Chapter

Protective Effects of Forests against Gravitational Natural Hazards

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Abstract

In this chapter, we give a short overview of the protective effects of forests against snow avalanches, landslides and rockfall hazards in mountain areas. The overview is based on the protective mechanisms provided by forest and connects them to the effect-related indicators of forest structure from literature and European protective forest management guidelines. The thresholds of the effect-related indicators are hazard-related silvicultural targets for forest management and critical values for hazard risk assessment. The assessment of the protective effects of forests is a central part of natural hazard risk analysis and requires information on different spatial levels from single tree to slope-scale attributes. Forests are efficient in preventing snow avalanche and landslide initiation; however, they are usually unable to stop large masses of snow, soil and rock in motion. Therefore, guidelines on silvicultural targets and practices must focus on the mitigation of hazard onset probabilities at the stand-scale; however, existing guidelines under- or overestimate the protective effects of forests. Effects of forests on hazard propagation are difficult to implement in forest and risk management practice. Hence, the European protective forest management guidelines do not contain any or only general specifications that simplify the determining factors and their relationships.

Keywords: protective forest, natural hazards, snow avalanche, rockfall, landslide, nature-based solutions

1. Introduction

The protection of settlements and infrastructures by so called protective forests (protection forests) against gravitational and hydrological natural hazards is of particular relevance in the mountain areas of Europe, as they are densely populated and used intensively by the population of other regions for recreation [1]. Therefore, special legal regulations and public funds have been introduced to maintain and improve the protective effects of forests in many European countries [2, 3]. The protective effects of forests are also addressed in literature by the terms protective function and protective role which are often used synonymously. Brang et al. [4] clearly differentiated the meanings of the terms protective function, potential, and effect of forest (see also chapter [5] of this book).

The term "protective function" refers to the task of forests to protect something of value like people, settlements or infrastructures from the impacts and damage by adverse climate or natural hazards [4, 6]. This task is assigned to forests or to other land use appropriate for afforestation by society, if there is a damage potential to people or assets, and the forest is or will be located on sites where a forest can give rise to mitigation of hazards and climate impacts. The allocation of protective functions to existing or future forests does not consider the present forest conditions and effectiveness in protection but refers to the societal demand for protection by forest due to environmental conditions and public interest as well as to a protective potential on this location. The "protective potential" of a forest is "a protective effect that a forest is likely to have if properly managed" [4]. This capability of forests to prevent or mitigate natural hazards depends on the (prospective) hazard type and intensity, on the location in the process area and the natural growth capacity of the site to produce protective forest structures.

The term "protective effect" refers to the degree of mitigation of hazards by forest [4] which ranges from no or low reduction of hazard frequencies and/or intensities to total hazard prevention. The term is also used to designate the protective mechanisms which generate the hazard mitigation by interaction of woody vegetation and abiotic components which control environmental processes [6]. The protective effects result from the current forest conditions and in the long-term from the stability of the forest [4]. The term may also imply the reduction of the damage risk to people and assets by forest. However, hazard and damage risk analysis are approaches beyond the determination of the protective effect of the forest including further steps of analysis.

In this context, this chapter will give a short overview of the protective effects of forests against gravitational natural hazards in mountain areas. The overview is based on the presentation of the protective mechanisms provided by woody vegetation and connects them to the effect-related indicators of forest composition and density. Protective effect-related indicators and thresholds have been issued by several European guidelines for protective forest management [7]. The thresholds of the protective effect-related indicators are hazard-related silvicultural targets for forest management on stand-scale and critical values required for hazard risk assessment at stand- and slope-scale. Therefore, we relate knowledge from the literature and hazard observations to these common concepts on protective forests. We limit the presentation to the protective effects of forest against snow avalanches, landslides and rockfall which may be mitigated by forest effectively on slope-scale, whereas the effectiveness of forest in mitigating hydrogeomorphic hazards like (torrential debris) floods is more dependent on the temporal and spatial scale of view as well as on the total share of forest use at the watershed-scale (see chapter [8] of this book).

2. Protective effects of forests and related forest conditions

Forests prevent and mitigate gravitational natural hazards by two mechanisms: 1) they prevent hazard initiation or reduce mass displacements in potential starting zones by the retainment of solid materials on site, and 2) they break down, narrow laterally and eventually limit the propagation of the mass movement [9–11]. The prevention or limitation of hazard initiations is clearly the most efficient and therefore important protective effect of forest to be considered by forest management. Forests are usually unable to stop large masses of snow, soil, and rock [9]. However, the importance of release prevention in potential starting zones in relation to mass deceleration in possible transit zones by forest is strictly related to the hazard type.

Furthermore, the magnitude of the mass movement, the conditions of materials in motion, the distance, and the terrain relief from the starting zone to assets at risk as well as the proportion of the runout zone covered by high and dense enough forest impact hazard propagation.

