In Costa Rica, oak (*Quercus*) forest regeneration is pulsed as a consequence of the synchronous life cycle of the *Chusquea* bamboos due to gregarious flowering. The *Chusquea* bamboo normally grows as the understory in the oak forests. In the steady state, the understory *Chusquea* clumps are small because of limited light conditions. If there are fires or gap creation through tree fall, the *Chusquea* rapidly responds to the increased availability of light, and grows up to become the local dominant species with a closed canopy under which saplings of trees now grow in a suppressed state because of the low light conditions under the bamboo canopy. When the *Chusquea* flowers gregariously and dies, the forest floor is more illuminated, and the already established suppressed saplings shoot up. The new generation of bamboo then grows under the newly formed tree canopy.

Bamboos in Fire-Disturbed Lands

Bamboos are one community that colonizes disturbed lands in the tropics especially after fire, because of its well-developed underground rhizome system. The widespread distribution of *Melocanna baccifera* throughout eastern India, Bangladesh, northern Myanmar, and Thailand and of species of *Thyrsostachys* in Thailand and *Schizostachyum* in Vietnam mainly occurs as secondary vegetation due to the destruction of tropical rainforest by fire, shifting cultivation, and logging.

As a result of shifting agriculture, huge expanses of bamboo forests have been established in Asia. In northeast India, bamboos constitute the major vegetation after slash-and-burn agriculture, and due to their adaptability and nutrient conservational role, they play a special role in succession. Shortening of the cycle when the bamboos are still the dominant species largely results in the reduction and often elimination of tree species, such that the fire-tolerant bamboos that survive through the underground rhizomes become the permanent dominant species. Repeated firing over short cycles results in almost pure stands of bamboo over vast areas in the hills. While shrubs and trees tend to grow more slowly, the competitive bamboos have rapid rates of dry matter production, continuous stem extension and leaf production during the growing period, and rapid phenotypic adjustments in leaf area and shoot morphology in response to shade. The competitive bamboos also store more nitrogen, phosphorus, and potassium than stress-tolerant shrubs and trees while the reverse is true for calcium and magnesium. Overall it is seen that bamboos follow a strategy of faster uptake and storage of essential elements and a quicker turnover to supplement the soil fluxes, thus efficiently dominating the stress-tolerant shrubs and tree species for a long duration. Overall, bamboos promote stability in the ecosystem through regulation of its functions like other competitive early successional species.

See also: **Tropical Ecosystems**: Bamboos, Palms and Rattans. **Tropical Forests**: Tropical Dry Forests; Tropical Moist Forests; Tropical Montane Forests.

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Natural Stand Regeneration

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Introduction

There are two possible methods of forest stand establishment, namely natural and artificial regeneration. The process of natural regeneration involves the renewal of forests by means of self-sown seeds, root suckers, or coppicing. In natural forests, conifers rely almost entirely on regeneration through seed. Most of the broadleaves, however, are able to regenerate by means of the emergence of shoots from stumps (coppice) and broken stems. This type of forest reestablishment has obviously been important in temperate natural forests, as well as in tropical forests. A few broadleaves, such as aspen (*Populus tremula)*, Oriental plane (*Platanus orientalis*), and Oriental beech (*Fagus orientalis)*, can regenerate from root suckers, if their roots have been injured. Vegetative reproduction by means of sprouts and suckers merely renews the aboveground parts of plants and the old roots remain. Strictly speaking only sexual reproduction from seeds that results in a total natural renewal of the stand can be defined as regeneration.

In Europe regeneration by natural distribution of seeds was the standard means of forest renewal for thousands of years until overexploitation, in combination with intensive grazing, which has taken place since the late Middle Ages, led to a gradual depletion of the forests and severely inhibited regrowth. At the beginning of the nineteenth century, extensive afforestation took place in Central Europe by means of sowing and planting, predominantly with conifers. Since then, natural regeneration has been limited to the renewal of beech (*Fagus sylvatica*) and its main associates, such as ash *(Fraxinus excelsior*), sycamore (*Acer pseudoplatanus*), and wild cherry (*Prunus avium*).

At the end of the nineteenth century, however, an early back-to-nature movement brought about an increasing interest in the natural regeneration of managed forests, and the creation of a variety of silvicultural systems such as shelterwood strip, strip and group, and wedge system. Most of these systems were geared towards the creation of favorable ecological conditions for the production and germination of seeds, as well as adequate growing conditions for seedlings and saplings. The new ecological movement towards nature-orientated, nature-based, or seminatural silviculture and forestry, which began in the 1980s, has once again revived an interest in natural regeneration.

