D.T1.4.1 Report on "Protection forest management in practice in the AS – a silvicultural and economical survey"

WP1

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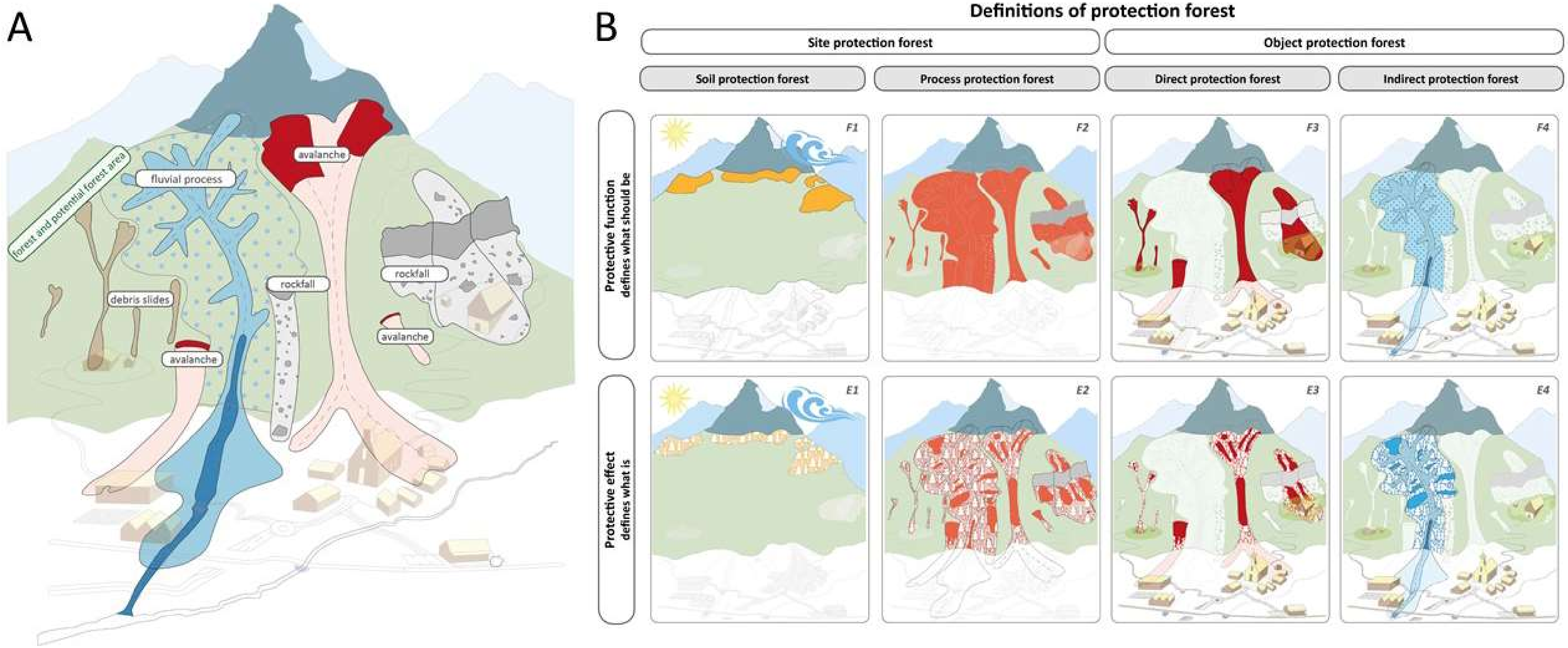
1 INTRODUCTION

Mountain forests that cover alpine slopes are key in ecosystem-based disaster risk reduction and management. The overall aim of GreenRisk4ALPs (GR4A) is, therefore, to develop ecosystem-based approaches that support risk mitigation actions in connection with natural hazards and climate change. Understanding interaction between natural hazard processes and forest ecosystems is important for the development of such approaches.

The important role of mountain forests is reflected in various terms such as protection forest, protective function and protective effect that are used inconsistently and sometimes misleadingly both nationally and internationally. To support a clear communication among scientists, engineers, stakeholders and with the public, we developed a consistent Protection Forest Definition Matrix (Figure 1; Kleemayr et al., 2019).

In GR4A and this report, we mainly focus on direct object protection forest where the Protection Forest Definition Matrix clearly distinguishes between protective function and protective effect. That is, a forest with a direct object protective function designation is a forest or a potential forest area intended to protect against gravitational natural hazards. In contrast, the term protective effect implies a description of the forest structure (e.g. in terms of tree species composition, diameter at breast height [dbh] distribution, basal area, stand height, forest layering), which allows one to assess the actual protective capacity of a protection forest.

This report provides a summary of protection forest management practices in the Alpine Space (AS) and of state-of-the-art of scientific knowledge on protective effects of forests against natural hazards. After a brief introduction on basic concepts and features of protection forests in the AS (Chapter 2), we included a review of important literature (Chapter 3) and an analysis of the different legislative frameworks for protection forest management that exist across the AS countries (Chapter 4). In Chapters 5 and 6, we present a detailed description of the characteristics of a typical protection forest in relation to different hazards and compare them to technical protection measures. The report ends with a conclusion summarizing the gathered information (Chapter 7).



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2 PROTECTION FORESTS IN THE ALPINE SPACE

Forests serve important roles in protection against natural hazard due to their ability to affect natural hazard frequencies and magnitudes. From an ecological point of view, natural hazards are defined as "a natural factor that has the potential to cause damage to people or assets" (Brang et al., 2001). Protection forests are defined as "a forest that has as its primary function the protection of people or assets against the impacts of natural hazards or adverse climate" (Brang et al., 2001). Simultaneously to protection, mountain forests also provide many other ecosystem services (ES) such as clean drinking water, biodiversity, recreation and wood production (Grêt-Regamey et al., 2008).

The mismanagement and consequent decline of forest ecosystems can be a trigger for natural hazards, such as avalanches, landslides and rockfall, which not only limits the capacities of ecosystems to reduce the risk from natural hazards, but also increases hazard levels. To slow this unsustainable development, in 2000 the "Millennium Development Goals" highlighted the urgency of cooperating between countries to reduce the number and severity of natural hazards (de Jesùs Arce-Mojica et al., 2019). The Fifth Meeting of the Conference of the Parties to the Convention on Biological Diversity (COP-05, 2005) defined "preserving of ecosystem structure and functioning to sustain ecosystem services" as primary objective for the management, conservation and sustainable use of natural resources (land, water and living resources) (de Jesùs Arce-Mojica et al., 2019). Later in 2012, outcomes of the United Nations Conference on Sustainable Development (Rio+20, 2012) contain clear and practical measures for implementing sustainable development. The Member States decided to launch a process to develop a set of 17 Sustainable Development Goals (SDGs), which were adopted by all United Nations Member States in 2015.

The protective function of forests is primarily provided by the presence of living trees. For example, tree stems interact with falling rocks and can stop them, tree crowns intercept snow and prevent the creation of homogeneous weak snow layers that are key to avalanche formation, tree root systems increase soil stability reducing soil erosion and increasing the available soil volume for water storage. Dead standing or downed trees, logs and stumps have an important role as well, acting as a barrier and obstacle for downslope mass transfer or stabilizing the snowpack (Dorren et al., 2005; Teich et al., 2019). Similarly, root systems of dead trees can maintain their soil stabilization effect for a few years after a disturbance event (Brang et al., 2006). The protective function of forests should be permanently maintained; to obtain this the ecosystem has to be "stable". Ecological stability is a complex concept used to explain how ecosystems react to disturbance agents. In our context, and on a long-time scale, stability may be summarized in three main concepts that are related to the management of forests ecosystems: resistance, resilience and elasticity (Brang, 2001). Grimm and Wissel (1997) defined them as:

- Resistance: the capacity to "staying essentially unchanged despite the presence of disturbances".
- Resilience: the ability of a system to "returning to the reference state (or dynamic) after a temporary disturbance".
- Elasticity: the "speed of return to the reference state (or dynamic) after a temporary disturbance".

Resilience and elasticity have similar meanings. Here, we assume that they are two aspects of resilience (Brang et al., 2001). To understand these concepts though, one must define what a reference state is. In the European Alps, the reference state is a result of the interaction between natural dynamics and human disturbance regimes, even if the "true" reference state should be a natural forest, which is not easy to identify because of past climatic, ecological and land-use changes. Therefore, after a disturbance event it is suggested to allow ecosystems to develop along natural successional pathways (Brang et al., 2001). However, high resistance and high resilience are not required for all ecosystem characteristics, but only for those that are fundamental for the protective function and functioning of forest ecosystems (Brang et al., 2001). Thus, protection forest management has the objective to maintain and improve the capacity of a stand to remain as unchanged as possible when affected by a disturbance (resistance) and to return to an optimal protective effect as soon as possible after a disturbance (resilience-elasticity) (Vergani et al., 2017b). To optimize management strategies, we commonly use and monitor parameters such as canopy cover, stem-diameter distribution, basal area and species composition of forest stands (Brang et al., 2006; Gauquelin et al., 2006).

