reclamation project, understood, and then adhered to. There are many stages in the reclamation process, and failure at any of them will compromise forest performance. Effective management is therefore essential.

See also: **Afforestation**: Species Choice. **Landscape and Planning**: Forest Amenity Planning Approaches. **Site-Specific Silviculture**: Silviculture in Polluted Areas. **Social and Collaborative Forestry**: Social and Community Forestry. **Soil Development and Properties**: Nutrient Cycling. **Temperate Ecosystems**: Alders, Birches and Willows. **Tree Physiology**: A Whole Tree Perspective.

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Silviculture in Mountain Forests

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Mountain Forests are of Global Importance

What is a mountain forest? Definitions are, to a certain extent, arbitrary. Defining criteria usually include altitude, slope, and local elevation range (**Table 1**). Thus, steep mountain forests can also occur in the lowlands. Mountain regions cover 24% of the earth's land surface and contain 28% of the world's closed forests. Fifty-five percent of these mountain forests occur below altitudes of 1000 m above sea level. Mountain forests are found in areas with tropical, subtropical, temperate, and boreal climates. While only one in 10 people live in mountain regions, what happens in these regions affects many more people living in the lowlands. For example, deforestation in mountain forests may have an impact on climates and contribute to flooding in lower regions. Mountain forests are therefore globally important.

Rather than adopting a definition based on arbitrarily chosen ranges of altitude and slope, we take a silvicultural perspective in this article. Our focus is on those forests that require specific silvicultural treatments due to particular characteristics, or because they provide forest products and services associated with high altitudes and/or steep slopes. We therefore exclude, e.g., forests on flat highlands that are primarily used for timber production. We also exclude mountain forests in nature reserves since these are not silviculturally treated.

We first describe the characteristics of mountain forests, and then outline the silvicultural systems used in them. Since our areas of expertise focus on temperate mountain forests of the northern hemisphere, this article makes most reference to this forest type.

Mountain Forests are Different from Lowland Forests

Mountain forests of the montane and subalpine zones differ from lowland forests with regard to physical

Table 1 Areas (km^2) of mountain forest types in different mountain classes

Forest type according to altitude, slope, and elevation range	*≥ 4500 m*	*3500–4500 m*	*2500–3500 m*	*1500–2500 m and slope ≥ 2°*	*1000–1500 m and slope ≥ 5° or local elevation range > 300 m*	*300–1000 m and local elevation range > 300 m*	*Total*	*%*
Tropical (and subtropical) moist forests	19 359	83 597	139 607	399 656	482 061	1 197 610	2 321 890	24.5
Tropical (and subtropical) dry forests	183	15 054	35 293	50 565	107 267	343 390	551 752	5.8
Temperate and boreal evergreen conifer forests	2008	22 954	151 809	547 984	788 684	1 377 105	2 890 544	30.5
Temperate and boreal deciduous conifer forests			1241	76 209	313 908	985 600	1 376 958	14.5
Temperate and boreal deciduous broadleaf and mixed forests	1713	19 832	122 858	476 865	441 055	1 275 723	2 338 046	24.7
Total	23 263	141 437	450 808	1 551 279	2 132 975	5 179 428	9 479 190	100
%	0.2	1.5	4.8	16.4	22.5	54.6	100	

Reproduced with permission from Kapos V, Rhind J, Edwards M, *et al.* (2000) In: Price MN and Butt N (eds) *Forests in Sustainable Mountain Development. A State of Knowledge Report for 2000.* IUFRO Research Series 5. Oxford, UK: CABI Publishing http://www.wcmc.org.uk/habitats/mountains/statistics/htm.

conditions, species composition, stand structure, disturbance regimes, and the products and services they provide. Forest management must take into account the characteristics of mountain forests and the fact that the range of silvicultural options becomes smaller with increasing altitude or steepness.