Planting nevertheless will remain the dominant regeneration method for various reasons, such as the conversion of species, the need for suitable provenances and ease of operation.

Nature-orientated forestry is based on the adaptation of natural dynamics as much as possible, and mimics natural regeneration processes in particular.

Therefore, it is necessary to highlight some of the ecological factors essential to the regeneration process in natural forests, before natural regeneration in naturally managed forests can be discussed.

Natural Regeneration in Natural Forests

Regeneration in natural forests is very much influenced by abiotic stress conditions, such as drought, or catastrophic events like fires, storms, snow, and ice (**Figures 1** and **2**).

On sites with medium to good nutrient and water supplies, the following situations are possible:

- Landslides, fires, and floods create large bare areas, which are colonized by the seeds of pioneer species distributed by the wind, including poplars, willows, and birches. According to succession models, this initial forest cover acts as a nurse crop, improving soil and ecological conditions, paving the way for intermediate successional stage species such as Norway spruce (*Picea abies*) and sycamore (**Figures 3** and **4**). These intermediate species will in turn gradually be replaced by shade tolerant species such as hornbeam (*Carpinus betulus*), beech, and silver fir (*Abies alba*).
- On storm-felled stands, a mixture of pioneer and late successional species may develop together, if advance regeneration already exists beneath the original stand, which is usually the case.

Figure 1 Small-scale storm damage from 1999 in the natural beech dominated forest Suserup, Denmark, which has not been managed since about 1850.

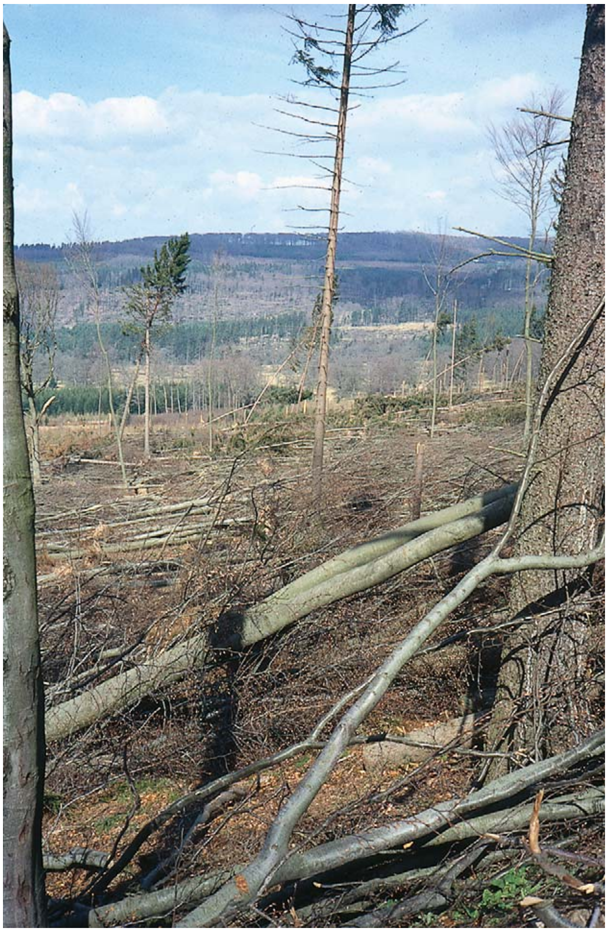

Figure 2 Large-scale storm damage from 1990 in beech/ Norway spruce stands (Sobernheim, Germany).