2.1 Protective effects of forests against snow avalanches

Avalanches may be classified into canyon avalanches (nowadays, they are called channelized avalanches) and slope avalanches, according to their physiogeographic situation and spatial relation to forest, with many intermediate forms [12]. A canyon avalanche originates on the head of a canyon above the current timberline or in areas of open forests and follows the gorge. Because of the frequent occurrence and damaging effects, the upper flow path is usually free of taller woody vegetation, or only overgrown by bushes, but, dependent on the frequency and intensity of the mass movement and the terrain, the hazard zone may also be stocked by high timber. In case of infrequent high snow accumulation, these situations are difficult in risk management, as the hazard and damage potentials are not obvious due to the condition of the woody vegetation. Slope avalanches occur outside of canyons on steep mountain slopes. As they are mainly covered by high and dense forests, damage to infrastructure by naturally triggered slope avalanches is less frequent in the Alps even in snow rich winters. Snow avalanches which originate in forests are called forest avalanches (**Figure 1**) [13, 14].

Most avalanches that are perceived in Alpine settlement areas as coming from forested terrain originate from slopes or canyon heads above the current timberline or from currently open areas [15]. Nevertheless, forests on steep mountain slopes should never be considered as areas not prone to avalanche formation [16]. The basic avalanche release susceptibility of forested slopes in the Alps is not evident in hazard and damage statistics, as it is masked by the protective effect of the mainly dense woody vegetation and by artificial snow supporting structures which already have been established at the beginning of the 20th century in forests with high protective functions and low protective effects [7].

Figure 1.
Muddy snow avalanches from forest triggered in March 1988 by rain after 38 cm snowfall within 3 days. Photo: K. Perzl, 1988.

2.1.1 Prevention and reduction of snow avalanche release by forest

A forest cover prevents snow avalanche initiation by stabilizing the snowpack on the ground as a result of these mechanisms: A) reduction of the formation of firm bed surfaces and weak snow layers (crusts, faceted snow, depth and surface hoar) by balancing the radiation and temperature budget of the snowpack, B) disturbance of the stratification of the snowpack and C) reduction of the snow depth by canopy interception of snow precipitation, D) reduction of the accumulation of wind-driven snow by deceleration of wind speed, E) reduction of the formation of basal gliding (ice and wet snow) planes due to the usually high infiltration capacity and roughness of the forest floor, and F) support of the snowpack by stems, snags, stumps, logs and low woody vegetation [13, 15, 17–22].

The mechanisms A to D are forest canopy effects, and therefore the foliar cover of the forest in winter regulates the snowpack stabilization. However, leafless twigs, branches and stems contribute to the modification of the radiation and temperature regimes of the snowpack as well as to the interception of snowfall. The density and spatial distribution of stems and coarse woody debris, which are the main controllers of the mechanism F, also reduce the formation of weak layers. In addition to soil properties, coarse woody debris, and the understory, all of them influenced by forest composition and density, and finally by forest management, control the mechanism E.

Because of the complex interaction of these mechanisms with snow and terrain characteristics, it is difficult to differ main and minor protective mechanisms and controllers of the protective effect of forests against avalanche release. A forest is largely able to prevent new and old snow avalanche releases except for small loose snow avalanches by the mechanisms A to C. The preconditions for this are a rather dry and cohesive snowpack as well as a sufficient forest canopy cover. A foliated canopy cover by evergreen conifers is most effective but may be substituted by the surface area of branches and stems of deciduous trees and snags. The woody area of the canopy, especially the branchwood surface area, plays an important role in the modification of radiative, thermal, and hydrologic conditions [23]. The similar protective canopy cover observed in both evergreen and deciduous coniferous stands [14] and the little influence of the leaf area on the spatial variability in snow stratigraphy [24] may be an effect of the woody area of the canopy. However, avalanche initiations are observed more frequent in deciduous forests than in evergreen forests and occur under closed deciduous canopies [13, 14, 19], which indicates a limited protective effect of trees without leaves in case of heavy and stormy snowfall or other than cold-dry conditions.

Tree canopies prevent avalanche release when they overtop the snowpack. On steep slopes prone to avalanche formation, young trees and bushes are bent down by the snow load and the pressure of the snowpack. As a result, they can be uprooted, broken and overlaid by weak snow layers and cohesive snow slabs. However, it is not clear and easy to determine how large and tall trees or bushes must be to have a protective effect. This depends on numerous factors such as slope inclination, surface roughness, tree species composition and stand structure, and ultimately also on the risk-analytical assessment basis of possible (design) snow depths. In addition, the protective height and/or diameter of trees likely depends on the density of the woody vegetation. Observations indicate that trees overtop the snow cover when the tree height exceeds the maximum snow height by one to two times [25–27]. These relationships lead to quite different protective tree heights up to over 5 m, depending on the design snow depths used in risk analysis, as well as to questions on the method and accuracy of stand height and snow depth assessments. These relationships do not directly refer to the avalanche activity. Observations of snow avalanche activity caused by logging indicate a protective height of the woody vegetation of about 2 m [28]. This may be an effect of the increased surface roughness at loggings. The snowpack support by stumps, logs and other terrain roughness features may considerably mask the protective height and density of young growth.