Physical Environment of Mountain Forests

Many mountain forests at lower elevations are among the most productive in the world. However, the physical conditions of mountains change and usually deteriorate with increasing altitude. Mountains are exposed to excessive solar radiation. At 1800 m above sea level solar radiation is doubled compared to sea level. In contrast to lower altitudes, soil and vegetation absorb most heat from direct insolation, not from warm air currents. Wind speeds increase, and between 500 and 2500 m above sea level precipitations increase by about 100 mm per 100 m. Moreover, soil and air temperatures decrease, in the case of air temperature by about 0.55°C per 100 m in the free atmosphere. Precipitations fall partly as snow, and the duration of the snow cover increases by about 10 days per 100 m. Correspondingly, the growing seasons are shorter (about 1 week per 100 m), especially for young trees covered by snow. Tree growth is slow, seed production rare, and seedling establishment threatened by browsing ungulates, pathogenic fungi, snow movement, and climatic injuries. A unique feature of mountains is the Foehn, a frequent strong, warm, dry, falling wind, which in some regions can raise the temperature considerably above the usual values, but also cause severe windthrows.

On steep terrain in higher altitudes pronounced variations in slope and aspect give rise to steep gradients in site factors and a high variability in mesoclimate and small-scale microhabitat patterns. Here surface erosion and rockfalls may have considerable impact on the forest and vice versa.

The harsher climate at higher altitudes affects tree growth and forest dynamics. Snow cover and snow movements, ranging from creeping and gliding to avalanches, damage trees mechanically, and can uproot and kill seedlings. The growth and regeneration dynamics of trees are slowed down, reducing productivity and tree size. Regeneration is often scarce since seed years are infrequent; the harsh climate impedes the reestablishment of trees after logging or natural disturbances, and successful establishment is confined to favorable microsites. Moreover, established seedlings at high altitudes grow slowly and may therefore be potentially affected by competing vegetation, pathogenic fungi, and browsing ungulates for several years or decades.

Timberline

With increasing altitude the trees become gradually smaller. Finally, above the upper or alpine timberline (treeline), regeneration and growth of trees are no longer possible. The timberline can vary from sea level in polar up to about 4500 m in tropical regions. The current location of the timberline can have climatic, orographic, edaphic, or anthropogenic causes. In many parts of the world it has been considerably lowered by human activities, mainly by livestock grazing over the centuries. A variety of factors may locally be responsible for the timberline: low air and soil temperatures, negative CO_2 balance, frost damage, winter desiccation, wind abrasion, short growing season due to long-lasting snow cover, pathogenic fungi, or mechanical damage by moving snow. The transition between the forest and alpine meadows is often not a line but a zigzag ecotone. Trees growing in the timberline ecotone are often restricted to the most favorable microsites and are forced to adjust their growth forms to the respective conditions (e.g., tree islands, flag shape, carpets). Near the timberline many tree species almost exclusively regenerate by layering. In some arid regions of the world, mountain forests not only have an upper, but also a lower timberline, which grades into grasslands.

Species Composition of Mountain Forests

The number of tree species that are able to cope with the increasingly harsh environment at higher altitudes decreases from the montane to the subalpine zone. The lower elevations of the wet tropics are often covered with very complex montane rainforests, whereas the upper parts carry cloud forests, which are extremely rich in endemic species. On the medium and high mountains of the temperate zone and on the high mountains of the tropics needle-bearing genera such as *Abies, Cedrus, Juniperus, Larix, Picea, Pinus, Tsuga,* and *Dacrycarpus* prevail, often accompanied by *Betula* and *Alnus*. In the southern hemisphere the genera *Nothofagus, Libocedrus, Podocarpus, Dacrydium,* and *Eucalyptus* are prominent. Important timberline species in the tropics are *Senecio*, *Polylepis*, and many others. In the subalpine zone, the resulting stands are typically rather poor in species, sometimes even almost monospecific.

Structure of Mountain Forests

The northern coniferous mountain forests at lower and medium altitudes usually have a rather homogeneous stand structure, similar to many lowland forests. Towards the subalpine zone near the timberline, the horizontal stand structure is increasingly open, with single trees or tree clusters alternating with gaps of different sizes (**Figure 1**). The open texture is often accentuated by human activities, such as livestock pasturing or tree cuttings. The upper parts of these forests grade into tree islands and then into the alpine environment above the timberline. Avalanche tracks or screes often interrupt the forest canopy. Open stands have extensive internal margins and green crowns reaching close to the ground. Such forests are referred to as 'mountain selection forests' or 'group selection forests.' However, not all subalpine forests are open. *Nothofagus* forests in the southern hemisphere can form completely closed canopies near the timberline.