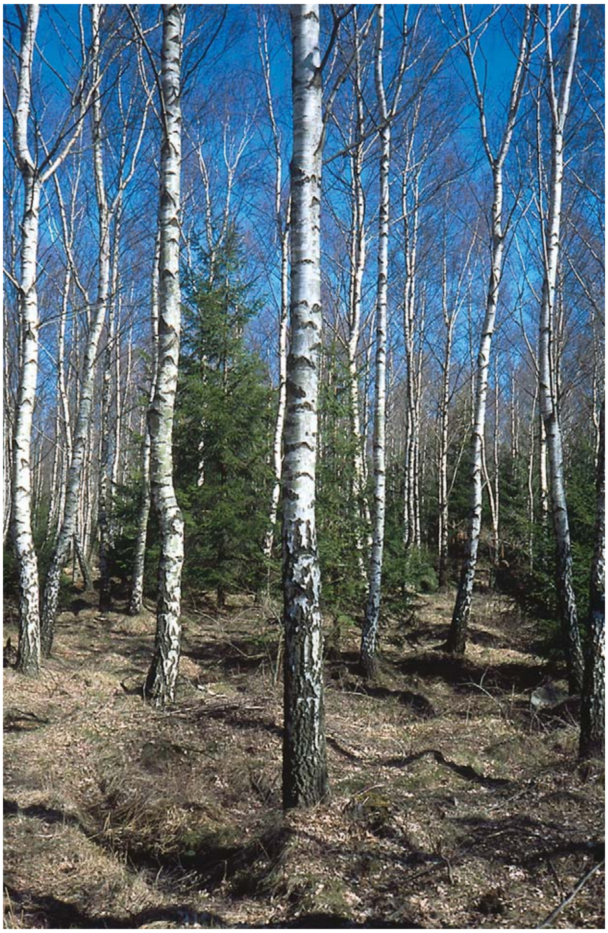

Figure 4 Birch acting as a nurse crop for Norway spruce (South Sweden).

Figure 3 Natural regeneration of birch, Scots pine and a few oaks in a 1985 storm-damaged area which does not need much enrichment (Hesse, Germany).

- In the absence of the above situations, smaller gaps are created by individual old trees gradually dying. These smaller gaps provide conditions under which shade-tolerant species, such as beech, silver fir (*Abies alba*), and yew (*Taxus baccata*) can develop, rising up through the canopy and eventually filling the gaps.

On extreme sites (very dry, wet, or cold), however, these general successional trends do not reach any definitive climax stage, as only stress tolerant species are able to grow on them.

Tree species employ different strategies in order to colonize ground effectively. Some of the more important characteristics of a number of selected species are illustrated in **Table 1**.

Flowering

Flowering begins early in the very light demanding pioneers and decades later for most of the shade-tolerant species. Not all species, however, follow this strategy, e.g., hornbeam flowers relatively early. Pioneers usually flower on an almost annual basis. In the case of intermediate and late successional species in particular, flowering is induced by the weather conditions of the preceding summer, and possibly even two growing seasons earlier. This has only recently been discovered for beech. Dominant individuals with large crowns begin flowering earlier and flower more abundantly.

Seed Production

Seed production requires favorable weather conditions during flowering and the development of seeds, as well as the absence of damaging insects. Pioneers, in general, produce more and lighter seeds. Only the oaks (*Quercus* spp.) do not follow this rule. Storage conditions become important immediately after ripening of the seeds. These are usually released from the tree, distributed by wind or animals and deposited on the ground, where they can germinate. Once on the ground, seeds are subject to predation by mammals, birds and insects, as well as fungal attack. Seed survival rates are higher on mineral soils after uprooting of trees by storm. Survival rates are even higher when seeds are buried in the soil, for example by wild boars (*Sus scofra*), 'sown' by jays (*Garrulus glandarius*) or stored in the soil by mice. Therefore, storage conditions are important in determining the proportion of seeds that eventually germinate.

Germination

Germination of the seeds of pioneer species begins immediately upon deposition on the ground. Pioneer seeds have no nutrient reserves and require subsoil conditions that permit easy penetration and access to water, such as mineral soils. The seeds of most other species have a chilling requirement and only germinate after winter has ended and the conditions are again suitable for seedlings to grow. Such seeds exhibit a period of dormancy, which is broken by a change of temperature. Oak again is an exception. Provided that temperatures are adequate in late autumn, the acorns generally develop a radicle, in order to secure a supply of water.

Germination is induced by an adequate temperature and humidity. In contrast to some species in the tropics light is not necessary for the first phases of germination of the species in the temperate zones. Direct light becomes essential once the cotyledons have spread and photosynthesis starts.

Following germination, the further development of the seedlings is very much dependant on the following ecological conditions:

- The water supply becomes a vital factor shortly after germination. Seeds that have germinated in

Table 1 Seed production strategies of some representative tree species

Species	*Light requirement*	*Succession type*	*Beginning of seed production (age in years)*	*Weight of seeds (mg)*	*Agent of seed dispersal*
Populus tremula		Pioneer	10–15	<0.2	Wind
Betula pendula	Very light demanding		10–15	0.2	
Pinus sylvestris			15–20	6	
Fraxinus excelsior			20–30	56	
Quercus petraea		Long-lived pioneer	40–50	3030	Birds, rodents
Acer pseudoplatanus	Light demanding		15–25	125	Wind
Picea abies	Intermediate		30–40	8	
Carpinus betulus	Shade-tolerant	Late successional species	15–20	33	
Fagus sylvatica	Very shade tolerant		40–50	192	Birds, rodents
Abies alba			40–60	44	Wind

leaf litter or needles regularly die during dry periods, which are particularly frequent in European regions with a continentally influenced climate. In mountainous areas, a maritime climate usually prevails and regeneration tends to be more successful. Seedlings on mineral soils tend to suffer fewer losses, as their roots can extend into the lower soil horizons and the water supply. Decayed coarse woody debris acts as a sponge, making it a perfect substrate for seedlings to grow on and is of great relevance in natural forests. Norway spruce, in particular, profits from the presence of dead wood (**Figure 5**).