Usually, a canopy cover of upright-growing woody plants with an average height of about 5 m may overtop and shade the snowpack. Hence, they provide the protective effects A to C and F. The recommendations of the European guidelines for protective forest management for the protective stand height and canopy cover differ considerably [7]. These expert-based guidelines from four European countries suggest a range of canopy cover targets from 30 to 70% for a high level of protection which is not defined clearly but may refer to a low release probability (**Table 1**). Furthermore, the guidelines refer either to the total (TCCP) or to the wintergreen canopy cover percentage (WCCP). Guidelines, which refer to the WCCP, use the total stem density for inferring the protective effect in case of forests with low proportions of evergreen canopies.

A validation of these targets based on a sample of observed snow avalanche initiations in Alpine forests (total sample size 295) shows a low misclassification of all approaches in terms of false negative rates [7]. The false negative rate (FNR) is the proportion of observed hazard releases that would not have been classified as critical situations based on the forest and site condition according to the criteria of a guideline. The FNRs in the range of 22 to 30% of the approaches using a critical TCCP of 50% are considerably higher than those of the guidelines using the WCCP (0 to 2%) (**Table 1**). This indicates an overestimation and limited protective effect of leafless canopies, whereas the high targets in terms of the WCCP, ranging from 30 to 70%, clearly underestimate effects of the foliar cover and of the woody area in deciduous stands. 75% of all snow avalanches in the sample initiated on sites with a WCCP smaller than 16%, and initiations under evergreen canopy cover of more than 40 to 60% were rare outliers. Therefore, even a small proportion of evergreen trees can significantly reduce the likelihood of avalanche formation and deciduous trees also provide a reduction of the release width (RRW) in relation to low canopy covers (**Table 1**).

The comparatively high miss rates (FNR) of assessments based on the total canopy cover are an effect of the presence of deciduous forests in the sample, especially of the high broadleaved forests with small surface roughness [7]. In broadleaved deciduous stands, with a low proportion of evergreen trees and low total stem density, avalanches may initiate even when the canopy is fully closed [13, 14, 34]. This is a result of several limitations of the protective effect of (deciduous) canopies. In some special conditions, the ability of forest to prevent avalanche formation by the mechanisms A to C is reduced. Such conditions are heavy and enduring snowfall at low temperatures without intermittent radiation, (heavy) snowfall followed by rain-on-snow (**Figure 1**) or strong sudden air temperature rise (**Figure 2**) [13, 15, 35].

A cohesionless snow layer or snowpack of fluffy or wet snow outer performs the mechanisms A and B. The mechanics C to D, especially the snow depth reduction by interception effects, become more important. However, snow depth reduction is limited in deciduous forests. In addition, snowpack support by stems (mechanism F) is reduced for both cohesionless and cohesive but heavy and moist snowpack. Supporting the snowpack by upright stems requires contact with the snowpack [19]. Thus, paradoxically, this mechanism is more effective for large snow depths than for small ones [36]. However, in all situations with low effectiveness of the mechanisms A to C, and especially in deciduous forests, the anchoring and therefore an adequate stem density is important to stabilize the snowpack. The protective effect of deciduous forests is more dependent on stem density and surface roughness than clearly connected to the canopy cover [16, 34, 37, 38].

Guideline	NaiS	SFP	GSM-N	GSM-S				ISDW		
Level of protec-tion	**"high"**	**"high"**	**"high"**	**high**	**medium**	**low**	**no**	**high**	**medium**	**low**
Slope	TCCP	TCCP	WCCP	WCCP	WCCP	WCCP	WCCP	WCCP	WCCP	WCCP
≥30°	>50%	>50%	>30%	>70%	>30%	>10%	≤10%	≥45%	≥35%	<35%
≥35°	>50%	>50%	>50%	>70%	>30%	>10%	≤10%	≥55%	≥35%	<35%
≥40°	>50%	>50%	>70%	>70%	>30%	>10%	≤10%	≥65%	≥35%	<35%
FNR CC	22–30%		0–2%	0–1%				0–2%		
RRW	−40 m		—	−30 m				−30 m		
FNR all	43%	42%	32%	6%	—	—	—	5%	—	—

TCCP, total canopy cover percentage (all tree species); WCCP, canopy cover percentage of evergreen species; FNR, false negative rate in percent of the sample; "CC" refers to the validation of canopy cover targets, "all" to the combination of all indicators (canopy cover, gap size, stem density); RRW, maximum reduction of slab release width in relation to the non-target (low) canopy cover.

