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Snow and Avalanche Control

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Introduction

Snow has a strong effect on the hydrology of forests. In contrast to rain, much more snow is intercepted by the branches and temporarily stored on the forest floor. Snow also modifies the radiation balance of trees. Snow–forest processes are much more complex and important due to the increased three-dimensionality of trees than in open land (**Figure 1**). Management practices can strongly influence the snow storage capacity of forest, and therefore significantly contribute to runoff and runoff timing. This is especially important where water from mountains is used for irrigation and water supply (e.g., the Sierra Nevada in California, southern slopes of the Himalayas). Another locally very important effect in mountain regions concerns the prevention of snow avalanches. The preventive effect of forests on the formation of snow avalanches was recognized in different Alpine regions in Europe as early as the Middle Ages. By then, the intensified logging and clearing of mountain forests for timber and the creation of pastures had caused the formation of new starting zones and avalanche paths and required the relocation of farms and primitive measures for the protection of buildings. In addition, mountain forests were protected and declared untouchable by decree of local authorities. The physical processes underlying the formation of snow avalanches and the most effective ways of reducing their occurrence and intensity were investigated more intensively in the latter part of the twentieth century, mostly in the European Alps and the Rocky Mountains. The effect of forests on avalanche formation is limited; forests are unable to stop avalanches as soon as their size exceeds a few hundred square meters. In fact, avalanches carrying trees in their debris often cause larger damage than 'clean' snow avalanches. In this article an overview is presented of forest–snow relationships, which are important for the understanding of the hydrology of forests in regions where snowfall occurs, and snow avalanche formation in forested areas. In addition, the implications for forest management with respect to snow hydrology and avalanche protection are discussed briefly.

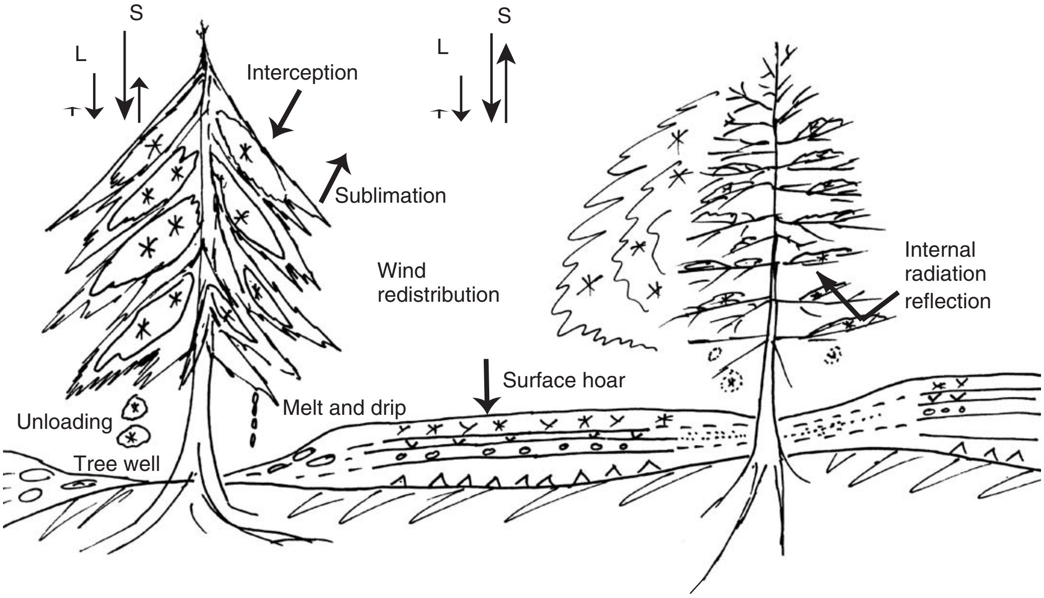

Figure 1 Processes in a snowy forest. The snow precipitation is unevenly deposited. Part of the snow is retained by interception on the trees, and later unloaded by mechanical shaking, melting and dripping as water, redistributed by wind, or sublimated back into the atmosphere. The intensity of these processes depends on weather and tree species. Incoming and outgoing shortwave solar radiation (S) and longwave radiation (L) depend on tree species, amount of interception, and topography. This modifies the condition for snowmelt and snow metamorphism.

