Approach

Various stand 'improvement' treatments are available to increase light and soil resource availability to commercial species and thereby increase their productivity. In natural forest management in the tropics, these treatments typically involve competition control. Although we are very aware of aboveground competition for light, belowground competition for water and nutrients can also be intense. In this section, weed control and thinning are considered separately even though they are sometimes hard to distinguish.

Weed Control

A 'weed' can be defined as a plant growing where it is not wanted. Depending on the type of weed to be controlled and the ease to which damage to future crop trees can be avoided, silviculturalists can choose from a wide variety of mechanical and chemical treatments or may opt to perform controlled burns.

Among the mechanical weed control methods available, roller chopping, disking, and other tractor-requiring treatments are generally only useful in young stands regenerating after clear-cutting. More often in managed natural forests, weeds interfering with future crop trees are cut with a machete, brush axe, motor-driven weed whacker, or chainsaw. Although many weeds resprout vigorously after cutting, well-timed mechanical treatments can promote growth of future crop trees that may then shade out light-demanding weeds. Generally, mechanical control is most effective early during the season of most active growth when most carbohydrates and other storage materials have been translocated to the aboveground parts that are removed.

When used properly, modern herbicides can be safe, useful, and cost-effective components of a silviculturalist's toolbox. Chemical weed control methods have improved a great deal during the last decade. Compounds used in the 1960s such as sodium arsenite and 2,4,5-trichlorophenoxyacetic acid (2-4-5T) contaminated with dioxins posed serious environmental and health hazards and are now generally banned. In comparison, herbicides such as glyphosate, tryclopyr, hexazinone, and 2,4-dichlorophenoxyacetic acid (2-4D) have low toxicity to animals, brief residence times in the soil, and apparently safe breakdown products. Modern herbicides are all expensive but vary substantially in their modes of action. For example, some are absorbed by roots (e.g., hexazinone) whereas others penetrate leaf cuticles (e.g., glyphosate).

If after weighing the costs and benefits you decide to use herbicides for weed control, there are a number of choices of commercially available products, tank mixtures, dyes, wetting agents (i.e., surfactants), and modes of application.

Suitable ways to apply herbicides vary with the species and size of the target plants, the number of plants you intend to treat, the season, the type of herbicide, and available equipment. Some herbicides, like glyphosate, are often sprayed or wiped on foliage, whereas others, like Garlon 4, are more often squirted around the inside of the bark (i.e., on the vascular cambium) of fresh-cut stumps or into frill girdles cut with a chainsaw or hatchet. To penetrate the waxy coating (cuticle) on leaves, a surfactant is sometimes needed. Because herbicides disrupt metabolic functions, they are best applied when plants are metabolically active. Late growing season applications are often particularly effective because that is when many plants are moving sugars belowground to store for the winter or dry season. Volatile herbicides should be applied when the air is cool and still, lest the fumes escape and kill plants that you were trying to save. And whether herbicides are being applied to bark, stumps, girdles, or leaves, never apply so much that the chemical runs off the surface.

Woody vines, including climbing bamboos, pose serious silvicultural problems in many tropical forests. Vine infestations are especially common in logged forests, particularly those where logging was uncontrolled and carried out by untrained crews. Because many vines survive when their host trees are felled and sprout vigorously from fallen stems, many of the vines in logged areas propagate vegetatively. Prefelling cutting of vines, therefore, can have substantial postfelling advantages in addition to reducing logging damage. Furthermore, due to easier forest interior access prior to logging, prefelling vine cutting is generally more cost effective than trying to control vines in vine-infested logged forests. Finally, because vine leaves may constitute 25% or more of the total forest leaf area, vine cutting is analogous to carrying out a light shelterwood cut; tree seedling densities and growth rates may increase in response to vine removal. Silviculturalists trying to rescue commercial trees in heavily vine-infested forests are generally advised to focus on liberating the crowns of future crop trees rather than trying to cut all of the vines in the entire management area, which is generally too costly.

Thinning

Where future crop trees are crowded by neighbors, thinning can result in substantial increases in growth due to release of soil resources and increased access to light. Thinning treatments can be applied to entire stands or just in the near vicinities of selected future crop trees. Both commercial thinning, in which the thinned trees are extracted and sold, and precommercial thinning are reasonable options in some stands. But before discussing some of the many types of thinning, a few of the silvicultural costs and benefits of thinning need to be considered.

While diameter or volume increments of selected future crop trees can be improved by removing neighbors, heavy stand thinning can lead to retention and growth of lower branches, formation of epicormic branches, increased stem taper, barkscald, abrupt changes in wood properties, and other changes that lead to reductions in stem or wood quality. Thinning stands can also make the remaining trees susceptible to windthrow and weed encroachment. Finally, thinning does not invariably result in the desired growth response. For example, after long periods of suppression, trees of many species do not respond well to thinning; some previously suppressed trees may even die if they are too rapidly exposed to high light intensities, high temperatures, and the consequent water deficits. Where exposure is less rapid and less extreme, formerly suppressed trees that are released from competition may adjust to the new conditions by replacing their shade-adapted leaves with thicker leaves, with thicker cuticles, and other characteristics of 'sun' leaves. Released individuals also adjust their root : shoot ratios so as to increase their water uptake capacities in the more water-demanding conditions of thinned stands.