In general, Alpine forests show a satisfying degree of resilience, as demonstrated by the fast recovery of forests over the last two centuries after long periods of human disturbances. This recovery through forest expansion and densification is also due to artificial afforestation (Brang, 2001). European mountain ecosystems with low resilience can be found on sites where soil erosion is the main ongoing process and, in these cases, recovery may take place over long time periods (several centuries) or full recovery may never be reached. Resilience of a protection forest mainly depends on the presence of seedlings and saplings in a stand along with their growth patterns and density (Brang, 2001).

Presently, subalpine forests often have long restoration times (over several decades) because of an often-exiguous seedbank. This is due to a variety of factors, including low presence of seed trees, infrequent years of seed production and slow tree growth rates that decrease with increasing altitude (Brang, 2001; Brang et al., 2006). Other factors that influence regeneration, especially in case of conifers, is the absence of suitable seedbeds, in particular nurse logs that can be scarce in managed forests. Also, ecological factors such as light, water and competition with herbaceous layers negatively influence the success rate of seedlings. Finally, ungulate browsing and pathogen attacks further decrease regeneration of forest stand (Brang et al., 2006). Most of the subalpine forests in Europe are composed of coniferous species such as Norway spruce (*Picea abies* Karst.), silver fir (*Abies alba* Mill.) and European larch (*Larix decidua* Mill.), while broadleaved species such as European beech (*Fagus sylvatica* L.), mountain maple (*Acer pseudoplatanus* L.), oak species (*Quercus* L.), hazelnut (*Corylus avellane* L.) or chestnut (*Castanea sativa* Mill.) are dominating at lower altitudes. Although in many central European areas these broadleaved forests have been replaced by Norway spruce monocultures for economic reasons, the relevance of broadleaves is high especially under changing climate conditions.

3 LITERATURE REVIEW

We searched the existing scientific literature (Scopus database) using the query ‘TITLE-ABS-KEY’ (Title, Abstract, Keywords) with the search terms “protection” or “protective” and “forest*” and “natural hazard” or “natural disturbance”. The search resulted in 382 unique records and after filtering out irrelevant and inaccessible publications, the total number of reviewed studies was 86.

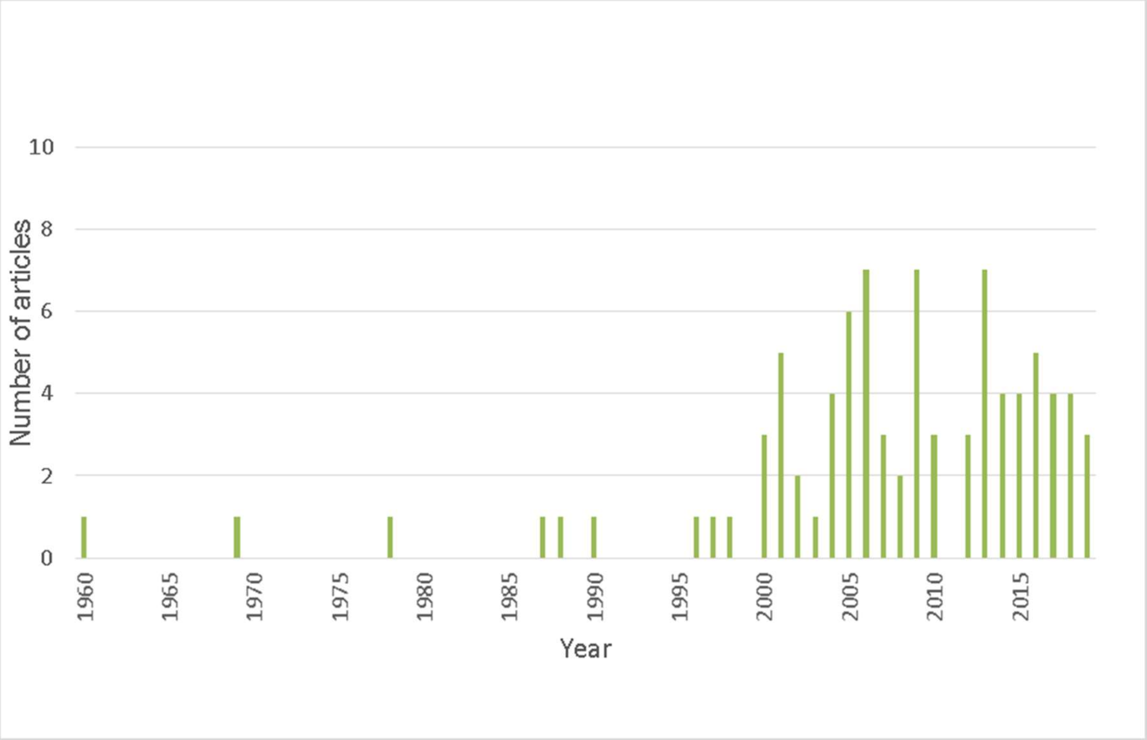
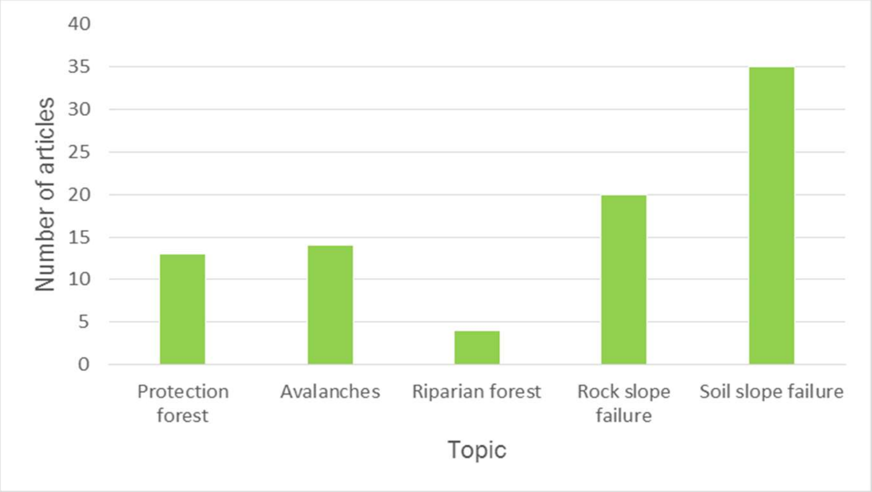


Figure 2. Temporal trend between 1960 and 2019 of the number of papers obtained from a literature review (Scopus database) using the query ‘TITLE-ABS-KEY’ (Title, Abstract, Keywords) with the search terms “protection” or “protective” and “forest*” and “natural hazard” or “natural disturbance”.

The selected articles were published between 1960 and 2019, but the largest majority (90%) were published in the last twenty years (Figure 2).

Dividing the articles by topic, we found that 41% of the studies focused on soil slope (shallow landslides) and 24% rock slope (rockfall) failures (see Section 4.2 for definitions), 16% on snow avalanches and 5% on fluvial processes. The remaining 14% were about protection forests in general (Figure 3).

Most of the papers found through this literature review were used to write the present report, but many other publications and “grey” literature in non-English languages were added to make this state-of-the-art summary more complete. For example, in addition to peer-reviewed manuscripts, we also used manuals and other technical documents covering the management of protection or riparian forests.



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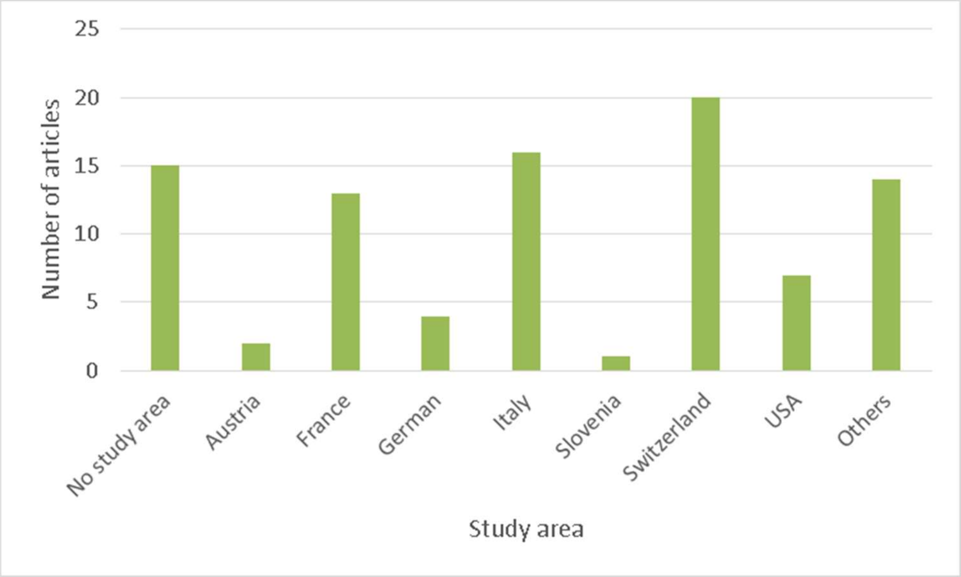


Figure 4. Number of papers obtained from a literature review (Scopus database), divided by geographic location.

The majority (50%) of the publications were focused on the Alpine Space region: Switzerland (22%), Italy (17%), France (14%), Germany (4%), Austria (2%) and Slovenia (1%). The rest of studies were located in other European countries (15%) or the United States of America (8%) (Figure 4). If we look at the journals that published the majority of papers on the topic "protection forests against natural hazards" we observe a very diverse situation, which means that the topic is particularly multi-disciplinary including disciplines such as ecology, engineering, geology and others (Figure 5).