Forest–snowpack Interactions

Snow changes the climate of a forest in winter and early spring through its high albedo and energy storage capacity (**Figure 2**).

Snow as the solid phase of water is stored at the surface of the forest floor, and because of the high energy necessary to melt it, its release as liquid water is delayed. These properties can be used to influence regional hydrology by specific forest management schemes. Snow deposition occurs in a forest at different heights and intensity, leading to a snowpack that varies spatially in terms of depth and water equivalent. Snow depth normally decreases with decreasing distance to the stem. Snow depth and water equivalent are usually higher beneath deciduous trees compared to coniferous species. In dry winter climates up to one-third of the intercepted snow is sublimated, thus reducing the amount of water available for melting in spring. Clearings with a diameter of up to seven times the height of the surrounding trees can increase the water equivalent of the snowpack, with maximum values around two to fives times tree height (**Figure 3**). However, the effect of wind erosion and redistribution of snow in alpine terrain can completely invert this behavior, such that the water equivalent of snow deposited in a spruce forest is 120% compared to that in shrub tundra.

Figure 2 Snow-covered branches of a spruce (*Picea* sp.). Solar radiation reflected by the highly reflective snow surface is absorbed by the dark underside of the branches, causing higher temperatures and melting or increased sublimation from the bottom.

The main effect of trees and forests on avalanche formation is through the modification of the snow's mechanical properties. Relevant processes include the interception of falling snow by the trees, the modification of the radiation and, therefore, temperature regimes beneath and around the trees, and the reduction of near-surface wind speeds. External topographic factors are slope aspect and steepness. Direct support of the snowpack by tree stems is relevant in the case of dense forests and especially snow gliding. Continuous snow layers of low internal mechanical strength often show preferential fracture planes that favor so-called slab avalanche formation. The formation of such unstable layers is reduced in forests through the processes and factors mentioned earlier, i.e., snow interception (reducing the amount of snow reaching the ground) and the moderation of the radiation regime (reductions in both incoming shortwave radiation and outgoing longwave radiation), but also by increased unloading of intercepted snow from the trees by wind.

Snow Interception

Interception of falling snow by the branches of the trees is usually followed by partial unloading in the form of irregular lumps of snow caused by warming and wind. This tends to result in a highly irregular snowpack around the trees. The direct effects of this are typically visible within a distance of about 1.5 times the crown projection (see **Figure 4**). Such tree-induced disturbances of snowpack layering are most pronounced below evergreen trees; the effect is less visible in the case of deciduous trees which tend to intercept less snow due to their much reduced trapping capacity in winter. The overall stability of the snowpack as determined by mechanical tests is similar, however, between snowpacks in evergreen coniferous and deciduous forest.

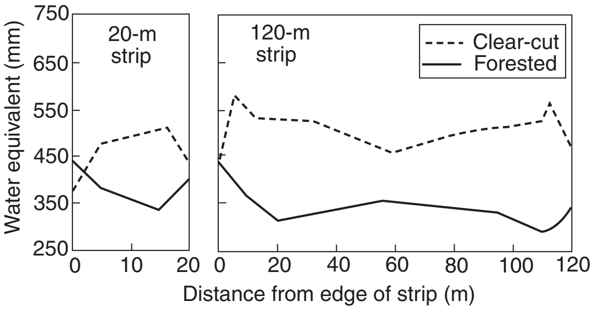

Figure 3 Transects of snow water equivalent monitored in alternate forested and clear-cut strips in the Fraser Experimental Forest, Colorado, USA. Reproduced with permission from Alexander RR, Troendle CA, and Kaufmann MR (1985) *The Fraser Experimental Forest, Colorado: Research Program and Published Research 1937–1985*. General Technical Report no. RM-118. Fort Collins, CO: US Department of Agriculture Forest Service. http://www.fs.fed.us/rm/fraser/pdf_blue_book.pdf.