In silviculturally managed natural forests in the tropics, perhaps the most common thinning operation is the release of selected future crop trees from competition from immediate neighbors. This treatment, often referred to as 'liberation thinning,' has many silvicultural, financial, and environmental advantages in the poorly stocked stands in which tropical foresters generally work. By restricting thinning operations to the near vicinities of future crop trees, portions of most stands remain untreated, which often makes silvicultural sense, saves money, and avoids needless environmental disruption.

Liberation thinning prescriptions generally call for cutting, frill-girdling, or arboriciding trees with crowns above or within some lateral distance (e.g., 2–4 m) of the crowns of future crop trees. The appropriate extent of lateral opening varies with the species and size of the tree to be released. For example, tree species that typically develop broad spreading crowns may require large openings for maximum growth, at least after the selected individual has developed the desired length of branch-free bole.

To maximize the likelihood of increased timber volume increments, future crop trees selected should not have been heavily suppressed for long periods of time. Because stand records are seldom available, the silviculturalist must rely on visible characteristics of trees themselves to determine their histories of suppression. Crown form is generally the best indicator of the conditions under which a tree has been growing. Trees with small, sparse, or poorly formed crowns are likely to have been suppressed for a long time and may not respond well when released from competition. Heavily vine-laden trees may also not be good candidates for liberation treatments. Due to the complexity of liberation thinning operations, tree marking should be carried out by trained staff and the silvicultural responses should be monitored in permanent research plots. Repeated liberation may be required for maximum stand production if the benefits of liberation do not persist for the duration of stand retention.

The primary thinning treatment that most natural forests receive is timber harvesting. All too often logging is not considered to be the silvicultural treatment that it actually represents. In stands with substantial advanced regeneration of commercial species and where some trees have been marked for harvesting and others for retention, timber harvesting is equivalent to heavy thinning and results in similar growth responses of future crop trees.

Environmental Impacts of Silvicultural Treatments

Liberation thinning, vine cutting, soil scarification, and other stand 'improvement' treatments are not improvements at all from the perspective of the vines that are cut, the trees that are girdled, or all the various animal species that depend on the plants selected against. Stands that are intensively managed for timber can be essentially converted into plantations, with all the attendant negative impacts on biodiversity. In most of the tropics the problem is too little, not too much management, but silviculturalists nevertheless should be aware of this concern.

Impatience is a common threat to environmentally, silviculturally, and fiscally sound silviculture. Sometimes the best decision is to let a stand recover slowly on its own, without silvicultural intervention. And some silvicultural treatments may be misapplied. For example, an overstory of fast-growing, short-lived, light-demanding trees may serve as a nurse crop for the slower-growing commercial species that grow up in their sparse shade – removing the cover crop would be wasteful and ineffective. Also, dense stands can be left to self-thin, at no direct cost to the forest manager. And heavily thinned stands may suffer excessive windthrow and other damages. The best overall advice when prescribing and applying timber stand improvement treatments is to be gentle unless the forest indicates otherwise. Silviculturalists need to remember that a noncommercial species today may fetch a high price tomorrow and that today's weed may be tomorrow's wonder crop.

Complicating the challenges faced by tropical silviculturalists is increased awareness of the importance of stand history in determining stand structure and composition. Radical differences between old-growth forests and young (<50 years old) secondary forests developing after abandonment of agricultural clearings are well known. Less widely recognized are the persisting influences of agricultural interventions even several centuries after abandonment. Given the drastic declines in Amerindian populations after European colonization and similar demographic and cultural upheavals elsewhere in the tropics, history cannot be ignored when silvicultural options are being investigated. Similarly, major natural perturbations, such as windstorms and fires, even if they occur at intervals of centuries, can have lasting effects on forests in which trees can live for several hundred years.

It is widely known that well-managed monospecific plantations of fast-growing trees generally out-yield natural forests by up to a factor of 10. Some proponents of plantation forestry argue that given their high productivity, plantations should be established to reduce pressure on natural forests. Although plantations have a substantial role to play in many tropical countries, this argument is weakened by the fact that the wood produced by trees in natural forests is of a quality unlikely ever to be matched in plantations. Furthermore, given the many non-timber benefits derived from tropical forests (e.g., biodiversity protection, carbon sequestration, hydrological functions), it is not reasonable to compare plantations and natural forests solely on the basis of volume yields. Finally, it is critical to remember that forests are more than trees and should be managed accordingly.

See also: **Biodiversity**: Plant Diversity in Forests. **Ecology**: Natural Disturbance in Forest Environments. **Harvesting**: Forest Operations in the Tropics, Reduced Impact Logging. **Plantation Silviculture**: Tending. **Silviculture**: Managing for Tropical Non-timber Forest Products; Natural Regeneration of Tropical Rain Forests; Natural Stand Regeneration. **Site-Specific Silviculture**: Ecology and Silviculture of Tropical Wetland Forests. **Sustainable Forest Management**: Overview.

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