Disturbance Regimes in Mountain Forests

Mountain forests are subject to most of the well-known natural disturbance agents, such as fires, wind storms, droughts, insect and pathogen outbreaks (**Figure 2**). Human disturbance occurs as a result of road construction, timber harvesting, fire, or livestock grazing. Some disturbance agents are specific features of high-altitude mountain environments: for example, snow gliding can cause stem deformations, avalanches are capable of destroying whole stands, while rock and ice fall often injure stems or break trees.

The establishment and growth of seedlings and saplings may be hampered by livestock or browsing wild ungulates, by pathogenic fungi developing in the snow pack, or by frost injuries and winter desiccation. These agents may reduce growth or sometimes even kill regeneration established over decades. While mountain forests are not generally less resistant to most disturbance agents than lowland forests, their recovery after disturbance (resilience) becomes increasingly slow the closer the timberline is. This special feature of mountain forests must be considered in any silvicultural operations.

The Value of Mountain Forests

People use forest products and services in a variety of ways: for protection, for cultural and leisure activities, and as sources of timber and food. Some of these are specific to mountain forests.

The protection of the human environment against natural hazards is nowadays often regarded as the most important economic value of forests in mountain regions with high population densities. Most such hazards primarily pose risks on steep slopes, and some occur only at high altitudes. Steep slopes are prone to all sorts of mass movements, such as soil erosion, debris flows, mud- and landslides, rockfall, torrents, and snow avalanches (**Figure 3**). Many mountain forests provide the people or objects of value beneath them with direct protection. The

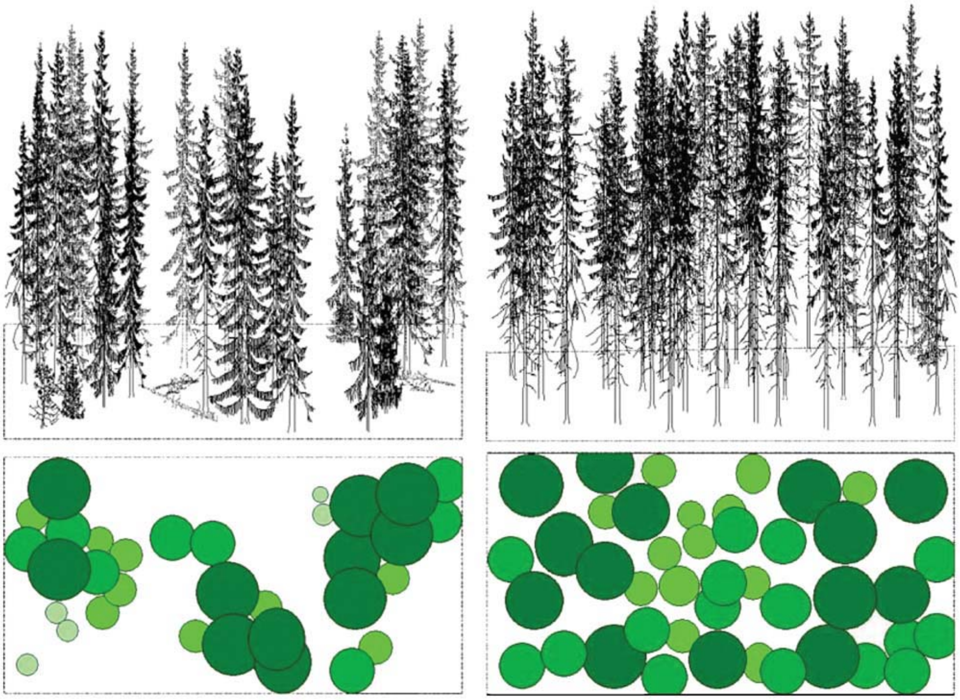

Figure 1 Cluster structure in a natural spruce mountain forest (left) in contrast to the typical uniform and homogeneous structure of a forest originating from afforestation (right). The clustered stand allows enough light and warmth to penetrate to the ground, thus creating good microsites for regeneration. The trees within a cluster maintain a common crown reaching almost to the ground. In the uniform stand there is not enough light for long crowns and forest regeneration. Reproduced with permission from Price MF and Butt (eds) (2000) *Forests in Sustainable Mountain Development. A State of Knowledge Report for 2000*. IUFRO Research Series 5. CABI Publishing.