Radiation

The energy balance within a forest is very different from that in the open. Both amounts and duration of solar radiation are much reduced beneath a tree cover whereas outgoing longwave radiation (mostly at night) is reduced as well (see **Figure 1**). Snow has a strong effect on the reflection of incoming radiation, as it is almost perfectly reflecting in the visible part of the spectrum and represents a near-perfect black body in the thermal infrared part of the spectrum. The associated fluctuations in surface temperatures cause the rapid formation of surface hoar frost in open fields. Surface hoar frost is a major cause of slab avalanche formation because this type of snow crystal is very brittle and can fracture after later burial by new snow. Surface hoar (and therefore slab avalanche formation) is much less probable in forest where fluctuations in snowpack surface temperatures are much more moderate because of the shielding effect of the canopy.

Wind

Wind is a major factor in the formation of avalanches in open areas through snow redistribution. Even the presence of rather open forest already causes a significant reduction in wind speed such that only minor relocation of snow occurs. This results in a more homogeneous distribution of the snow, and prevents extreme accumulation in gullies and depressions, as tends to occur in open areas.

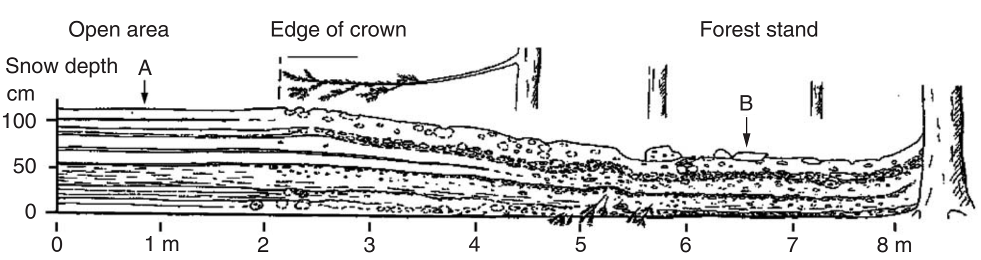

Figure 4 Snow profile in the forest. Reproduced with permission from Imbeck H (1987) *Schneeprofile im Wald*, Winterbericht Eidgenössisches Institut für Schnee- und Lawinenforschung 1985/86, no. 50.

Forests and Avalanche Control

Avalanche formation is also intimately linked to terrain features, notably slope exposure, steepness, and surface roughness. Trees and the associated modifications of the various physical processes described above form an additional modifying element compared to open, non-wooded slopes.

Terrain: Slope Angle, Aspect, and Roughness

A necessary condition for snow avalanche formation is a slope gradient exceeding 20°. In the Swiss Alps, avalanche formation on forested slopes has only been observed on slopes exceeding 30°. This value is probably valid worldwide, as the underlying mechanical processes will be similar. Slope aspect is especially relevant for the type of avalanche that occurs. Wet-snow avalanches occur mostly on sun-exposed slopes, while dry slab avalanches have only been observed on shaded sites. The frequency of avalanche releases is also higher on convex slopes (which tend to become steeper as one goes downslope) than on concave slopes where gradients generally decrease going downslope.

The roughness of the terrain underneath the snowpack is decisive for the occurrence of snow gliding and subsequent wet-snow avalanches. Grassy, abandoned meadows are especially prone to snow gliding. Fallen logs, remnant stumps of logged or snapped trees, root plates of upturned trees, and large rocks can all prevent the formation of small avalanches, but not extreme ones. Such surface features also promote regrowth by preventing subsequent mechanical damage by new avalanches to the young trees, and by providing favorable microsites for tree seedling establishment.

Effect of Forest Structural Properties

The density of a forest cover (both in terms of the number of trees per hectare and percentage canopy cover) and the size and distribution of forest gaps are often regarded as the chief forest structural parameters influencing the triggering of avalanches in forested areas. Although quantitative data on the minimum size for this ‘gap effect’ to happen are scarce, a first estimation of the quantitative relationships between stand structural and topographical variables may be derived from pioneering work conducted in the Swiss Alps. **Figure 5** shows the relationship between gap width and crown cover density for different categories of slope steepness based on a multivariate analysis of 112 avalanches triggered in coniferous forests in Switzerland. As gap width increases, the neighboring forest has to be increasingly dense so as to decrease the risk of avalanche formation. For a crown cover density of 60%, which is typical for subalpine forests in the Swiss Alps, a minimum gap width of approximately 20 m is expected to be sufficient to enable the triggering of avalanches on a 35° forested slope. When crown cover density decreases below 35%, the minimum gap width decreases to 10 m (see **Figure 5**).