Table 1.
Canopy cover targets to prevent avalanche initiation in forests according to the European protective forest management guidelines NaiS [29], SFP [30], GSM-N [31], GSM-S [32] and ISDW [33], and false negative rates of avalanche occurrence and reductions of release widths calculated based on a sample of observed forest avalanches (total sample size 295) (for details see [7]).

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Figure 2.
Release of a snow avalanche in a spruce forest triggered by air temperature rise from −12 to 6°C within few hours. The 208 m long avalanche with a vertical drop of 147 m buried a local road. Photo: F. Perzl, 2021.

The literature on protective stem densities is based on different analytical approaches and they vary considerably. They refer to different caliper thresholds and mean diameters of the stems at breast height (DBH). Thresholds of protective stem densities are usually related to slope inclination. Approaches based on mechanical calculations show stem densities needed to stabilize the snowpack, for example with an average DBH of 5 cm, from about 2,000 on gentle slopes to more than 10,000 stems per hectare on steep slopes [34, 36]. These calculations are very sensitive to slope, DBH and snow conditions. Observations and statistical approaches [14, 16, 26] usually do not confirm them. **Figure 3** shows stem densities recommended by the European guidelines to stabilize snowpack versus a sample of 142 observed snow avalanche initiations in forests mainly provided by a Swiss database [14]. Based on this sample, the miss rates (FNR) of the guidelines are low, not exceeding 15%. However, most of the guidelines tend to propose quite higher stem densities than observed and underestimate the effects of the trees [7]. Snow avalanche initiations in forests with stem densities of more than 900 per hectares (DBH >6 cm) seem to be statistical outliers allocated to deciduous broadleaved and mixed forests on very steep slopes [7].

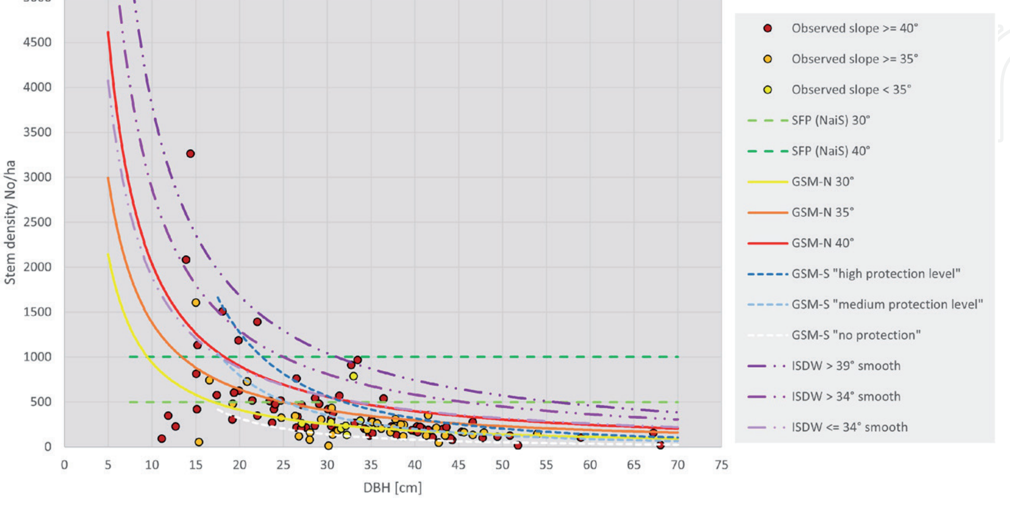

Figure 3.
Targets of critical stem densities for snow avalanche initiation in relation to observed stem densities dependent on slope [7]. Acronyms in the legend refer to the national European guidelines NaiS [29], SFP [30], GSM-N [31], GSM-S [32] and ISDW [33]. NaiS and SFP propose fixed values without considering the natural reduction of stem densities with increasing mean tree diameters. However, in NaiS, the stem density is mentioned but not part of the assessment criteria.

Stem density observations in avalanche initiation sites are rare and difficult to compare, as they refer to different measurement methods. Additionally, the effects of trees depend on their spatial distribution. Most avalanches in high forests initiate in canopy openings. The term "gap" is usually used for small openings, but the term may also refer to all openings ranging from the size of a tree crown to large clear-cut areas. The size of canopy openings is an important issue for the management of forests with an object-protective function. Forest regeneration may be suppressed by too small canopy openings because of light deficiency, but inappropriately large openings carry the risk of avalanche formation.

One approach to assess critical canopy openings followed by some European guidelines assumes that limiting the length of cuts in the flow direction will reduce the probability of avalanche release as well as the avalanche propagation. This assumption and the recommended critical gap (opening) lengths in the range of 25 to 60 m depending on slope are based on physical calculations [39–41]. The validation of the implementations in the European guidelines delivered FNRs in the range of 36 to 49% [7]. These results show low influence of the proposed critical gap lengths on the probability of avalanche release but a reduction of runout lengths by 50 m on average which is statistically not significant. The reduction of the release probability in cuts as well as avalanche propagation is not primarily a question of the gap length in the release zone, but also dependent on the gap width, the surface roughness in the opening and the density of woody vegetation at the lower edge of the opening [13, 14, 42]. The terrain and forest conditions along the total flow path are crucial for the runout length.