Figure 2 Windthrow is an important disturbance agent in mountain forests. In protection forests natural hazards, such as rockfall, avalanches, and surface erosion, are matters of concern. Windthrow area near Disentis, Switzerland, caused by the winterstorm Vivian in 1990.

protective effect must be maintained continuously at the stand level, and not just at the landscape scale. If such a stand is destroyed, it must be replaced by expensive technical defense constructions. In direct protection forests the silvicultural options are therefore limited. Other protection forests provide only indirect protection, i.e., their effect is regional or at the scale of a whole landscape. Examples of indirect protection are forests that help to mitigate floods, or forested water catchments that ensure continuing

Figure 3 Mountain forests are capable of preventing natural hazards, in this case avalanche release, and of protecting people and assets. Andermatt, Swiss Alps.

Figure 4 Steep slopes hamper timber harvesting. Cable crane logging is a suitable technology developed for mountain forests. Photo courtesy of F Frutig.

supply of clean water and protect against soil erosion. In such cases, the exact location of the protection forest is not the important factor, but rather the proportion of the area stocked. In indirect protection forests more silvicultural options are available.

Timber production is not easy in mountain forests. Steep slopes and high altitude complicate timber harvesting operations (**Figure 4**). Access to the forests is usually difficult, so that logging is expensive and may be impossible in winter. Road construction is often costly if the roads are not to lead to more landslides. The potential for rationalization is limited in mountain forests. Most harvesting and planting technologies have been developed for lowland forests and cannot be used on steep terrain. But cable crane logging is one technological development that is suitable for harvesting in mountain forests. Another factor is that slow tree growth at high altitudes also means low forest productivity. This makes investing in a permanent infrastructure in mountain forests unattractive. It will only pay off if large enough quantities of timber are harvested; this may be excessive and unsustainable.

In less developed regions mountain people still depend directly on their local forests to satisfy many needs. However, timber production for fuel and construction wood has lost much of its former importance in industrialized regions during recent decades because cheaper fuel and imported timber mean it is no longer economically competitive.

With regard to nontimber products and uses mountain forests perform important functions as wildlife habitats, hunting areas, and livestock pastures. Forest products include fodder from forest trees, forest litter, fruits, mushrooms, fibers, resins, gums, medicinal plants, and agricultural crops in agroforests. These products are of variable importance over the world. In addition, the social, ecological, and amenity functions of forests are becoming increasingly valuable. For example, forests are essential for preserving biodiversity, for nature and soil conservation, for storing CO_2, as sources of fresh water, as recreation areas, and as areas of scenic beauty with spiritual or sacred values. Mountain regions play a special role in providing areas where these services can be performed because many mountain forests are still relatively uninfluenced by human activities.

While all mountain forests are multifunctional and provide several products and services, one function often dominates and guides silvicultural decision-making in a particular case. In some stands, silvicultural operations may not be required since either there is no specific local requirement for forest products or services, or a natural forest development is unlikely to impair the forest's ability to fulfill existing demands.

Silvicultural Systems for Mountain Forests

Historically, many mountain forests have been subject to severe degradation followed by erosion, which has caused loss of soil and site productivity. Large parts of the European Alps, for instance, were destroyed by excessive felling, burning, and grazing, before their restoration during the last 150 years. Most of the bushlands that cover the eroded mountains surrounding the Mediterranean today were once forest. Such silvicultural treatments – or maltreatments – have shaped many forests ('silvae' in Latin), but certainly not in the sense of a 'culture.' And the degradation continues today: silvicultural practices in mountain forests still deviate greatly, in some regions of the world, from recommended practice. Silviculture as a scientific discipline and wide-ranging practice only has a history of about 200 years. During this time several silvicultural systems, i.e., planned series of treatments for tending, harvesting, and reestablishing stands, have been developed for managing forests in a sustainable way.