Other important variables for avalanche control include gap length and the distance between the starting point of an avalanche in an open area and the nearest downslope forest edge. In contrast to gap width and crown cover density, which control the microclimatic influence of the forest (cf. **Figure 1**), these distances also affect the speed and, therefore, the destructive force of an avalanche. Generally avalanches with acceleration distances of more than 150 m cannot be stopped by forests, and the trees will be destroyed (**Figure 6**). For shorter acceleration distances, the efficiency of the forest’s resistance to

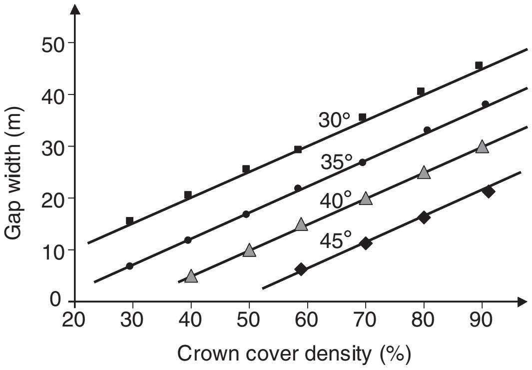

Figure 5 Relationship between critical gap widths and crown cover densities for the triggering of avalanches for different categories of slope steepness. The correlations are based on a multiple linear regression model of 112 avalanches in subalpine coniferous forests of Switzerland. R. Pfister, Swiss Federal Institute for Snow and Avalanche Research, unpublished data.

Figure 6 The devastating effect on a forest caused by an avalanche starting high above the tree line. Photograph by Swiss Federal Institute for Snow and Avalanche Research.

disturbance and the resulting degree of damage are mainly a function of slope angle, avalanche size and capacity, and the distribution and size of the trees.

Stand structural requirements for the triggering of avalanches in forests differ between evergreen forest types (mostly conifers) and broadleaved forests (mostly deciduous). The minimum gap widths required for avalanche formation are smaller in deciduous broadleaved forests. For example, in beech (*Fagus*)-dominated forests in the European Alps, a gap width of 5–10 m may already reduce the forest's snow interception capability below a critical threshold (see **Figure 7**). However, in contrast to the general perception, deciduous coniferous trees, such as larch (*Larix* spp.), are almost equally effective when it comes to preventing avalanche formation as are evergreen coniferous trees (spruce, fir), as long as stand densities are comparable. Deciduous trees are less effective in reducing avalanching than evergreen trees when the temperature during snowfall is lower. Under such conditions the snowflakes do not stick to twigs without needles.

Open-structured forests, which are more susceptible to the triggering of avalanches, are often more frequent at higher elevations and near the timberline. This is particularly valid in the case of coniferous forest in the northern hemisphere, where scattered, single trees and small clusters of trees tend to dominate in the subalpine timberline zone. Elsewhere, dense broadleaved forests (such as the *Nothofagus* forests in New Zealand) may continue all the way up to the timberline whereas under dry montane conditions open forests may form well below the temperature-controlled timberline (e.g., *Pinus ponderosa* forest in the Rocky Mountains).