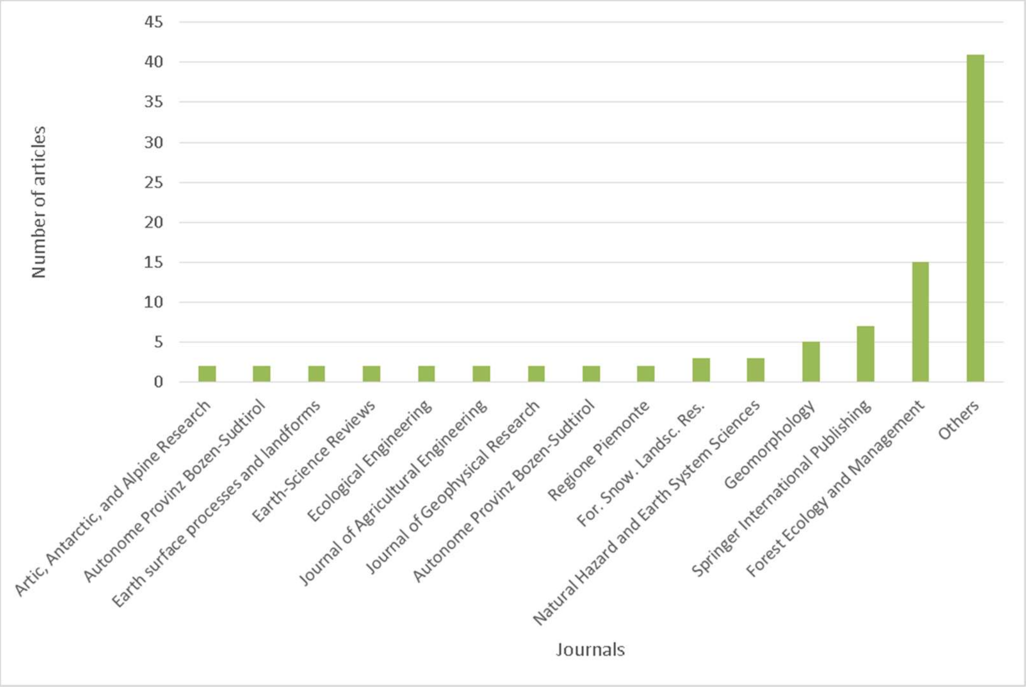


Figure 5. Number of papers obtained from a literature review (Scopus database), divided by scientific journal (source of publication).

4 NATIONAL CRITERIA FOR THE DEFINITION OF PROTECTION FORESTS

In the Alpine Space, the state-of-the-art of legal regulations for protection forest definitions and management are highly variable since each country has a different set of regulations. In all the alpine countries there are laws and rules that define what a protection forest is and, in most of the cases, how it must be managed or which actions are prohibited.

In the following chapter, brief descriptions of legal regulations for each country of the Alpine Space are presented.

4.1 AUSTRIA

4.1.1 Regulations

The Austrian Forest Act (ForstG, 1975) regulates and defines the various functions of forests such as protection against natural hazards, together with the corresponding executive regulations (WEP-V, 1977) and guidelines (BMLFUW, 2012).

4.1.2 Definitions

Protection forest can have two functions:

- To protect people, settlements, and infrastructure from impact by natural hazards or harmful emissions (object protection forest);
- To protect the soil from degradation and erosion, and to ensure forest growth capacity (site protection forest) (ForstG, 1975; Perzl, 2014).

The Austrian regulatory framework implies a differentiation between "forests with protective functions" and "protection forests" (Perzl, 2014). The terms "protective function" and "protective effect" of forests are used synonymously in Austrian regulations and guidelines, but they may in fact describe different aspects (Riegert & Bader, 2010; Perzl, 2014). In the forest act (ForstG, 1975), the term protective effect is mainly used in the context of protection measures, forest or risk management since the protective effect describes the actual protective capacity of a forest against natural hazards or soil degradation.

The term protective function is used to define functional areas ("forests with protective functions") as stated in the Forest Development Plan (Waldentwicklungsplan WEP) according to the Regulation of the Forest Development Plan (WEP-V, 1977). However, the technical guideline on forest function mapping (BMLFUW, 2012) also uses the term "forest with protective effect" for forests with protective function. This confusing mix of terms will be changed and clarified in the next technical guideline.

If there is a need for site and/or object protection due to the natural or man-made situation, the forest has an assigned protective function, regardless of the condition of the forest (BMLFUW, 2012). A forest with protective function is designated as a protection forest, if a specific forest management strategy is necessary in order to achieve or maintain the protective effect (ForstG, 1975).

4.1.3 Management

Site and object protection forests are subject to specific legislations of federal and state law. The Austrian Forest Act (ForstG, 1975) and the regulation of the management and use of protection forests (SchutzwaldV, 1977) contain regulations different from non-protection forests at the federal level.

For example, clear-cutting is completely prohibited if it endangers the protective effect of object and site protection forests (ForstG 1975, § 82, 1 a). Official authorization is needed for clear-cutting of forest that reduce the crown coverage to less than 50% of an area of 0.5 ha or more (ForstG 1975, § 82, 85). For protection forests the thresholds are 80% and 0.2 ha (SchutzwaldV 1977, § 1). The states of Salzburg, Tyrol and Vorarlberg however are entitled to lower the threshold values for the approval of clear-cutting operations. In Tyrol und Vorarlberg, all harvesting in protection forests and in Salzburg at the tree line are subject to registration and authorization. Forest authorities are also obliged or entitled to adjust regeneration time frames (ForstG 1975, § 13) and to determine methods of reforestation, slope stabilization, and to restrict forest use for pasture or harvesting (ForstG 1975, § 24, § 100, § 101, SchutzwaldV 1977, § 2, § 3).

The mapping of "forests with protective functions" and the strategic planning of measures to maintain and improve the protective effect of forests is the content of the Forest Development Plan (BMLFUW 2012). The cartographic representation of "forests with protective functions" is part of the forest function map. The scale of the forest function map is 1:50,000 with a minimum size of 10 ha per mapped polygon. However, this map does not show the “direct object protection forests" or the degree of protection by forests, but functional landscape units where the protective effect of the forest would be important, which could also be the case on non-forested areas.

Another instrument of natural hazard management in connection with protective functions and effects is the hazard zone mapping. In order to reduce the impact of natural hazards on infrastructure and settlements, the hazard zone plans in Austria show hazard zones of torrents, floods, debris floods and avalanches on different map scales (hazard susceptibility and hazard zone maps). Landslides (rock and soil slope failures) are entered as hazard susceptibility in hazard zone maps, but the legal regulations concerning these hazards are not sufficient to designate legally binding hazard zones of landslides (Sausgruber, 2019). The hazard zone plans support protection forest management as they point to areas with forests of limited protective effect. However, this information is limited to the forests concerning the main area of settlement (Perzl & Huber, 2015).

4.2 FRANCE

4.2.1 Regulations

During the period 1845-1860, all the major French rivers flooded and, using the concepts of hydrology, these floods had very high return periods, often far exceeding the centennial reference (flood with a one in a hundred chance of occurring in a given year). These floods escalated the debate on erosion and the need for reforestation. These debates were the origin of the law of 1860 on afforestation, in 1864 of the law on the "re-grassing" of mountains and finally of the law of 1882 for the restoration of land in the mountains. This last law established the “RTM” (Restauration de Terrain en Montagne: restoration of land in the mountains) perimeter for public lands. The law of 28 April 1922 established the status of protection forest, known as the "Chauveau law", that made it possible, beyond the public RTM perimeters, to classify wooded plots whose conservation was necessary to maintain the land, and thus to fight against the abusive exploitation of certain forests. This law provided that the classification was pronounced by ministerial decree, after the opinion of the State Council. The Chauveau law was a judicious addition to the 1882 law. It allowed the administration to subject forests, whoever the owners, to very restrictive regulations without any obligation of expropriation or defense.

Nowadays, the public utility of restoration and reforestation necessary for the maintenance and protection of land in mountain areas and for the regulation of the water regime is declared by decree in the Council State at the request of the Minister in charge of forests, a local authority or a group of local authorities. This decree, which sets the perimeter of the land on which the work is to be carried out, is taken after:

- An investigation opened in each of the municipalities concerned;
- A deliberation of the municipal councils of these municipalities;
- The opinion of the departmental council;
- The opinion of a special commission, the composition of which, fixed by decree, and includes representatives of the State and representatives of the territorial authorities concerned in equal shares. The departmental councilor representing the canton where the land included in the scope of work is located, as well as the owners of such land, may not be part of this commission.

In 1949 it was accepted that classification could also be pronounced by prefectural decree, if the project had not met with any opposition. The prefectural decree is based on a verbal report drawn up by the Departmental Director of Agriculture (DDA), in collaboration with the competent services, the ONF (National Forest Service), the CRPF (Regional Centre for Forest Property) and the mayors of the municipalities concerned or the private owner. However, only few forests have the official status of protection forests. In large part, they are public property and this designation generally covers the public RTM perimeters.

This law has been regularly amended since 1976 for taking into account the evolution of scientific and technical knowledge but also the societal demand for the valorization of ecosystem services.