2.1.2 Reduction of snow avalanche propagation by forest

The European guidelines for protective forest management do not consider the avalanche braking effect of the forest in the transit zone as normally slab avalanches with critical fracture size will flow through forests or destroy them until they run out on slopes of low inclination or the energy is dissipated by the fall over steep cliffs [12, 17, 40, 41, 43]. Trees are unfavorable resistance elements against avalanches due to their small obstacle width, shape and material properties. Depending on the elasticity of the species and the diameter of the plants, powder cloud avalanches with a pressure of about 3–5 kN/m^2 and higher, and flow avalanches of about 10–50 kN/m^2, which are possible even with small snow masses, break or uproot the trees [39, 41] as soon as the trees lose the flexibility of the juvenile stage (**Figure 4**).

Forests can stop or significantly slow down small-to-medium avalanches starting within dense forests, in small gaps of dense forests or next to the upper timberline by snow detrainment [40, 44, 45]. The breakage, uprooting and overturning of trees as well as the entrainment of coarse woody debris and snow deposition behind trees (**Figure 5**) may cause a loss of energy and reduce runout lengths of medium to large avalanches originating from sites above the timberline or from large clear-cuts [46–48]. Indications on the distance from the release area (in forest cover openings or above the timberline) to forest cover penetration and on the release size which ensure braking effects of the forest cover vary from 30 to 200 m and from <5,000 to 30,000 m^3 [21, 22, 40, 44, 46, 49].

The allocation of (potential) hazard zones to avalanches that may or may not be slowed down by the forest, is difficult and not only an issue of the release size. It must be remembered that stopping an avalanche within the forest may not be an effect of the forest, but a consequence of snow and terrain conditions in the transit zone as well as the elevation of the starting zone. The reduction of damages by silvicultural interventions in the transit zones is limited to the enhancement of the

Figure 4.
Destruction of a young deciduous forest by an avalanche. Photo: K. Suntinger, 2009.

Figure 5.
Detrainment of avalanche snow by trees. Photo: F. Perzl, 2008.

surface roughness on short-slopes and to promoting stand stability by species selection, formation of resistant individuals and acceptance of shrub-dominated growth.

2.2 Protective effects of forests against (shallow-seated) landslides

2.2.1 Prevention and reduction of landslide initiation by forest

Effects of forests on deep-seated landslides are a debated issue, while it is widely accepted that forests can prevent the development of shallow-seated landslides. This topic is further complicated by the fact that there is no uniform definition of deep-seated landslides, and that the distinction from shallow to deep is transitional. Part of this problem are numerous different landslide classifications with fuzziness of process descriptions as well as different transcriptions of landslide type definitions from one language to another.

We refer to mainly deep-seated permanent landslides and mainly shallow-seated spontaneous regolith (debris) slides according to the Swiss approach of hazard risk assessment [50]. Permanent landslides are masses that have already been displaced and are therefore in motion with phases of activity or inactivity. The term spontaneous landslide refers to first-time failures with no further movement of the deposits except secondary erosion.

Spontaneous debris slides may be classified for practical purposes into 1) slides and slumps without flow-like mass movements, 2) spoon, shell or wedge-shaped slides followed by material flows 2.1) without (debris avalanches) or 2.2) with linear erosion (debris flows) of the transit zone (**Figure 6**).

Spontaneous landslides of the flow type (2) are most common on steep mountain slopes and in mountain forests, because of the excessive release and runoff of subsurface and surface water from the scars of the initial slope failure. A further classification of landslides important for forest management is to distinguish hillside and channel bank failures. Slope stabilization effects of forest are limited at river embankments, as storm flows undercut root systems.

Many forest practices boards (e.g., [29, 51]) allocate limited effects of forests on deep-seated landslides or associate the effects to the water recharge and toe areas, which are prone to shallow landslide initiation. There are no studies that investigate or clearly show a cause-and-effect relationship between forest conditions and the reactivation of deep-seated landslides except one study [52] that showed that an increased velocity after clear-cut harvest was not correlated to change in precipitation [53]. Most authors (e.g., [10, 54, 55]) agree and silvicultural guidelines (e.g., [29, 31]) stating that a protective effect of forests is given especially in shallow-seated zones of potential depletion, as the roots do not stabilize soil layers deeper than 2 m. Although landslide inventories are biased by the forest cover, this is substantiated by studies on effects of forest practices and landslide inventories (e.g., [56]), which usually show a lower density of shallow-seated landslides on forested (forest cover) areas than on non-forested areas. However, there is no evidence that a high protective potential of forests is limited to depths smaller than about 2 m [7, 53]. Woody vegetation influence water budgets [53] and especially the moisture of soils rich in clay or silt, which are susceptible to slope failures, down to a depth of about 3 to 10 meters (e.g., [57–59]). On the other hand, shallow soils on steep slopes with a dense forest cover fail, if the bedrock below is impervious or pipeflow is blocked, and the pressure of the subsurface flow leads to an explosive collapse of the soil [60, 61]. Therefore, the protective effect of the forest cover is also limited in case of shallow soils.