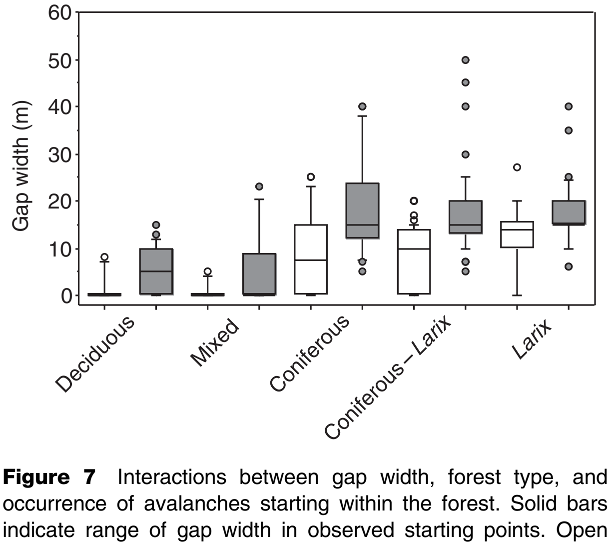

Figure 7 Interactions between gap width, forest type, and occurrence of avalanches starting within the forest. Solid bars indicate range of gap width in observed starting points. Open bars: range of gap width in control plots without avalanche release. Reproduced with permission from Schneebeli M and Meyer-Grass M (1992) Avalanche starting zones below the timberline: structure of forest. In *Proceedings of the International Snow Science Workshop*, 4–8 October 1992, Breckenridge, CO, pp. 176–181.

Stand properties related to avalanche control are permanently changing and may be altered dramatically after natural disturbances (extreme wind, landslides, avalanches, forest fires) or human intervention (mostly logging). The relevance of such disturbances in altering the forest's potential for avalanche control is dependent on: (1) the size and intensity of the disturbance, and therefore the degree of destruction, (2) the ability of remnant trees to maintain sufficient surface roughness, and (3) the time required for the establishment of a new effective forest cover.

Management Implications

In mountainous regions, the protection of human settlements against avalanches is often considered to be the most important forest function. When discussing management implications we therefore have to differentiate between cases where the forest fulfills such a protective function (German: *Schutzwald*), and where management should aim mainly at increasing forest water retention or timber production.

In a *Schutzwald*, the following measures may be applied to improve or support the protective role of forests with respect to the reduction and prevention of snow avalanches:

- silvicultural measures relating to the intensity and method of timber harvesting, and reforestation of open or deforested spaces
- structural measures including all kinds of engineering works like wooden avalanche defense structures (**Figure 8**)
- hazard mapping (as a base for land-use planning) on the basis of slope steepness, aspect, surface roughness, and tree cover
- organizational measures (early warning systems, forecasting of heavy snowfall or sudden increases in temperature, temporary road closure).

The practical importance of these measures is strongly related to population and infrastructural densities. Silvicultural and technical measures to improve avalanche control have a long tradition in steep, densely populated areas such as the European Alps, but such measures become less important in sparsely populated areas or where much damage may be avoided by the proper planning of settlements, roads, and other infrastructural works. In avalanche protection forests on very steep slopes, silvicultural measures generally aim to avoid the (persistent)

Figure 8 Avalanche starting zone in a gap within the forest protected with wooden defense structures in the Taminatal, Switzerland. The design life of such temporary wooden constructions is at least 50 years and allows time for young trees to become well established.

occurrence of large gaps and open forest. However, because natural regeneration in mountain forests often requires openings with sufficient light availability, optimal silvicultural measures for avalanche protection are often difficult to establish and time-consuming to execute. Where natural tree regeneration is too slow to guarantee a protective effect or is impeded by unfavorable microsite conditions, silvicultural treatment may have to be complemented by temporary or permanent technical support structures. Furthermore, as labor and material costs continue to rise, silvicultural and technical measures in remote mountain forests are gradually becoming less cost-effective. It is therefore inevitable to restrict such measures to the most critical areas and combine them with organizational measures wherever possible to achieve maximum effect against minimum expense. Logs lying about and upturned root plates often enhance the protective effect of a forest by increasing the overall roughness of the terrain and by providing favorable microsites for subsequent tree regeneration. Management strategies, both in disturbed and intact avalanche protection forests, should therefore rely more on naturally occurring forest dynamics and stimulate the inclusion of areas without silvicultural intervention in the planning process.

Storage of snow and therefore increased water retention of a forest can be optimized by limiting the size of any clear-cuts to about five times the tree height or by favoring a forest structure with variable heights. While these requirements are always fulfilled in the variously aged stands that are considered optimal for *Schutzwald*, this kind of management is rarely introduced where timber production is considered more important.

See also: **Ecology**: Natural Disturbance in Forest Environments. **Harvesting**: Forest Operations under Mountainous Conditions. **Hydrology**: Impacts of Forest Management on Streamflow. **Site-Specific Silviculture**: Silviculture in Mountain Forests. **Temperate and Mediterranean Forests**: Northern Coniferous Forests; Southern Coniferous Forests.

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