Silvicultural systems vary in their ability to handle the management constraints in mountain forests. These constraints are related to the steep terrain, difficult forest access, harsh climate, slow tree growth, and natural hazards. Taking these constraints into account is part of a preventive silvicultural practice which strives to avoid costly restoration measures, regardless of whether they are biological (e.g., planting) or technical (e.g., erosion control).

Below we describe those silvicultural systems that are especially important and useful for managing mountain forests and make recommendations for how they should be applied. They include clearcutting, shelterwood, border cutting, selection, and coppice systems. Other systems that can be successfully practiced in mountain forests are agroforestry and variable retention systems (*see* **Silviculture**: Silvicultural Systems).

Clear-Cutting

Clear-cutting is a silvicultural system that removes an entire stand of trees from an area of 1 ha or more, and greater than two tree heights in width, in a single harvesting operation (**Figure 5**). It can be highly profitable. However, its application in mountain forests often involves unacceptable risks, or impairs landscape values.

Clear-cutting mountain forests can initiate erosion processes which may result in a complete loss of the soil. On a regional scale, higher altitudes in mountain areas usually receive higher precipitation. Steep slopes are prone to surface erosion (gullying, rill erosion),

Figure 5 A clear-cut and subsequent planting in Austria. On steep slopes clearcutting may lead to serious erosion problems.

nutrient leaching, landslides, and debris flows. Clear-cutting often contributes to reductions in root strength and soil water-holding capacity, due to soil compaction and reduced transpiration. Moreover, the removal of the forest cover exposes the soil surface to heavy precipitation and large variations in temperature. If natural hazards are to be prevented, the size of clear-cut areas in protection forests must be kept small. Thus, clear-cutting is often not an option.

Unstocked, even slopes steeper than about 30° at high altitudes are prone to avalanche release. If a slope exceeds 45°, snow avalanches can start in canopy gaps exceeding 30 m perpendicular to the contour line. Any rough surface structure, such as a rock, trunk, or tree, reduces the risk of snow movement by creating heterogeneity in the snow layer and 'nailing' the snow to the ground. While forests can rarely stop flowing snow avalanches, they are highly effective in preventing avalanche release. Surface roughness is also important for impeding rockfalls. However, in this case, forests serve not to prevent rockfall starting, but rather stop falling rocks.

If clear-cutting is not properly applied as a silvicultural system and is the first step to permanent deforestation, it usually has a negative impact on the fresh water supply. More than half of the world's population relies on clean water from mountains. While the demand is increasing, the supply is endangered. Mountains are the sources of most rivers, and mountain forests help to ensure that the water supply is seasonally balanced and that the water is of high quality. Clear-cutting large mountain forests without restoration cannot, therefore, be considered at all sustainable.

The impact of clear-cutting will obviously depend on the size of the clear-cut area. Large clear cuts in environments with pronounced climatic extremes, where tree regeneration depends on the beneficial effects of adult trees, must be avoided. This means that clear-cutting is not appropriate on very dry, very cold, or very wet sites, as it can lead to failures in stand renewal, even with repeated plantings. A system of small patch cuts is similar to the selection system, whereas leaving seed-dispersing trees to facilitate natural regeneration (the seed tree system) is comparable to the shelterwood system.

Not all damage attributed to clear-cutting is caused by the unwanted side-effects of the silvicultural system itself. The damage may actually be the result of inadequate road construction, of inappropriate site preparation treatments such as burning, or of careless logging practices, which damage the advance regeneration. However, even careful clear-cutting should not be used in those mountain forests where protection from natural hazards is needed, where erosion is a matter of major concern, and where the sites do not restock easily.

Shelterwood System

The shelterwood system is a silvicultural system in which trees are removed in a series of cuts designed to achieve a new stand under the shelter of remaining trees (**Figure 6**). In contrast to clear-cutting, it avoids having time periods where there are no trees to give shelter and to protect the soil, and thus reduces the associated risks. This system, therefore, has potential in mountain forests. However, it involves more costly

Figure 6 A shelterwood area with larch (*Larix occidentalis*) retained to provide seeds and to shade the regeneration. British Columbia, Canada.

timber harvesting than the clear-cutting system, and careful logging is required to avoid damage to the remaining stand and to the regeneration, particularly on steep slopes. If the individual trees in a protection forest are vulnerable to wind damage, shelterwood cuts will destabilize the stand and are therefore not advisable. The final cut can only be carried out when the regeneration has grown up sufficiently to ensure the protective effect is maintained.