- The further development of the young trees is subject to the light conditions. In open areas, light-demanding pioneers are highly competitive in the early decades because of their fast growth and will dominate the stands at the establishment stage. Under the shelter of old trees, however, the shade tolerance of the seedlings will determine their ability to survive. Even young shade-tolerant plants die if the canopy remains closed, however. The greater the nutrient reserves stored in the seed, the longer a seedling will be able to endure in a waiting position.
- Various biotic stress factors may decimate the seedlings from the moment of germination. They can become infected by fungi. Mice, birds, and snails often reduce the numbers sharply (**Figure 6**). Saplings are very susceptible to browsing and bark peeling by larger mammals, such as roe deer (*Capreolus capreolus*) and red deer (*Cervus elaphus*) (**Figures 7** and **8**). Under the natural conditions prevalent in times past, the density of these animals was probably not very high and browsing pressure not too severe. There is, however, intense debate over the ecological impact of megaherbivores on the forest cover prior to large-scale interference by humans.

Figure 5 Regeneration of Norway spruce seedlings on coarse woody debris (North Sweden).

As a general conclusion the natural regeneration of natural forests is steered by a great variety of abiotic and biotic factors, and their interactions. Undoubtedly, natural forests exhibit a high degree of site adaptation. The characteristics of a forest type will mirror the prevailing site factors, such as climate and soils. Additionally, the soil mosaic often leads to a further differentiation of the tree species distribution. The aforementioned ‘catastrophes’ may pave the way for the early stages of pioneer forests, which will evolve towards later successional stages over the course of centuries. In many cases, a form of climax forest may never be achieved, as the process is set back by further catastrophes. Even in the climax phases the species composition may vary purely as a result of chance, depending on, for example, which species produces seed in a given year and develops on a certain spot in the forest, whereas in another year a different species may have regenerated and conquered the available space.

Figure 6 Bark peeling by voles destroying beech seedlings and saplings (Zwiefalten, Southwest Germany).

Figure 7 Browsing by red deer heavily affecting the growth of young beech (Kempfeld, Germany).

All successional models, therefore, only show a general direction leading to later stages of development.

Natural Regeneration in Managed Forests

The management of forests generally aims towards production and/or service goals. This is never the case for purely natural forests, however. Nature-based silviculture seeks to make use of natural forest dynamics to as great a degree as possible, to meet both ecological and economic targets, yet aims to avoid or minimize the disadvantages.

There are several reasons both for and against the practical application of natural regeneration as a means of stand establishment (**Table 2**).

Although some of the advantages of natural regeneration are very appealing, many of the disadvantages provide serious practical obstacles to large-scale natural regeneration (**Figure 9**). Included in the disadvantages are a lack of experience, shortage of qualified and motivated personnel and, of course, impatience – the greatest problem in forestry.

Preconditions

Apart from the sociological and organizational constraints mentioned above, some preconditions must also be met in order to make use of natural regeneration processes.

During the afforestation period of the last two centuries in Europe, which continues to this day,

Figure 8 Browsing of Norway spruce by roe deer. The saplings start to grow normally as soon as they exceed the browsing height (Grafing, Germany).

Table 2 Arguments for and against using natural regeneration in practice

	Comments
Arguments for	
Preservation of site-adapted autochthonous populations	Reduced risk of receiving the wrong provenances from private nurseries.
High degree of adaptation of young plants to the site mosaic	Effective use of microsite differences by the species in mixed stands.
Undisturbed growth of young plants	Development of a regular root system; no deformations following planting, a particular problem on heavy soils.
Saving on high investment costs of plant material and planting procedures	Remarkable savings can be made in the establishment phase. Natural regeneration may require spending on site preparation and fencing, however.
Possible production of wildlings	Uses of site adapted wildlings for: • filling in incomplete young stands • transfer of plants to other regeneration areas • production of transplants in the nursery.
Increased number of potential crop trees for selection at later tending phases	Good sapling quality due to the high density of individuals and the intensive natural differentiation in the young stands; often results in savings on tending costs.
Arguments against	
Dependence on seed production and volume of seeds produced	Requires economic flexibility on the part of forest enterprises because of the irregularity of mast years
Irregular densities of natural regrowth and additional costs of filling in	Risk of reduced sapling quality, especially bordering on gaps. Necessity of filling in gaps in certain areas and of lowering the densities at other places. Difficulties of surveying naturally regenerated young stands, resulting in improper tending measures.
Greater risk to seedlings and saplings	Extended period of exposure to fungi, insects, birds, rodents, and game, especially in the seedling phase, not to mention increased competition with ground vegetation.
Technical problems involved in felling old trees over regrowth	Natural regeneration mainly takes place under the shelter of old trees. The several cuttings necessary to remove the old trees result in damage during harvesting and extraction procedures. Removal of damaged individuals is necessary.
Extended tending efforts/expenditure in the thicket/pole stage	The following measures, not required in the case of plantations, are necessary for the: • reduction of high plant densities • correction of stocking irregularities • elimination of excessively vigorous and coarse trees (wolves) • elimination of unwanted mixture trees.
Extended duration of the regeneration period	The length of time between seed production and the end of the tending process is normally much longer than in plantations. This presents problems of continuity for forest enterprises.