Forests enhance slope stability by A) dewatering due to evapotranspiration, B) internal redistribution of water due to the hydraulic lift (maintenance of

Figure 6.
Left – soil clod grown by trees moving downslope on a permanent landslide, center – debris avalanche, right – debris flow in forest. Photos: F. Perzl.

conductivity), C) prevention of dry cracks in soils by shadowing, D) reduction of near-surface downflow and distribution of the soil water by impacting the infiltration capacity of the soil, and E) mechanical reinforcement of slopes through roots [57, 62–64].

The impact of evapotranspiration on soil saturation (A) and soil water distribution (B) is secondary for preventing (shallow-seated) landslides in humid-temperate and boreal mountain-ecosystems with limited depths of nearly saturated soils, as intense rainfall and snowmelt are the key-drivers of landslide occurrence, which saturate the soils rapidly without time for dewatering [57, 65].

Dry cracking is not evident to drive landslides in Alpine conditions and is limited to soils rich in clay or silt. But effects (B, C) reducing contraction-induced soil openings and swelling pressure [66] may be important for deep-seated regolith under temporarily dry conditions.

The protective potential of the mitigation of near-surface downflow by forest (D) may be secondary in relation to (E) for short slopes and shallow soils. However, the mitigation of flow from upslope contributing areas is not negligible for landslides of the flow type (2), depending on the characteristic of contributing areas and issues of hydrological connectivity [67].

The anchoring to bedrock, and the additional soil strength or cohesion provided by roots (E) are the most significant contributions of woody vegetation to slope stability [54, 65]. Deciduous broadleaved species generally show higher root resistance than conifers [68], and their tensile strength is influenced by root water status [69]. The influence of the tree load is rather small in relation to root reinforcement [70], whereas the transmission of wind loads by trees to soil may negatively affect slope stability. The weight of trees, combined with root decay and an imbalance of above- and below-ground biomass, may increase erosion by uprooting especially in abandoned coppice stands [71].

All protective effects (A-E) are dependent on the ground coverage by healthy woody vegetation. Additionally, the root reinforcement of soils (E) and seasonal dewatering by evapotranspiration (A, B) depend on the stage of development and the forest's species composition. It is frequently observed that clear-cutting or forest-dieback promote slope instability, although the effects of the remaining roots can stabilize the slope for several (3 to 15) years until root decay [57, 72].

Although the influence of forest management on landslide occurrence is addressed frequently in literature, only few authors provide information about the critical canopy cover and size of canopy openings like clear-cuts. The information useful for practice is limited to the recommendations in the European guidelines (**Table 2**); numerous erosion control guidelines avoid quantitative statements.

There are many references addressing the mitigation of landslide occurrence by a site-appropriate tree species composition. Although plausible, we could not find clear and direct evidence of a relationship between the proportions of tree species, their spatial distribution and landslide activity in the literature. That is, even if the root systems of broadleaved hardwoods seem to provide better soil reinforcement than conifers, statistical analysis do not show this clearly. Amishev et al. [73] propose small clear-cuts of maximum 1 ha to maintain the protective effect of forests. This is a much larger critical area than recommended by the European guidelines (**Table 2**). Moos [74] identified the canopy cover, the length of canopy openings ("gaps") and the distance to the next tree as the forest characteristics that influence landslide susceptibility; the area of openings was not included in the analyses. Her results indicate that a canopy cover (height >3 m) lower than 60% and a gap length longer than 20 m are critical especially on steep slopes. However, an influence of the gap length could only be ascertained in one of two study areas. **Table 2** shows canopy opening and canopy cover targets recommended by the European guidelines to avoid

	Canopy opening (gap)					Canopy cover [%]				
	No regeneration			regeneration						
Indicators and miss rates	NaiS minimal	SFP minimal	ISDW	NaiS minimal	SFP minimal	NaiS minimal	SFP minimal	GSM-N	GSM-S	ISDW
Gap area [m²]	≤600	<600	—	≤1200	<1200	—	—	—	—	—
FNR Gap area [%]	25	25	—	34	34	—	—	—	—	—
Gap dimension link rule	—	AND	—	AND*	AND	—	—	—	—	—
Gap length [m]	—	<20	—	—	<25	—	—	—	—	—
FNR Gap length [%]	—	18	—	—	68	—	—	—	—	—
Gap width [m]	—	—	≤25	≤20*	—	—	—	—	—	—
FNR Gap width [%]	—	—	47	39	—	—	—	—	—	—
Trees h >10 m	—	—	—	—	—	≥40	≥40	—	—	—
All trees	—	—	—	—	—	—	—	>70	>70	>65
Large-sized trees	—	—	—	—	—	—	0	—	—	<25
FNR gap or cover [%]	25	19	47	34	31	42		38		42
FNR large-sized [%]	—	—	—	—	—	—	66	—	—	98
FNR combined [%]	—	—	—	—	—	45	21	38	38	39