Border-Cutting System

The border-cutting system (or strip-cut system) may also be appropriate in mountain forests (**Figure** 7). It involves successive cuttings in narrow strips, which combine the advantages of concentrated harvesting operations (one cut in one area) with limited harvesting damage. It does not create an open-land climate that impedes natural regeneration. In avalanche protection forests, the borders need to be sufficiently narrow to prevent avalanche release and must not be parallel to the slope. The borders can be laid out in the direction of cable crane lines.

Selection System

Selection systems remove mature timber either as single scattered trees or small groups at short, repeated intervals. Selection systems can be applied in a highly variable manner. They can range from small-scale patch cuts, shelterwood cuts and border cuts, to the single-tree selection system where only single trees are harvested. Selection systems are based on a heterogeneous stand structure and are therefore most suitable for ensuring continuous cover on steep slopes. A patchwork of tree groups of variable sizes and gaps is most efficient in structuring snow deposition, and can thus prevent, or at least reduce, avalanche release. Natural disturbance regimes can create this structural diversity, in particular in forests in extreme edaphic or climatic environments. However, on more productive sites, natural disturbances often lead to rather uniform stands, which then require conversion treatments.

Limited accessibility often makes the selection system too costly since the timber to be harvested is distributed over large areas, and very careful logging practices are required to avoid damage to the remaining stand. In some cases, cable cranes or even helicopters need to be used.

Group selection (or patch-cut) systems create openings narrower than twice the height of mature trees in the stand, and leave groups of up to about 20 trees in a cluster (**Figure** 8). They can be flexibly designed to fulfill potentially conflicting requirements in protection forests, namely high stand density in tree groups to ensure effective protection against avalanches and rockfall, and open canopy patches to allow sufficient regeneration and thus ensure continuous protection. Group selection, with special focus on the retention of small tree clusters and gaps, is referred to as ‘mountain group selection.’

Selection systems also facilitate advance regeneration and thus ensure high resilience after disturbances. In subalpine forests, the gaps created with single-tree selection systems may be too small to ensure sufficient regeneration. Examples are the numerous dense, uniform Norway spruce stands in the European Alps, which are often the result of

Figure 7 An example of a border cutting in a Norway spruce–larch forest with narrow strips and replanting in Austria.

Figure 8 Tending in a regular thicket of Norway spruce to create clusters and gaps in Switzerland.

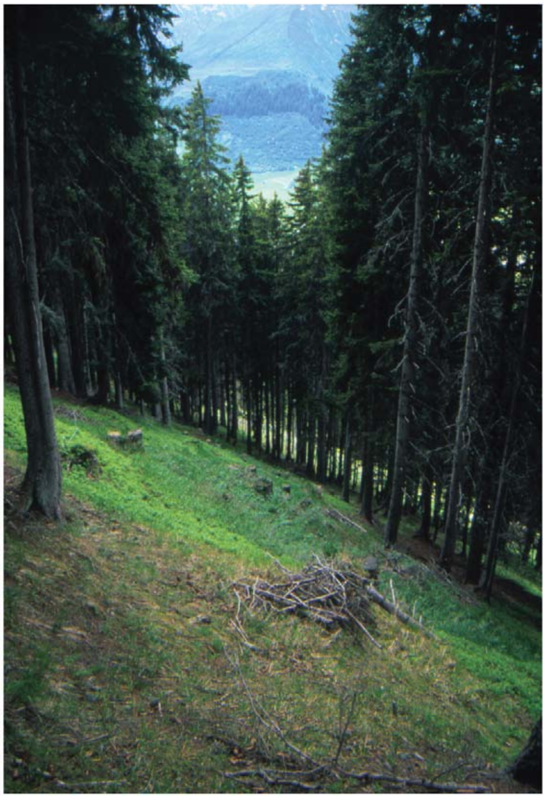

Figure 9 An example of a slit opening in a Norway spruce stand to stimulate forest regeneration in Switzerland.

untended regular plantings or of natural regeneration after large-scale disturbance. They can be opened up with slit-shaped openings to stimulate natural regeneration (**Figure 9**). Leaving 'nurse logs' is a good long-term means of encouraging future regeneration on decaying wood.