Figure 9 Natural regeneration of different species often early needs tending procedures.

conifers, in particular, have often been planted on the wrong sites. Unfortunately, some of them now regenerate freely and have to be removed at great expense. One of the most important examples of this is the natural regeneration of Norway spruce on compacted soils, with anaerobic subsoil conditions, for example, pseudogleys. Such stands are often prone to storm damage (**Figures 10** and **11**). To avoid further species selection mistakes, a site classification survey would prove to be an invaluable source of basic information.

The use of unsuitable provenances in years gone by, due to a lack of knowledge of the importance of genetically adapted plant material, with respect to abiotic and biotic site factors, would appear to be just as serious a problem. Conifer provenances such as Norway spruce from the lowlands have been planted at high elevations, where they are susceptible to ice and snow break (**Figure 12**), and Scots pine (*Pinus sylvestris*) and European larch (*Larix decidua*) transferred from continentally influenced regions into maritime areas suffer from fungal attacks.

Significantly fewer mistakes have been made with broadleaves because of their lower economic value.

Figure 10 Norway spruce with a flat root system on a shallow pseudogley soil after having been uprooted by a storm (Schaidt, Germany).

Figure 12 Norway spruce from the lowlands suffering from storm, ice, and snow at high elevations (Freiburg, Germany).

Figure 11 Beech, also with a flat root system, uprooted by storm on a pseudogley (Schaidt, Germany).

In order to be successful, it is important, therefore, that there is an adequate distribution of site-adapted tree species in the forest stand to be regenerated, or in its vicinity.

Active Promotion of Natural Processes

In order to minimize the disadvantages and the problems associated with natural regeneration, the following procedures may be helpful and are used in practice.

Promoting seed production As has already been mentioned, some pioneer species flower annually. Most other trees, however, flower irregularly. Their seed production is highly dependent on the prevailing climatic conditions, as well as conditions in the preceding years, and cannot, therefore, be influenced by the forester. However, vigorous dominant trees with large crowns and sufficient growing space begin to flower earlier, and they do so more frequently and more intensively. Early and continued crown thinning will improve seed production effectively and sustainably, but requires continuity and a great deal of staying-power. Often thinnings are neglected, especially in the case of most broadleaves (**Figure 13**).

It has been shown, however, that dominant individuals of certain species, including beech and oak, increase seed production when their crowns receive more light. This is true even after very late crown thinning. The process of natural regeneration, therefore, normally begins a few years in advance of seed production, with an intensive crown thinning of the dominant individuals in the stand.

Influencing tree species proportion Tree species distribution and proportion can be influenced using the following procedures.

Choice of an appropriate silvicultural system Silvicultural systems are geared towards creating favorable ecological conditions for particular species, depending on its demands (**Figures 14–16**). Ensuring protection against the main wind direction, as well as providing an infrastructure for felling and extraction, with an adequate road and timber extraction line system, are further components.

Some silvicultural systems are listed in **Table 3**, according to the ecological needs of the respective tree species.

Generally, natural regeneration of intermediate and late successional species is more important in Central Europe. Therefore, stronger emphasis is laid on these systems compared with regeneration of light demanding species on bare land.

Choice of mast year Flowering and fruit development can be observed and inventoried during the growing season. In a mast year, natural regeneration is usually initiated by opening the canopy slightly and, if necessary, preparing the soil. If the sheltering stands, or those nearby, contain the desired species, the initial procedures can begin once the trees start to produce seed.

Regulating the light regime In the event of two or more tree species germinating, with each likely to establish themselves, it is possible to manipulate their proportions by regulating the light regime within the

Figure 13 Poorly thinned beech with very small crowns will not be able to produce seeds later on (Tuttlingen, Germany).