The latest important evolution to date of the chapter on the prevention of natural risks in the French forestry code is the creation of article L144 (Order n°2012-92 of 26 January 2012 - art. V) which stipulates:

- The plans for the prevention of foreseeable natural risks (PPRn in French), drawn up in accordance with the articles of the Environmental Code, the purpose of which is to prevent flooding, land movements or avalanches, may provide for rules for forest management and exploitation in the risk areas they determine.

These approved rules are required:

- To forest owners and operators;
- To the authorities responsible for approving forest management documents drawn up pursuant to this code, as well as to those responsible for examining the cutting authorizations provided for in this code or the prior declaration provided for in the Town Planning Code.

4.2.2 Definitions

In consideration of the peculiar situation described above, in France, the official definition of protection forest is covering a wide range of different situations.

May be classified as protection forests, for reasons of public utility, after a public inquiry carried out in accordance with the French Forest Code and French Environmental Code:

- Woodlands and forests whose conservation are recognized as necessary to maintain land on mountains and slopes, to defend against avalanches, erosion and flooding of water and sand;
- Woodlands and forests located on the periphery of large urban areas;

- Woodlands and forests located in areas where their maintenance is necessary either for ecological reasons or for the well-being of the population.

Classification as a protection forest prohibits any change of use or land use that could compromise the conservation or protection of afforestation. As soon as the owner is notified of the intention to classify a forest as a protection forest, no modification may be made to the inventory of fixtures, no cutting may be carried out and no user rights created for fifteen months from the date of notification, unless authorized by the administrative authority of the State. When a wood or forest extends over several departments, the minister in charge of forests instructs one of the prefects to centralize the procedure.

4.2.3 Management

Protection forests are subject to a special regime, determined by decree by the Council of the State, concerning in particular the management and rules of exploitation, the exercise of grazing and use rights, excavations and extraction of materials as well as the research and exploitation of water resources by public authorities or their delegates.

The compensation that may be claimed by owners and holders of a right of use, in the event that the classification of their forests as protection forest results in a reduction in income, shall be paid, taking into account any capital gains resulting from the work carried out and the measures taken by the State, either by direct agreement with the administration or, failing that, by decision of the administrative court.

The State may also acquire the wood and forests thus classified. The owner may require this acquisition, if he justifies that the classification as a protection forest deprives him of half of the normal income he receives from his forest. The acquisition takes place either by mutual agreement or by expropriation.

No clearing, excavation, extraction of materials, public or private infrastructure rights-of-way, raising of the ground or deposition may be carried out in a protection forest, with the exception of work intended to create the equipment essential for the development and protection of the forest and provided that this work does not fundamentally change the forest designation of the land.

The owner may carry out this work subject to the application of laws and regulations, provided that the Departmental Director of Agriculture was notified two months in advance by registered letter and has not objected. The owner's declaration indicates the nature and importance of the work and is accompanied by a map. Where the work has been carried out in disregard of the provisions of Forestry Code, the restoration of the premises may be ordered and carried out.

Two guides for foresters are available to assess the protective effect of a stand and for defining forest management objectives and strategies: one for the northern part of the French Alps (Gauquelin et al., 2006), and one for the southern part of the French Alps (Ladier et al., 2011). These guide can be used for fixing the rules for forest management and exploitation in 1) the risk areas determined by the Risk Prevention Plan, 2) the forests defined as having a protective ecosystem service in the forest management plan (public and private ones), and 3) the allocation of the European Agricultural Fund for Rural Development in France for supporting material investments and silvicultural work aimed at reducing the intensity and frequency of natural risks.

4.3 GERMANY

4.3.1 Regulations

In Germany, the regulation framework is different from region to region. In case of the Bavarian Region, the Bavarian Forest Law (BayWaldG) is the only regulation in place.

4.3.2 Definitions

Art. 10 BayWaldG:

1) A protection forest is a forest that:

- Grows in the high alpine and ridge areas of the Alps and in the low mountain ranges;
- Grows on soils that are prone to karstification or are highly susceptible to erosion;
- Prevents avalanches, rockfall, landslides, floods, ground drifts or similar hazards, or preserves river banks.

2) A protection forest is a forest that protects neighboring forest stands from storm damage.

- For the protection forest referred to in point 1, protection forest directories shall be created ex officio within ten years of the entry into force of this act. Before the protection forest register is established, the protective function of a forest has to be defined. Apart from the forest owner, third parties who are able to prove a legitimate interest can also apply for this status.
- If, in the case of point 2, there are doubts as whether a forest is a protection forest or not, this shall be determined on application or by official initiative.
- The state government issues by ordinance rules on the creation, content and management of the protection forest directories and the inspection of these directories.

4.3.3 Management

The Bavarian Ministry of Food, Agriculture and Forestry is responsible for monitoring and compliance of the Bavarian Forest Law. Furthermore, to advice private forest owners is the task of the ministry respectively the local offices of Bavarian Ministry of Food, Agriculture and Forestry.

In the handbook “Der Berg- und Schutzwald in den Bayerischen Alpen” (The mountain and protection forest in the Bavarian Alps) the Bavarian Ministry of Food, Agriculture and Forestry (2016) has described its principles for the management of alpine forest for private forests as:

- Forests that protect against avalanches, floods, erosion and rockfall;
- Protection forests should be uneven aged and comprised of mixed stands;
- Protection forests have to be permanent;
- Interventions in a protection forest include:
  - Regeneration in timing;
  - Regular thinning treatment;
  - Protects the soil and ground;
  - A financial support to private forest owners provided by the State of Bavaria, since the cost of maintaining protection forests is expensive;
  - The state forest must be a role model.

Aside from the Bavarian Ministry of Food, Agriculture and Forestry, which oversees private forest owners, there is also the Bavarian State Forestry, a company that manages the Bavarian state forests. They have their own set of rules for managing alpine forests found in the handbook “Grundsätze für die Waldbewirtschaftung im Hochgebirge bei den Bayerischen Staatsforsten” (Principles for the forest management in the high mountains of the Bavarian State Forest Service; BaySF, 2018a, b). Some important points summarized from their document include:

- The preservation and improvement of protective functions of mountain forests always take precedence, in doubt, over all other requirements;
- Forest management in mountain forests is geared towards forest soils and their capacity, productive potential and protective effect, especially on shallow locations where the main focus is on the humus layer;
- Rising risks for mountain forests and its multiple functions due to climate change has to be addressed through the preservation and creation of site-adapted natural mixed mountain forests species. Risks to protection forests, in particular the risk of bark beetle infestations, are subject to active monitoring and effective preventive and counter measures;
- By regular moderate thinning wood supplies are kept at an optimal level so that the desired structural integrity and an ongoing regeneration can be achieved;
- In mountain forests, a permanently rejuvenated mixed regeneration over the largest possible areas to safeguard the protective functions and silvicultural measures are sought to achieve protective effect goals;
- The intensity of forest management and silvicultural measures is directed in mountain forests based on particular dimensions and site conditions;
- The concerns of conservation are integrated into the management of mountain forests. For conservation, valuable forests are designated separately for rare species, such as the capercaillie, and the silvicultural approach must be then customized to avoid adverse effects on protected species;
- The special significance of mountain forests as recreational areas is used in silvicultural planning and targeted forest management;
- The use of forest technology and infrastructure in mountain forests has to be carried on in order to maintain ecosystem stability, considering site characteristics.
- The hunting of red, chamois and roe deer in mountain forests is one strategy to protect natural regeneration from over browsing and is more site-appropriate in stands with mixed old stocks.

4.4 ITALY

4.4.1 Regulations

Italian legal regulations of protection forests are ascribed to two hierarchical levels: national and regional/province. At the national level, the new Legislative Decree 34/2018 “Consolidated Law on forests and forestry chains” provides definitions and guidelines for forest management. In addition to this, there are laws delegated to regions and to the Autonomous Provinces of Trento and Bolzano which are specified in:

- President of the Republic Decree 11/1972;
- President of the Republic Decree 616/1977;
- Legislative Decree 227/2001;
- Constitutional Law 3/2001.

Each region or Autonomous Province can and has to legislate independently from others. In the Italian side of the Alpine Space only Piedmont, Lombardy, Friuli-Venezia-Giulia and Autonomous Provinces of

Trento and Bolzano have regional/province forest regulations, while the remaining regions (Aosta Valley and Veneto) still follow the Royal Decree 3267/1923 “Outline Forestry Regulations and Strategy”.

4.4.2 Definitions

- Legislative Decree 34/2018, article 3, subparagraph 2r
- Definition of direct protection forests: “wooded area that for its special location plays a role of direct protection of people, property and infrastructure from natural hazards such as avalanches, rockfall, surface slips, torrential lave and others, preventing the event or mitigating the effect (…)”
- Legislative Decree 34/2018, article 8, subparagraph 7
- Forests having the function of direct protection of inhabitants, of strategic assets and infrastructures, identified and recognized by Regions and Autonomous Provinces, cannot be transformed and the land use cannot be changed (…).

4.4.3 Management

Management practices are not defined by legal regulation. However, there are some manuals (e.g. “Selvicoltura nelle foreste di protezione – Esperienze gestionali” Regione Piemonte, A.A. V.V., 2006) providing guidelines and main concepts: Each silvicultural activity must be aimed at improving or maintaining the stability of a forest stand. In most cases, broadleaved forests are preferred because of their ability to grow as coppice stands and to produce high density large diameter stands; coniferous forests are generally found at higher altitudes where site constraints become predominant.