Coppice System

Coppice systems lead to a high stem density and can therefore be recommended for rockfall protection forests if the areas cut are sufficiently small. This system is highly appropriate if there is need for fuel wood. Collecting fuel wood does not require heavy machinery and therefore is less of an erosion hazard than commercial timber harvesting.

Afforestation

The restoration of degraded mountain forests on pastures by means of afforestation is not a silvicultural system, but requires great silvicultural expertise. For afforestation at high altitudes, suitable species and provenances from similar environments need to be carefully selected. Damage due to grazing by wild or domestic animals needs to be limited to acceptable levels. In environments with extreme climates, planted seedlings may need further management interventions for decades, e.g., planting a forest of pioneer trees to reduce frost damage, watering during drought periods, or setting up temporary barriers to prevent snow gliding.

In contrast to the open structure of natural stands described above, many planted stands tend to become single-storyed, even-aged, uniform, monospecific, and short-crowned. In protection forests, new plantings should be arranged in an irregular, grouped pattern over the terrain, corresponding to the distinct microsite variations found at this altitude. Favorable microsites, such as locally raised areas, are planted, while unfavorable ones, such as gullies or patches with well-established tall forbs, are left unplanted. This minimizes losses among planted trees and prevents the formation of uniform thickets. Planting should take place over a long time span to create uneven-aged structures of different sizes.

Conclusions

Mountain forests provide goods and services that are vital for people's well-being throughout the globe. They are, however, notoriously difficult to manage: their special topographic and climatic features mean that they are highly susceptible to degradation. To sustain mountain forests, careful and sometimes very sophisticated silvicultural approaches are required.

Careful silvicultural practices alone, however, will not ensure a sustainable future for the mountain forests of the world. A silvicultural system might be biologically perfect, but totally inappropriate if it fails to take into account the wider social context. Moreover, attempts must be made to anticipate the effects of changes in human demand, economic constraints, and ecological changes, such as global climate warming. Existing silvicultural systems must then be refined accordingly, or new innovative systems developed. Approaches such as the mountain group selection system, and their use on a large scale, are quite recent. Testing the real merits of these systems on an operational scale is a challenge that forest managers and scientists will have to face.

See also: **Harvesting**: Forest Operations in the Tropics, Reduced Impact Logging; Forest Operations under Mountainous Conditions. **Plantation Silviculture**: Multiple-use Silviculture in Temperate Plantation Forestry. **Silviculture**: Coppice Silviculture Practiced in Temperate Regions; Forest Rehabilitation; Silvicultural Systems. **Windbreaks and Shelterbelts**.

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Ecology and Silviculture of Tropical Wetland Forests

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Introduction

Tropical wetland forests comprise a highly diverse group of habitats scattered throughout the humid or coastal tropical regions of Africa, Asia, the Americas, and Australia. They include inland riverine and swamp forests and coastal mangroves. Depending on definition, the total area of tropical wetland forest is probably in the range $160–180 \times 10^6$ ha worldwide. The tree species of inland forests are often of poor quality as timber, and are difficult to extract: forest management and silviculture are therefore often rudimentary. Nevertheless, some trees, and many secondary products, are of economic value. Mangroves, or tidal forests, in contrast are often of high value, and may be intensively and efficiently managed for timber, as well as providing a range of other goods and services.

The defining character of a tropical wetland forest is that the soil in which the trees stand is submerged or waterlogged, either permanently or intermittently. Intermittent flooding may be seasonal, for months at a stretch or for shorter periods, with the forest sometimes reverting to virtually dry land conditions between inundations. In the case of coastal mangrove forests, flooding is tidal and typically occurs twice daily for hours at a time, with the soil remaining waterlogged between high tides.