Figure 14 A relatively open uniform shelterwood stand enables young Scots pine to grow in the initial years but has to be removed fairly early to allow sufficient light to reach the young growth (North Sweden).

Figure 15 Beech being regenerated in the group shelter system, protected for many years against late frost and drought (Kelheim, Germany).

forest stand. This is done by varying the intensity of cuttings. Under the canopy of old trees the suppression of young growth of light-demanding species is possible. The seedlings may even disappear because of a lack of light. On bare ground or in larger gaps this problem will not arise, however. The mixed montane forests common in Central Europe provide a good example of the way of regulating the light conditions according to the needs of the species. These forests consist mainly of three species: silver fir, beech, and Norway spruce. Very gradual, light shelterwood cuttings will maintain relatively dark conditions within the stand, which results in the dominance of the very shade-tolerant silver fir. Larger openings favor beech. More dramatic openings in the canopy are required in order to promote Norway spruce (**Table 4**). To increase the proportion of sycamore, a further component of these mixed montane forests, gaps must be made and enlarged further after a few years.

Figure 16 Silver fir and Norway spruce saplings naturally regenerated in a group shelterwood stand (Kelheim, Germany).

Table 3 Main silvicultural systems with regard to the ecological requirements of forest tree species

Silvicultural system	*Size of opening*		*Ecological type*	*Tree species[a] (examples)*	*Comments*
Clear-cut	Large	> 5 ha	Pioneer	*Betula* spp., *Populus* spp., *Alnus* spp., *Salix* spp.	No practical importance in Central Europe
	Small–medium	0.5 – 5 ha		*Pinus sylvestris*, *Larix decidua*	Common traditionally
Gap/strip felling	Small	0.05–0.5 ha < 100 m wide	Intermediate	*Picea abies*, *Fraxinus excelsior*, *Acer pseudoplatanus*, *A. platanoides*, *A. campestre*, *Quercus petraea*, *Q. robur*, *Prunus avium* (*Pinus sylvestris*)	Shelterwood system important traditionally. Transition to small-scale free mixture of the three adjacent systems becoming increasingly important.
Uniform shelterwood		Regular crown openings in large stands	Intermediate/ late successional	*Fagus sylvatica*, (*Quercus petraea*), *Tilia* spp., *Carpinus betulus*	The speed with which the crown cover is opened can be adapted to suit the demands of the species.
Group shelterwood; combination of shelter and strips		Groups of > 30 m in diameter	Late successional	*Abies alba*, *Fagus sylvatica*, *Picea abies*	Beech should be kept under shelter for 15–20 years, oak for only 5 years.
Selection		Single tree removal		*Abies alba* (*Fagus sylvatica*)	Special site conditions necessary, therefore restricted to specific areas.

[a] Tree names in brackets indicate species of minor importance within the system mentioned.

Another important example is beech, with its many potential admixed tree species. Beech will outcompete almost every other species, including oak (*Quercus petraea* and *Q. robur*), ash, and sycamore, if the canopy is not opened following the initial stand establishment phases. The only exceptions are even more shade-tolerant species, such as yew and silver fir. This has proven to be a very common problem.

Of course, it is important to bear in mind that, flexibility with regard to varying the tree species

Table 4 Effect of the rate of opening of canopy on the species distribution of the regrowth. The regeneration period begins when the initial openings of the canopy are made in order to encourage the development of seedlings and ends when the last tree is removed

Rate of progression of shelterwood treatments		*Dominance of species*	
Very slow	$>$50 years	Silver fir	*Abies alba*
Slow	$\sim$25 years	Beech	*Fagus silvatica*
Frequent and gentle	$\sim$15 years	Norway spruce	*Picea abies*
Cutting gaps and enlargement	$\sim$5 years	Sycamore	*Acer pseudoplatanus*

Table 5 Silvicultural means of improving conditions for the storage of seeds in the forest floor, for germination, and for the first phases of establishment