4.5 SLOVENIA

4.5.1 Regulations

In Slovenia there are three legal regulations that define what a protection forest is and how to manage it.

- Forest Act (Official Gazette of RS, Nos. 30/93 , 56/99 - ZON, 67/02 , 110/02 - ZGO-1 115/06 - ORZG40, 110/07 , 106/10 , 63/13 , 101/13 - ZDavNepr, 17/14 , 22/14 - dec. US, 24/15 , 9/16 - ZGGLRS and 77/16)
- Decree on protection forests and forests with a special purpose (Official Gazette of RS, Nos. 88/05 , 56/07 , 29/09 , 91/10 , 1/13 and 39/15)
- The regulation for forest management plans and game management (Official Gazette of RS, no. 91/10)

4.5.2 Definitions

Article 43 of the Slovenian Forest Act (ZG), protection forests are defined:

- Forests in adverse ecological conditions which protect themselves, their land and lower-lying land, and forests in which there is a particular emphasis on any other ecological function, shall be declared protection forests.

In section #2, paragraph #1 of the Decree on protection forests and forests with a special purpose, the definition of protection forests is the following:

- Protection forests are forests that protect their lands of sliding, rinsing and crumbling, forests on steep slopes or banks of waters, forests exposed to strong winds, forests that in the torrential areas delay water drainage and therefore protect the land from erosion and avalanches, forest bands protecting forests and land from the wind, water, snowdrifts and avalanches, forests in agricultural and suburban landscapes with an exceptionally emphasized biodiversity conservation function and forests at the upper limit of forest vegetation.

In the section #22 of The regulation for forest management plans and game management, protective functions of the forests are defined:

- Indirect protective function: the function of protecting forest land and stands (hereinafter: protective function); protecting the site and its surroundings from the effects of all types of erosion processes, in particular ensuring (preserving) the soil's resistance to the erosion phenomena caused by cold, snow, water and wind; prevention of the development (occurrence) of landslides and avalanches; preventing deepening of slope trenches; preventing the deployment of debris; retention of small flowing material; preserving the fertility of forest soils. In particular, forests on the upper forest boundary, in erosion or landslide areas, are determined in accordance with the regulations governing waters, on very steep slopes, dry places, shallow rocky or rocky soils.
- Direct protective function: protection of roads, settlements and other objects from natural phenomena such as falling of rocks and sand, avalanches, side winds and slipping of land, and ensuring the safety of living and infrastructure. Emphasized protective function is performed by forests on steep slopes above and below roads or railroads.

4.5.3 Management

The Slovenia forest service (SFS) is responsible for producing forest management plans for forest management regions and units for all forests in the country, regardless of property size and ownership. These contain all information about existing and proposed protection forests. The latter are divided into forest areas with special purpose and protection forests, where legal regimes permit the exploitation of forest products, and protected areas (protection forests, forests with a special purpose, where the exploitation of wood is not allowed - the regimes do not allow the exploitation of forest products). In *The regulation for forest management plans and game management* economic categories of forests are divided into:

- Multifunctional forests;
- Forests with a special purpose in which forestry measures are allowed;
- Forests with a special purpose in which forestry measures are not permitted or permitted only in exceptional cases;
- Protection forests.

As specified in the *Decree on protection forests and forests with a special purpose*, regarding the management regime for protection forests, SFS must ensure:

- Timely restoration or cutting of old trees;
- Execution of small surface cuts;
- Leaving high stumps when harvesting trees in areas where there is a danger of avalanches or landslides;
- Methods of harvesting and use of harvesting equipment, as defined by the forest management plan of the forest unit;
- Rehabilitation of damaged soils in order to prevent erosion;
- Removal of trees from torrential streams;

- Timely implementation of all forest breeding works that ensure the preservation and stabilization of the protective function of the forest;
- The use of biodegradable oils when working with machinery and appliances.

Furthermore, interventions in protection forests are determined:

- Interventions that are not connected with the management of protection forests and which do not significantly affect the functions of forests for which it was declared a protection forest may be implemented on the basis of a previously obtained permit issued by the Ministry of agriculture, forestry and food.
- The permit referred to in the preceding paragraph shall determine the conditions for carrying out an intervention on the basis of an assessment of the impact of the intervention on the protection forest carried out by the SFS.

SFS must ensure implementation of work that are defined in the forest management plans due to the implementation of the regime for the management of protection forests and forest reservations. Monitoring of the condition of protection forests and forest reservations is carried out by SFS in cooperation with providers of public services in the field of environmental protection, as well as scientific, research and educational organizations.

4.6 SWITZERLAND

4.6.1 Regulations

In Switzerland, the Federal Forest Act (Lfo), 1991, regulates this topic at federal level.

4.6.2 Definitions

- “A protection forest is a forest, which protects an acknowledged damage potential against a natural hazard or reduces the involved risks.”
- Art.19 Lfo: “Where necessary for the protection of human life and significant material assets, the cantons shall secure avalanche, landslide, erosion and rockfall areas and carry out torrent control works in forests. The measures used should be as natural as possible.”
- PLANAT, 2005: considers forests equal to technical or civil engineering measures regarding prevention of natural hazards.

4.6.3 Management

The Swiss guidelines “Nachhaltigkeit und Erfolgskontrolle im Schutzwald NaiS” (Frehner et al., 2005) and its partial translation *“Sustainability and Success Monitoring in Protection Forests”* (Frehner et al., 2007) define national criteria for protection forests against different natural hazard. That is, these guidelines define the forest structure, a minimum forest cover, a minimum gap size, as well as a required degree of regeneration and site-indigenous trees of an optimal protection forest.

5 PROTECTION FOREST STRUCTURE AND NATURAL HAZARDS

The prevention and mitigation of natural hazards is an important ecosystem service provided by forests in mountainous areas (Dorren et al., 2004). The protective capacity of a forest against natural hazard is the result of two main factors: hazard type and stand properties (Dorren et al., 2005). Forests can affect natural hazard dynamics, but protective effects depend on the nature of the process, the frequency and the intensity of damaging events and on the structure, age and the phytosanitary status of the protection forest. Collectively these factors influence the mitigation rate that the forest has on hazard development (Brang et al., 2006). In addition, stand structure is another important component, because each type of natural hazard requires a specific structural characteristic (mean DBH, horizontal distribution and species composition) to optimize forest protective effects. For example, a forest stand with a high protective effect against rockfall events has a different composition than a forest that has a high protective effect against avalanches.

The impact of natural forest disturbances on protective effects against natural hazards varies considerably. Forest stand structure is one of the most important variables in determining forest susceptibility to disturbances (O'Hara and Nagel, 2013). Large-scale disturbances, like wildfires, potentially may uniformly damage the stand. In contrast, snow avalanches usually affect a section of a forest and can leave many trees undamaged and alive outside the avalanche tracks that can still maintain some protective effect. Moreover, interactions between disturbances can amplify hazards. For example, insect outbreaks (e.g. Ips typographus) can increase the impact of storm or snow load through the reduction of canopy cover in infested stands which then also affects the avalanches hazard of a particular area (Brang et al., 2001; Teich et al., 2019). However, following a disturbance such as an insect outbreak or wind event forest stands may be removed or damaged and this may cause a decrease in the protective capacity over short to long time periods (Wohlgemuth et al., 2017). The impact of disturbances on forests is also influenced by stands ecological characteristics: younger and smaller trees are less vulnerable to disturbances like storm and snow load than mature and taller trees. Broadleaves are less vulnerable than conifers to the same natural agents (Brang et al., 2006).

Small-scale disturbances may influence only small areas of a stand leading to multi-aged stands, where individual trees that survive the disturbance form more complex structures compared to stand-replacing disturbance events (O'Hara and Nagel, 2013). Multi-aged stands are more resistant and resilient than even-aged stands (O'Hara and Nagel, 2013) since the range of tree ages and sizes and the diverse stand structure provide more stand resistance thanks to the high spatial heterogeneity. Multi-aged and mixed stands are often more resilient and respond more quickly to disturbances due to the different responses of different species (O'Hara and Nagel, 2013). Moreover, these stands have a multi-layered structure that facilitates the regeneration and the persistence of the protective effect of subalpine forests (Mayer and Stöckli, 2005). Forests that are often affected by natural hazards are low-density stands populated by shade intolerant and pioneer species. In addition, they show limitations in tree development such as small diameter classes, shorter heights and slower annual grow rates (Bebi et al., 2009).

Many protection forests, especially in the central-southern parts of Europe were managed with coppice systems (Figure 6).