*h, stand height; FNR, false negative rate in percent of the sample, "combined" refers to the final assessment by the combination of all targets (canopy cover, gap size, canopy cover of large trees). *The combination rule is not clearly documented.*

Table 2.
Canopy opening and canopy cover targets to prevent shallow landslide initiation according to the European guidelines NaiS [29] and SFP [30] (minimal requirements), GSM-N [31], GSM-S [32] and ISDW [33], and results of a validation based on 555 observations of shallow-seated landslides in Alpine forests [7].

landslide initiation in forests and validation results based on a sample of 555 shallow landslides [7]. The guidelines assume that regeneration contributes to slope stabilization. Therefore, openings with secured regeneration that are twice the area of critical openings without regeneration are not considered as critical. The validation of the canopy opening targets showed significantly higher FNR even if the length of the gap was additionally restricted. A canopy cover of tall trees of only 40% yielded similar FNR to a canopy cover of 70% with young growth and shrubs considered. Very high miss rates (≥66%) arise from the target of low occurrence of large-sized timber to reduce tree load of slopes and landslide-induced log jams in rivers. However, similar to the case of snow avalanches, the overall result of the assessment of the protective effect against landslides is highly dependent on the combination of indicators. The FNR of the guidelines are higher than in case of snow avalanche. In line with literature, these results indicate a protective potential of closed (natural) mature and old-growth forests without disturbances but limited protective effects of young growth.

2.2.2 Reduction of debris flow runout by forest

Trees and coarse woody debris can retain mobilized sediments and therefore reduce hillslope and torrential debris flows [75–79]. Large-scale datasets indicate lower frequencies [80] and runout lengths [81] of debris flows and debris avalanches in mature forests in relation to other land uses or clear-cuts and young forest. However, the reduction of runout lengths may be an effect of smaller landslide densities and erosion volumes in mature forests rather than a barrier effect [76]. Results of [78] indicate a higher potential of trees and logs to retain debris at low-order section of rivers than on alluvial fans. Detrainment of debris on alluvial fans by forest depends on sediment concentration and tree density [82]. Trees increase the flow resistance and favor the deposition of materials due to detrainment of (coarse) debris, but the protective effect is difficult to assess (**Figure 7**).

Figure 7.
Detrainment of coarse debris from a debris flow by forest at the alluvial fan. Photo: F. Perzl, 2012.

2.3 Protective effects of forests against rockfall

The main function and effect of forests in rockfall protection is to stop or to mitigate rockfall propagation in the transit or deposition zone. Effects of forests in rockfall starting zones are ambiguous [83, 84], and presence of forest may increase the onset probability of rockfall by chemical rock weathering through root exudates, root pressure and transmission of loads. The mitigation of rockfall initiation on steep and rocky release areas by silvicultural measures is limited to the removal of unstable trees to avoid block mobilization.

Forests reduce the propagation probability and the intensity of rockfall as impacts on trees and logs along the track dissipate kinetic energy as well as that rocks get caught by the stems [85]. Forests do not resist large rock masses in motion. Statements on single block volumes that might be stopped or slowed down by forest vary from about 1 m^3 to a maximum of 20 m^3 [86, 87]. However, the protective potential of forests in rockfall mitigation depends on the local situation and cannot be based on block volume alone. The protective effect is an issue at the stand-scale and especially at the slope-scale but influenced by single tree characteristics.

Trees absorb most of the impact energy of rocks by the root soil system followed by bending of stems and penetration into the wooden body [88]. The anchorage to soil correlates positively to stem and tree biomass [88]. Consequently, trees large in diameter and with long canopies are appropriate for energy dissipation. However, small trees are also able to stop larger rocks dependent on the hazard, terrain, and forest conditions, especially if the energy has already been dissipated along the trajectory by enough impacts on large trees (**Figure 8**) [85]. The protective effect of smaller trees depends on their spatial arrangement into interceptive collectives like coppice crops [89] and is adequate for smaller boulders (<0.5 m^3) [90]. The stem density targets in the European guidelines reflect the discussions on protective diameters which vary from a minimum DBH of 12 to 34 cm (**Table 3**) but may also be influenced by measurement conventions. Broadleaved hardwoods can absorb more energy than conifers and broadleaved softwoods [86]. Additionally, the capacity of broadleaved species to recover from rockfall damage due to wound healing and sprouting is higher than of conifers [91]. In high mountain areas, where growth capacities of angiosperms are limited, *Larix decidua* Mill. is an option to improve rockfall protection by tree selection, since European larch shows considerable resistance and damage recovery (**Figure 8**) [91, 92].