Procedure	*Specification*	*Description of procedure*	*Comments*
Conversion of surface layers not conducive to natural regeneration	Opening of the canopy in order to stimulate soil activity by improving the temperature and water supply	Removal of all individuals that create heavy shade and intercept precipitation, i.e., dominant trees with large crowns, as well as intermediate and suppressed trees	Common starting procedure of many silvicultural systems. Slow, long-term response. Possible development of competing ground vegetation if employed too rigidly.
	Soil preparation to promote soil activity	Breaking up the uppermost organic soil layers and mixing with mineral soil	Necessary in areas with thick raw humus layers or inhibited mineralization.
	Mineral fertilization to promote soil activity	Distribution of limestone dust or compound fertilizer across the whole area; occasionally combined with opening of the canopy and soil preparation	On poor or acid soils, this is only to be recommended if carried out several years in advance of the start of regeneration. Promotes the development of nutrient demanding species, as well as increment growth of the old trees.
Removal of surface layers not conducive to natural regeneration	Exposing mineral soil by removing surface layers in strips or patches (Figs 18 + 19)	Use of small tractors with soil preparation fittings	Important means of improving the germination rate, especially of beech and Scots pine. Growing concerns over soil compaction as a result of driving in the stands. Increasing importance as a measure for mitigating soil acidification.
	Burning of surface layers	Mainly the result of accidental forest fires; controlled burning also possible	Improves establishment conditions, especially for pioneers. Mostly in dry areas, with increasing importance worldwide.
Removal of competing ground vegetation	Removal of ground vegetation in strips or patches prior to germination	Use of small tractors with fitted weeding equipment	Gaining importance with increasing problems with the development of grass cover.
		Herbicides	More and more herbicides have been banned as a result of environmental/ecological concerns.

composition is only possible if the desired species have regenerated naturally.

Improving the seed storage, germination and early development conditions of the young plants In managed forests, the soil surface often fails to provide favorable conditions for storage, germination, and plant establishment. This is true of 'normal' conditions, as well as special climatic situations, which arise only periodically. There are frequently neither sufficient volumes of coarse woody debris nor large enough areas of mineral soil to support the regeneration process. It may, therefore, be necessary to promote it by employing one or a combination of the procedures mentioned in **Table 5**. These measures are very much specific to each site, however (**Figures 17–19**).

The following developments have taken place in Central Europe in the last two to three decades, with regard to the procedures mentioned in **Table 5**:

- The intensification of thinnings has led to better crown development in the stands of a number of forest enterprises. Preparatory fellings have tended to become less important in certain areas.

- During the last two decades, an increase in seed production has been very obvious for most tree species. Therefore, foresters no longer rely on isolated mast years, as in the past.
- Soils have recovered remarkably from centuries of overuse in the production of timber and firewood, as well as litter extraction. Raw humus layers have become rare. To date, nitrogen inputs from pollution (NH_4 from agriculture and NO_X mainly from traffic) have had an advantageous effect, in spite of increasing acidification. The necessity of soil preparation has, therefore, decreased in some areas.
- Compensatory fertilizing has been used widely as a means of combating acidification. A side effect of this is that, more demanding species are favored in the regeneration process.

Figure 17 Scarification of the soil to improve soil activity and promote natural regeneration (Fuhrberg, Germany).

Figure 19 Mineral soil allows for improved germination of Scots pine (North Sweden).

Figure 18 Line plowing to promote Scots pine regeneration (Sellhorn, Germany).

- Ground vegetation has evidently profited greatly from the rehabilitation of soils and nitrogen inputs, seriously impeding natural regeneration in many places. The problematic species include grasses, such as *Calamagrostis epigejos* and *C. villosa*, *Avellana flexuosa*, *Carex brizoides*, as well as climbers and shrubs including *Rubus fruticosus*, *R. idaeus*, *Clematis vitalba* and *Prunus serotina*. This tendency appears set to continue (**Figures 20** and **21**).

Minimizing biotic damage Seeds, seedlings, and young plants are very prone to damage caused by snails, rodents and game. Snails feed on seedlings shortly after germination, but will not harm them after the woody tissue has formed. Snails profit from the humid conditions under the shelter of the canopy.

Mice (Microtinae) live in grass cover and prefer warm open areas. They feed on the bark of hardwood saplings and are able to destroy whole groups of them up to the thicket stage. Regeneration under

Figure 20 Grasses (in this case *Calamagrostis epigeios)* increasingly cover large areas and are a serious obstacle to natural regeneration (Berlin, Germany).

Figure 21 Bramble (*Rubus fruticosus)* profits from nitrogen input as well as the recovery of soils, and increasingly competes with young forest plants (Saxony, Germany).

the canopy normally brings about a decline in the ground vegetation, resulting in the loss of their habitat. Unfortunately, keeping the canopy closed for a longer period of time is not possible in many stands. This also requires long-term planning and will favor shade-tolerant species, such as beech.

Game, the omnipresent roe deer, in particular, but also red deer, fallow deer (*Cervus dama*), and some other locally distributed species, such as mouflon (*Ovis ammon musimon*) and chamois (*Rupicapra rupicapra*), are the greatest hazard to young plants. Broadleaves are especially susceptible. Roe deer, for example, prefers rare species such as occasional hardwoods in conifers as well as specific hardwoods like ash and sycamore in beech. Some of these trees have become almost extinct in certain areas because of the high browsing and debarking pressure, and damage caused by fraying. In general, there has been a widespread decline in the species mix and a tendency towards conifer monocultures. As the hunting lobby in almost all countries of the temperate zones has succeeded in resisting a

Figure 22 Fencing in order to promote growth, especially of endangered broadleaves, is often inevitable – and very expensive.