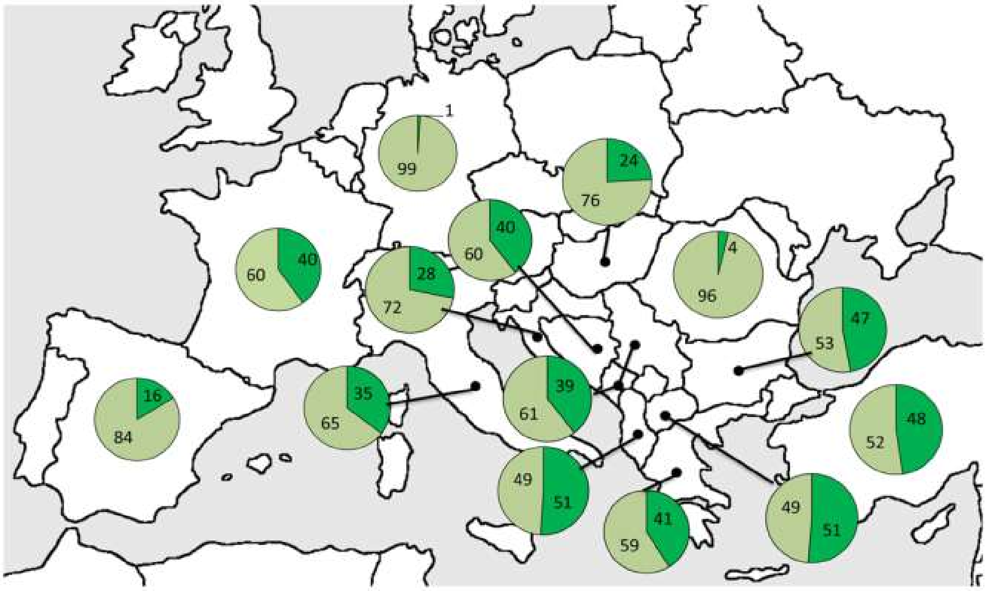


Figure 6. Coppice woodlands as ratio of total forested area per country, in percentage. Dark green: coppice; light green: other forests (Nicolescu et al., 2014).

The most common coppice species in Europe are: European beech (*Fagus sylvatica* L.), oaks (*Quercus* spp.), sweet chestnut (*Castanea sativa* Mill.), limes (*Tilia* spp.), maples (*Acer* spp.), ash (*Fraxinus* spp.), hazel (*Corylus avellana* L.), whitebeam and wild service tree (*Sorbus* spp.), hornbeam (*Carpinus betulus* L.), hop hornbeam (*Ostrya carpinifolia* Scop.), and black locust (*Robinia pseudoacacia* L.) (*Jancke et al.,* 2009).

With regard to their protective function, coppice forests can be advantageous because their higher stem density can reduce significantly rockfall runout length (depending of the volume of the boulder and the length of the forested slope) and the density of the root network increases soil stability. Additionally, their rapid re-growth from stools results in the formation of complete forest cover within a short period of time compared to coniferous forests. Management of coppice woodlands is particularly relevant in the context of protection forests because many coppice stands (in particular on the southern side of the Alps) are uneconomic and have been abandoned and left unmanaged (Vergani et al., 2017a). How to manage a coppice is a key question for practitioners: many different strategies have been developed, which sometimes contradict each other. Ciancio et al. (2006) suggest converting the stands to high forest, others authors (Bassanelli et al., 2013; Conedera et al., 2010) suggest to maintain traditional coppicing, justifying the management costs for this trade-off for the maintenance of slope protection (Vergani et al., 2017a).

5.1 AVALANCHES

Mountain protection forests are key for avalanche mitigation (Brang et al., 2006). The preventive effect of forests on the formation of snow avalanches was recognized in Europe as early as the Middle Ages (Schneebeli and Bebi, 2004), and used as basis for developing the concept of the first technical measures. Avalanches are a typical disturbance of subalpine forests but their return period is different depending on site characteristics such as topography and precipitation regimes. In steep and snow-rich areas, avalanches can occur several times during a single winter season, while in other areas avalanches are much more infrequent and return intervals can be on the order of centuries. Frequent phenomena contribute to maintain a characteristic habitat (e.g. *Alnus viridis* woodlands); on the contrary, infrequent but severe events are able to modify the ecosystem dynamics over long time periods. At sites where avalanches are of high severity and/or frequency, the disturbance can control survival, growth rates and growth forms of plants. With a reduction of severity and/or increase in the time interval between two events vegetation shifts from shrubs to erect trees (Bebi et al., 2009).

Avalanche occurrence is largely influenced by forest structure, snow characteristics and topography (Bebi et al., 2001). The influence of forest characteristics on avalanche occurrence can be either positive or negative. Trees can affect snow transportation by wind strongly affecting the pattern of snow deposition in a release area. For this reason, silviculture plays an important role having the ability to improve the protective effect of forests and reducing avalanche frequency (Brang et al., 2006). Forest management has to considerer the dual relationship between forest and avalanche:

- How do forests influence avalanches?
- How does avalanches affect forests?

Forest response to avalanches depends on the size and the flexibility of trees, the position of the avalanche release area and the avalanche type (e.g. slab, loose snow, glide snow, powder, dry snow and/or wet snow avalanches). Big trees can be broken by avalanches, if the force exerted on them is higher than the breaking strength of the tree, or uprooted, if the breaking strength of the stem is higher than the soil tensile strength of the roots (Bartelt and Stöckli, 2001; Bebi et al., 2009; Feistl et al., 2015). Young trees (height < 5 m) are more flexible and may suffer less damage. In subalpine forests, DBH range for breakage are between 6 to 14 cm, but this is higher for pioneer and short-living broadleaved species (*Betula, Alnus, Acer* and *Salix*) and also shrub-like trees, such as *Pinus mugo* (mountain pine), *Alnus viridis* (green alder) and Betula pendula (silver birch), because of their flexibility and their ability to bend. Plants with intermediate dimensions are often subject to splitting since they have a decreased flexibility but not so much as to bend themselves under the pressure of the snowpack (Bebi et al., 2009). Disturbance frequency also regulates stand structure and biodiversity of the vegetation mosaic in avalanches tracks. Kulakowski et al. (2006) could show that structural habitat diversity was greater in active avalanche paths than in areas in which avalanche activity was suppressed by artificial barriers.

Forests influence both the release and run out distance of avalanches, but knowledge on the latter is less developed. Forest effects in transition zones are limited to reduce lateral spread and speed of small- to medium-size avalanches, while forest structure seems to be negligible for stand-replacing events (Teich et al., 2012; Viglietti et al., 2009). The preventive role of forests on avalanche release depends on the physical processes that stabilize the snowpack within forests including interception of falling snow by tree crowns, modification of the solar radiation and temperature regimes, reduction of near-surface wind speed and direct support of the snowpack by stems (Figure 7) (Schneebeli and Bebi, 2004).

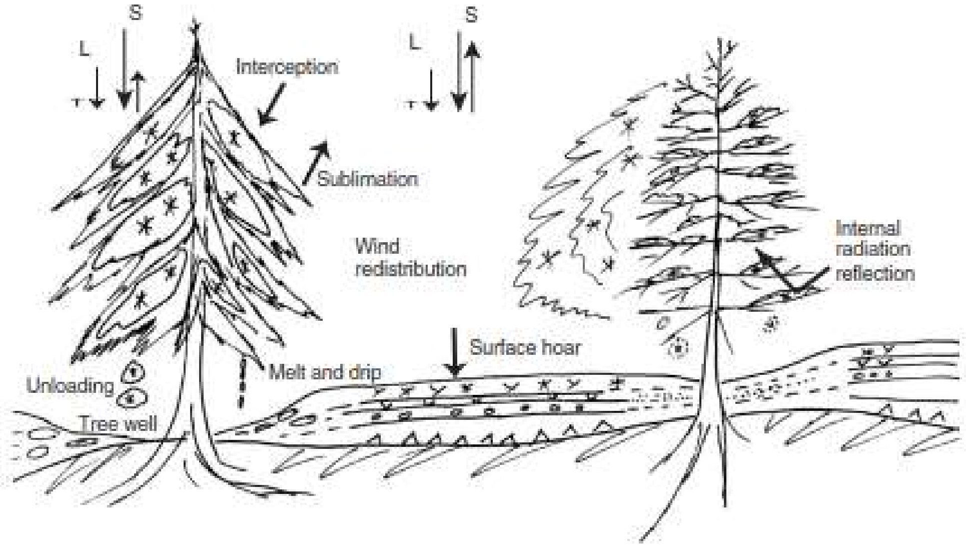
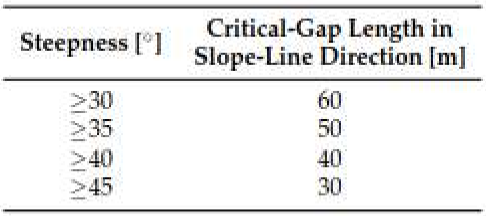


Figure 7. Processes in a snowy forest. The snow precipitation is unevenly deposited. Part of the snow is retained by interception on the trees, and later unloaded by mechanical shaking, melting and dripping as water, redistributed by wind, or sublimated back into the atmosphere. The intensity of these 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 (Schneebeli and Bebi, 2004).

The presence of a continuous forest cover has a stabilization effect on the snowpack. A study by Saeki and Matsuoka (1969) demonstrated that the average height of a tree necessary to stabilize the snowpack should be at least twice the snow depth. The amount of snow intercepted by tree branches depends on tree species and on meteorological conditions during snowfall. Interception of snow is followed by partial unloading caused by warming and wind, resulting in an irregular snowpack around trees, especially evergreen ones.