At the slope-scale, the protective effect of forest depends on the rock size, shape and energy, the terrain morphology and surface conditions like roughness and the damping potential of the soil, and the length of the forested slope as well as the density of the forest cover. The protective density of the forest is indicated by the (average) stem density or basal area (**Table 3**). Both approaches require the definition of the protective stem diameter. The usability of both approaches for risk assessments is limited by two facts: 1) forest density may vary considerably on a small spatial scale and stem distributions may change from random to clumped and 2) the length of the forested slope influences the protective density. Furthermore, concepts which are based on block diameters neglect that the block diameters of mobilizable rocks are

Figure 8.
Left – small beech and sycamore trees stopped a boulder of about 1.5 to 2 m^3 (Photo: F. Perzl), right – a wedge-shaped boulder caught by a larch and a spruce tree (Photo: K. Suntinger).

Guideline	NaiS & SFP "minimum"	GSM-N	GSM-S	ISDW
Spatial level	plot (stand)			site* (stand)
Starting zone	—	gap length ≤20 m	—	same values as in the transit zone
Transit zone	stem density	stem density	stem density & basal area	stem density & young growth
Block diameter <40 cm	≥400/ha DBH >12 cm	—	—	—
Block diameter 40–60 cm	≥300/ha DBH >24 cm	—	—	—
Block diameter 60–180 cm	≥150/ha DBH >34 cm	—	—	—
	—	≥796/ha DBH >20 cm (>25 m^2/ha)	>350/ha DBH >17.5 cm and >25 m^2/ha	>400/ha DBH >20 cm and CCPY ≥15%
	gap length	gap length	gap length	gap length
	<20 m	if coppice <20 m if high forest <40 m	—	≤20 m
Deposition zone	stem density	all criteria	all criteria	all criteria
—	≥400/ha DBH >12 cm	same as in the transit zone	same as in the transit zone	same as in the transit zone
—	gap length	—	—	gap length
—	<20 m	—	—	≤20 m
Length of the forested slope	—	>200 m	>200 m	—

DBH, diameter of stems at breast height [cm]; CCPY, canopy cover of "young" trees DBH <20 cm.
Sites along the rockfall slope defined by different slope gradients.

Table 3.
Protective effect-related targets of the forest structure against rockfall propagation according to the European guidelines NaiS [29], SFP [30], GSM-N [31], GSM-S [32] and ISDW [33].

difficult to predict, and that rockfall source areas usually deliver rocks of different sizes. Therefore, it is difficult to define applicable recommendations on silvicultural targets or critical values. A critical (average) forest density on the stand-scale does not indicate a low protection by forest inevitably as small-scale topographic features, stumps, logs or other stands may substitute the barrier effects or not. The gap concept implements the spatial variety in forest density but is affected by the same limitations. Kalberer [93] for example found a high rockfall risk reduction by forest in a study area, although the forest did not fulfill the requirements according to NaiS (**Table 3**). This was an effect of the length of the slope covered by forest and of cumulative effects of the woody vegetation [93]. Therefore, the recommendations in NaiS [29] have been replaced by an online tool, which implements the length of the forested slope, but refers to the average stem density or basal area on the slope-level [87].

The European guidelines consider the basal area (or stem density), some also a minimum length of the forested slope and the gap length, but they do not refer to effects of cumulative gap lengths and basal areas as proposed by [93, 94]. Some of the guidelines do not clearly disclose the relation of the targets to the considered spatial level [7]. However, a protective function (and effect) should not be allocated to a minimum slope length covered by forest as the protective potential also depends on the terrain morphology. It is not possible to define a forested slope length that has no relevant protective effect and thus no protective function [94].

3. Conclusions

Forests can prevent the formation of snow avalanches. They may also reduce the likelihood of shallow-seated slope failures and mitigate smaller rockfall. But they are unable to stop large masses of snow, soil and rock in motion. Therefore, natural hazard risk and forest management focus on the mitigation of onset probabilities at the stand-scale. The state of knowledge on protective effects of forests has been condensed into expert-based guidelines with quantitative forestry objectives. Forest effects on hazard propagation are difficult to implement in forest and risk management via guidelines, as local conditions vary considerably. The existing assessment procedures consider the protective mechanisms and their controlling conditions to varying degrees, depending on the state of knowledge and the complexity of data collection and process assessment that can be applied. Even in terms of hazard initiation, the guidelines propose quite different silvicultural targets which may result in under- or overestimations of protective effects. Recommendations on critical canopy covers, stem densities and sizes of openings should be treated with caution, even though they are frequently quoted and applied in a multitude of scientific and practical studies. The assessment of the protective effects of forest is still associated with uncertainty which also arise from the considered risk acceptance level, spatial scale and data issues.

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