Figure 23 Individual tree protection as a possible method for the promotion of a small number of endangered plants.

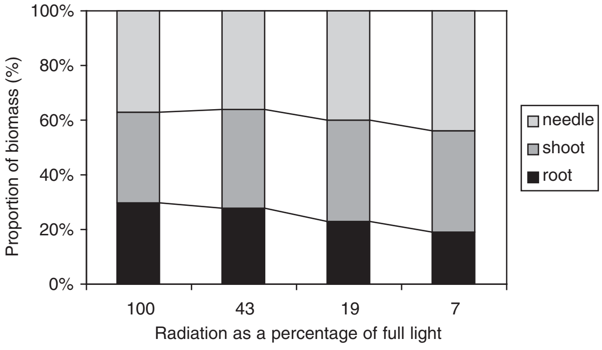

Figure 24 The change in biomass proportion (%) of needles, shoots, and roots of 4-year-old Norway spruce (*Picea abies*), after growing three years in a shading experiment. Apart from the general reduction of biomass, the additional reduction of the root biomass was disproportionately great. Young plants may, therefore, be greatly endangered in the event of water stress and often die in dry periods. (From Huss J 1971 *Untersuchungen über die Wirkung von Beschattung und Düngung auf das Wachstum junger Fichten*. Habilitation thesis, University of Göttingen, Germany.)

reasonable reduction of the high game stocks, fencing or single tree protection is the likely means of protection in many cases (**Figures 22** and **23**).

Securing a species mixture The canopy of an old stand provides shelter against late and early frosts, high temperatures, and desiccation. The regeneration of shade-tolerant tree species susceptible to these climatic stresses therefore normally takes place under the shelter of the old trees. The longer the regrowth is kept under shelter, however, the greater the likelihood of not only the light-demanding components of the mixture of trees dying or being overgrown, but also the risk of the shade-tolerant species suffering as a result of the low irradiation. Unlike in the tropics, all tree species found in Europe exhibit the greatest biomass production under full light. Under a closed canopy, biomass production and growth in diameter and height are reduced. For instance the biomass production of young Norway spruce was reduced to less than 10% when the global radiation was only 7%. Moreover biomass allocation (**Figure 24**), as well as stem and crown form, may also be affected **Figure 25**. The degree of canopy closure is regulated according to the development phase of the young plants (**Figure 26**).

Combining and optimizing all the different possible effects and goals of management, such as excluding ecological stress conditions on the one hand, and regulating growth and the species mix on the other, is a great challenge for the forester.

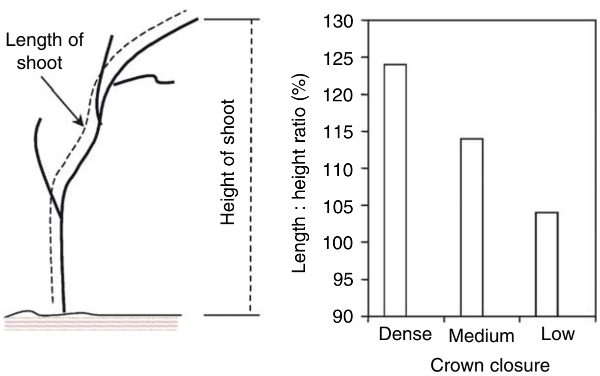

Figure 25 Changes to the stem form of beech wildings (*Fagus sylvatica*) after 9 years growing under the shelter of differentially thinned 55-year-old Norway spruce (*Pinus abies*). The 1–3-m high beech saplings show significant differences in the degree of bending, depending on the density of the canopy, as influenced by the thinning variation. Saplings in deep shade are bent to a much greater extent, and are less stable because their slim stems are more susceptible to snow damage, or even heavy rain.

The Future Role of Natural Regeneration in Forest Practice

It has been shown that the rehabilitation of the soil, as well as increased seed production rates, have improved the potential for natural regeneration over recent decades. The main obstacle to an increase in the use of natural regeneration, however, remains high game densities. There are some examples in Germany where the deer population has been successfully reduced, resulting in an overwhelming

Figure 26 Seedlings and saplings (here Norway spruce) show uneven growth according to varying light conditions in unevenly opened canopy (Gaildorf, Germany).

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.

Further Reading

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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).