Tree crowns intercepting falling snow contribute to create a more heterogeneous and thinner snowpack than areas located outside the forest and prevents the formation of weak layers without cohesion, one of the most important factors of snowpack instability (Viglietti et al., 2009). Forest canopy also acts on air temperature causing a lower temperature gradient between the soil and snow surface (Freppaz et al., 2006; Viglietti et al., 2010). The presence of trees also reduces wind speeds and, therefore, snow redistribution and compaction, so that snow layers become less homogenous and accumulations in gullies and depression are reduced (Bebi et al., 2009). On the contrary, in open areas (e.g. forest canopy gaps), wind can accelerate and create considerable snow accumulations (Viglietti et al., 2009). The dimension of gaps is one of the causes of avalanches release: forest gaps in slopes around 35° should not be wider than 50 m and longer than 40 m (Horvat and Zemljič, 1998). In forested areas with a crown cover of 60% and a slope angle of 35° the gap size is 10-15 m in deciduous forests and 20 m in evergreen coniferous ones (Viglietti et al., 2010). Slope steepness is not the only factor that restricts maximum dimensions of gaps, but also the avalanche type, and tree height and canopy cover (see above) are important. In subalpine and upper montane coniferous forests where slab avalanches predominate, the gap width should be smaller than 15 m according to the Swiss guidelines (Frehner et al., 2007). In upper and lower montane mixed forests where wet snow avalanches dominate the maximum gap width is 5 m; Table 1 shows corresponding critical gap lengths (Breschan et al.,2018), but only represents the effect of slope steepness; however, the vertical location of the weak layer in the snowpack and snow density are also important factors. For example, for a mean slope angle of 45° and a snow depth of 1.8 m the critical gap length is 23 m, but reducing the snow depth to 1.2 m the critical gap length increases to 30 m (Gauquelin et al., 2006).

Table 1. Critical-gap lengths for avalanche release proposed by the Swiss guidelines (applies to all forest types) (Breschan et al., 2018).



Steepness [°]	Critical-Gap Length in Slope-Line Direction [m]
≥30	60
≥35	50
≥40	40
≥45	30

Other studies found a correlation between forest structure parameters such as type of forest, density and DBH, and runout distances of avalanches (Teich et al., 2012). Every species has a different impact on avalanche mitigation: for example, conifers have a better snow interception capacity than broadleaves and avalanches that form in evergreen coniferous and mixed forests have a shorter runout distance than deciduous conifers (i.e. Larix decidua Mill.) (Teich et al., 2012). Contrary to general perception, larch forests can offer almost equal avalanche preventive effects compared to evergreen coniferous stands as long as stand densities are comparable (Schneebeli and Bebi, 2004). One consideration in coniferous stands is that the needle litter can enable good sliding conditions, which can cause avalanches, while deciduous species can prevent snow gliding during periods of smaller quantities of snow (Berger et al., 2013). Basal area may be an important factor to quantify the protective capacity of a stand. High basal area is related to high stem density and/or big diameter trees: in a dense stand, trees are able to support each other. On the other hand, plants growing in denser stands might lead to smaller diameter trees that are more vulnerable after a gap opening or after an intense thinning (Pukkala et al., 2016).

Downed woody debris including downed stems, stumps and root plates, are one of the main factors which contribute to small avalanche prevention by increasing forest floor site roughness and snowpack stability (Schneebeli and Bebi, 2004; Viglietti et al., 2009). After a high severity storm event, within the first few decades lying stems increase surface roughness in the starting zone (Teich et al., 2012; Wohlgemuth et al., 2017). Schönenberber et al. (2005) showed uncleared windthrown areas provided better protection against avalanches and rockfall compared to cleared and forested areas. Protection improvement depends on the roughness increasing and less on the presence of gaps because they are occupied by downed stems.

Another soil roughness element is stand density of trees higher than 2 meters that constitute an important factor in reducing the frequency of avalanches. Density relevance is due to the capacity of mature plants to stabilize snowpack only in a few meters (2-3 m) around the stem (Viglietti et al., 2009). A large part of avalanches release in forests are in areas where trees are smaller than 2 m in height (Viglietti et al., 2009).

Swiss guidelines have different opinions about the characteristics that a forest stand must have to protect against avalanche hazard indicating a minimum diameter (DBH) of 8 cm to be effective (Frehner et al., 2007); others refer to the height of the plants that has to be at minimum twice the extreme snow depth (Gauquelin et al., 2006; Vacik et al., 2010).

At the end of 20th century Meyer-Grass (1987) and Schneebeli and Meyer-Grass (1993) considered only diameter at breast height (DBH) bigger than 16 cm to be adequate because small stem diameters are not able to guarantee an effective stabilization, due to their lower resistance to the snow cover static pressure (Viglietti, 2010). Other researchers noticed that the percentage of small diameter trees (between 1 and 15 cm) show a positive effect in the runout zones of small and medium avalanches (Teich et al., 2012). Teich et al. (2012) demonstrated that small mean DBH are particularly important in the release area and in the first 200 m of an avalanche path, because avalanches released within larger diameter stands have a longer runout distance, due to negative correlations between tree size and tree density. On the contrary, smaller stems bending or subjected to a complete deflection may dissipate a lot of avalanche energy and decrease the speed of a small avalanche. Small trees, due to their elasticity, are not damaged during avalanche events so they can maintain their protective function afterwards (Teich et al., 2012). The combination of these two factors, high density of small diameter evergreen coniferous trees, prevented small avalanches from becoming larger due to increasing crown cover and higher interception effects (Teich et al., 2012). Meyer-Grass (1987) showed that the protective effect of forests against avalanches requires a stem density larger than 250 trees/ha and a tree height greater than 3 meters. If the avalanches start within a forest with a good stand structure, the forest itself is able to stop small avalanches within a critical distance of 200-400 m (Teich. et al., 2012). Other studies showed that if slope steepness and snow depth increase, larger stems (DBH greater than 16 cm) are needed because they can resist strong static pressure by snow cover (Meyer-Grass, 1987).

Topography also serve an important role on avalanche tracks and runout zones. Snow avalanches cover a longer path in concave terrain compared to flat or convex slopes. A high surface roughness in starting zones, reduces snow gliding and runout distance compared to starting zones comprised of bare soil (Teich et al., 2012; Viglietti et al., 2009). To achieve low-intensity glide rates 300-350 stems/ha on moderately steep slopes (30°), and 1000 to 2000 stems/ha on steeper (40° or more) slopes are required (Teich et al., 2012; Horvat and Zemljič, 1998). Analyses of the interacting effects of topography and forest presence showed that on sites where crown cover is less 30% avalanche formation is a question of steepness. When forest cover ranges between 30% and 50%, avalanches may occur on slope angles of 30° in presence of gaps in deciduous forests. Avalanches formation in coniferous stand with 60% of crown cover required bigger gaps than deciduous forests and a steepness of 35° (Schneebeli and Bebi et al., 2004). All parameters mentioned so far not only affect snowpack stability in potential release areas but may also influence the spatial/lateral extent of small and medium-sized avalanches (Bebi et al., 2009; Viglietti et al., 2010; Teich et al., 2012).

A summary of recommendations regarding optimal forest structures that offer the best protection against avalanches can be found in Table 2 (Schneebeli and Meyer-Grass, 1992; Bebi et al., 2009, Frehner et al., 2005; Berretti et al., 2006; Gauquelin et al., 2006; Berger et al., 2013).

Table 2. Most relevant forest characteristics that influence onset probability, propagation probability and intensity of snow avalanches.

PROTECTION FOREST CHARACTERISTICS AGAINST AVALANCHES				
FOREST CHARACTERISTICS	Release area	Source	Transit and run out zone	Source
canopy cover	Promote evergreen conifers (> 50%) > 80% if slope < 38° in deciduous > 70% if slope < 42° in mixed stands > 35% if slope < 38° in spruce stands > 30% if slope < 35° in spruce and larch stands > 35% if slope < 32° in larch stands	*Bebi et al., 2009; Berretti et al., 2006; Meyer-Grass and Schneebeli, 1992,*	Maintain effective winter canopy cover, > 30% if slope 30° > 50% if slope 35° > 70% if slope ≥ 40° Most relevant in first 100–200 m from the release area.	*Berger et al., 2013; Teich et al., 2012*

species composition	< 30 % of deciduous species (and Larch), Depends on the slope: larch →30°, coniferous →35°, mixed forest →35°, Deciduous trees prevent slow gliding at lower quantities of snow	*Berger et al., 2013; Berretti et al., 2006, Bebi et al., 2009*	Promote evergreen or mixed forest, corridor edge ≥ 70% otherwise ≥ 30%, in areas of powder avalanches, promote deciduous trees	*Teich et al., 2012; Berger et al., 2013*
terrain roughness	leave 1.3 m high stumps after cutting. snags, stumps, root plates, lying logs promotes roughness but are dangerous, because avalanches with debris are more destructive.	*Dorren et al., 2005; Berger et al., 2013*	leave 1.3 m high stumps after cutting. snags, stumps, root plates, lying logs promotes roughness but are dangerous, because avalanches with debris are more destructive.	*Dorren et al., 2005; Berger et al., 2013*
tree size	twice as high compared to snow depth, >2 m	*Frehner et al., 2005; McClung, 2001*		
gap length[α]	≤ 1.5 × average height of trees, absence of gaps > 25 in length, <60 m if slope ≥30° <50 m if slope ≥35° <40 m if slope ≥40° <30 m if slope ≥45°	*Frehner et al., 2005, Berretti et al., 2006, Berger et al., 2013,*	≤ 1.5 × average height of trees	*Berger et al., 2013*
gap width	< 15 m, If gap length is greater than indicated above, gap width must be < 5 (10) m, 5–10 m in deciduous stands 10–20 m in evergreen stands	*Meyer-Grass and Schneebeli, 1992; Berretti et al., 2006; Frehner et al., 2005; Berger et al., 2013, Bebi et al., 2009*	< 15 m	*Berger et al., 2013*
diameter distribution	500 stems/ha with DBH > 8 cm if slope > 30° (G > 2.5m^2/ha)1000 stems/ha with DBH > 8 cm if slope > 40°(G > 5.02m^2/ha)	*Frehner et al., 2005, Berretti et al., 2006*		
Crown size	Promote trees with crowns to their base, especially on the edge of gaps. Promote large crowns for best snow interception.	*Frehner et al., 2005, Berretti et al., 2006*		
Coefficient of stability value (H/D)[β]	coniferous: H/D ≤ 65 broadleaves: H/D ≤ 80	*Berger et al., 2013*	coniferous: H/D ≤ 65 broadleaves: H/D ≤ 80	*Berger et al., 2013*

[α] Measured along the line of the steepest slope. Thresholds for maximum gap lengths are listed; in ideal conditions gap length should be 5 - 10 m smaller.

[β] H/D = Height/DBH (diameter at breast height)

5.2 LANDSLIDES

5.2.1 Definition for practitioners

In the Alpine Space and mountain regions there is no uniform description of gravitational mass movements nor are there clear definitions that can be easily translated from one language into another. Varnes (1978) and Hungr et al. (2014) do provide some examples. However, in the Alpine countries there are different manifestations of these phenomena and therefore a translation for landslides is not consistent. We have therefore identified the need for practitioners to find the best translations and definitions of existing landslide types documented by country-specific definitions and use visual examples given in aerial images as well as through laser scan images to aid in this process. We present definitions for the various processes common in all Alpine countries and explain the definition envelopes for the processes in the different project languages. We use a simplified classification that allows for no differentiation of different geotechnical soils, because GreenRisk4Alps aims are at a regional scale. A geotechnical distinction of the source material is not necessary for a regional assessment of natural hazards, since no assessment of object protection measures is being undertaken. However, we must note at this point that a geotechnical classification of the subsoil is absolutely necessary for a hazard zone map at object protection level. A simple classification of landslides on regional scale might simply be based on geomorphological appearance and dimensions similar to the classification scheme by Crozier (1973).

Landslides occur when gravitational or other shear stresses within a slope exceeds the shear strength of the material forming the slope. The shear stresses might increase by over-steepening at the base of the slope by erosion or excavation. For spontaneous soil slope failures, one of the most important triggering factors are changes in the short-term stresses due to extreme precipitation, hail, snow melt, or earth quakes. Landslides are classified by source material (soil or rock), temporal deformation behavior (kinematics), movement type, process velocity and depth (Cruden and Varnes, 1996). Landslides are divided into two main groups after the velocity of sliding: the (1) slow-moving slope deformations (<1.6 m/a^{-1}) that are defined by complex or creep movement (2) and spontaneous landslides defined by velocities between 1.6 m/a^{-1} and >5 m/s (Cruden and Varnes, 1996; Hungr et al., 2014; Pánek and Klimeš, 2016). In the GreenRisk4Alps project we concentrate on moderate to extremely fast processes (Table 3).

Table 3. Landslide classification by velocity (Cruden and Varnes, 1996; Hungr et al., 2001; Hungr et al., 2014)

Description	Typical processes	Typical velocity	Velocity (mm/s)
Extremely rapid	Rockfall, rock slide, rock avalanche, soil flow, debris flow, debris flood, debris avalanche	5 m/s	$5x10^{3}$
very rapid	Debris avalanche, flow slide, sensitive clay flowslide/spread, debris flow, debris flood, rock slide	3 m/min	$5x10^{1}$
Rapid	Earthflow, rock slide, debris avalanche	1.8 m/h	$5x10^{-1}$
Moderate	Soil slide, earthflow, rock slide, debris slide, earth slide	13 m/month	$5x10^{-3}$
Slow	Slope deformations, earth slide, earthflow, rock slides, debris slide	1.6 m/a^{-1}	$5x10^{-5}$
Very slow	Slope deformations	16 mm/a^{-1}	$5x10^{-7}$
Extremely slow	Slope deformations		

The depth of landslides can be simply divided into shallow and medium to deep landslides, depending on the depth of the sliding surface. However, there are no clear criteria for the threshold values, these are rather dependent on various release depths occurring in different field areas (Perzl et al. 2017). Zaruba and Mêncl (1969) define the boundary between deep and shallow depths at 5 m, Eeckhaut et al. (2007) at 3 m, Dou et al. (2015) at 10 m. Besides velocity and depth, landslides are classified into different failure and movement processes such as falls, slides, spreads, flows, floods and slope deformation (Figure 8).

In GreenRisk4Alps we separate landslides into rock slope failures (rockfall; extremely rapid to slow slope failures in rock), slope deformation (slow to extremely slow creeping-style deformations in rock) and soil slope failures (shallow landslides; extremely rapid to slow failures in soil). The terms rock slope failure and rockfall as well as soil slope failure and shallow landslides are used interchangeable hereafter. Slope deformations are not part of the GreenRisk4Alps project and therefore are not further described. However, it should not be forgotten that shallow landslides and rockfall events occur more frequently in slope deformations, which has been suggested for at least a decade (Kellerer-Pirklbauer et al., 2010; Korup and Clague, 2009; Ostermann et al., 2016). Knowledge about the spatial distribution of slope deformations and their activity status is therefore critical to forecast potential higher frequency and spatial distribution of spontaneous rock and soil slope failures (Hermanns et al., 2012; Zangerl et al., 2008). Earth spreads, sensitive clay spreads and rock slope spreads are also not part of the GreenRisk4Alps project as those are not common in the high alpine regions of our pilot action regions with dominating gravitational processes.

Soil slope failures are further classified according to geotechnical material (Figure 8). Hungr et al. (2014) invented the various differentiations of soil material based on the grain size classifications of the soil (rock, boulder, debris, gravel, sand, silt, clay). The geotechnical definition of “soil” is defined as any unconsolidated rock, or loose rock. Soil in the sense of Quaternary Geology is defined as the physically or chemically weathered sediment or bedrock. Quaternary Geologists rather speak of sediment when talking about loose rock or unconsolidated rock, not about soil. Here we use “soil” in the geotechnical sense. Hungr et al. (2014) defines soils as residual, colluvial, alluvial, lacustrine, marine, aeolian, glacial, volcanic, organic, anthropogenic fills, mine tailings and sanitary waste. The geotechnical characterization of soil makes sense if outcrops or boreholes are available for local and object-based hazard analysis with regard to the nature and stability of the local conditions. For a regional overview in GreenRisk4Alps remote sensing methods are used to identify the different landslide types in the Pilot Action regions and drillings of the subsurface are not available, therefore no statements can be made whether the deposited material is of different geotechnical material. Spontaneous soil slope failures might remain in an initial stage and might be difficult to identify on aerial or satellite imagery.

The basic types of slides are rotational or translational movements on given gliding surfaces which arise inside a geotechnical continuum. The slip surface often remains relatively undisturbed. Planar sliding surfaces - so-called translational slides - are movements on given separating surfaces and preferably at the boundary between competent and incompetent rocks (Hungr et al., 2014; Hungr and McDougall, 2009). Cup-shaped sliding surfaces - so-called rotational slides - are also a common type. In homogeneous material, the sliding surface is often approximately circular. With pronounced rotational movement, the slip masses are often less disturbed than in translational slides. A slide has its release area in rock or unconsolidated sediment with one or several displacement planes, where movement is mainly controlled by sliding.

The geomechanical differentiation of the movement into “toppling, rotational and translational/planar” used in the Hungr et al. (2014) classification is of secondary importance for the simulation purposes on regional scale in GreenRisk4Alps. The movement process is often not comprehensible in aerial images on a regional scale. Soil topples and falls might develop into a soil slide or soil flow with fluid boundaries of involved mechanisms. In spontaneous soil slides without soil flow, the material remains in a coherent bond (the "slides" or "slumps", Varnes, 1978). It is deposited directly below the fracture surface. In the event of strong slope water leakage, the material liquefies and flows away over the slope as "debris flows", Varnes, 1978).

For rockfall the mechanical release process is of utmost importance and the geotechnical differentiation of topple, planar and wedge falling/sliding is important to evaluate in a local or object-based hazard susceptibility beneath a steep rock wall. Also, the identification of the failure mechanism is not needed on a regional level with remote sensing techniques. For the classification of rock slope stability local information on joint number, rock strength index, roughness, weathering and water content in the rock walls must be available. These data can only be obtained by local field work or drone photogrammetry. A local susceptibility evaluation needs to include a kinematic analysis of potential rockfall failure processes based on these local data on joint conditions and number and is therefore of little relevance on a regional level. Therefore, also for rockfall, the kinematic failure types of topple, planar and wedge failure needs to be simplified in GreenRisk4Alps to simply rockfall.

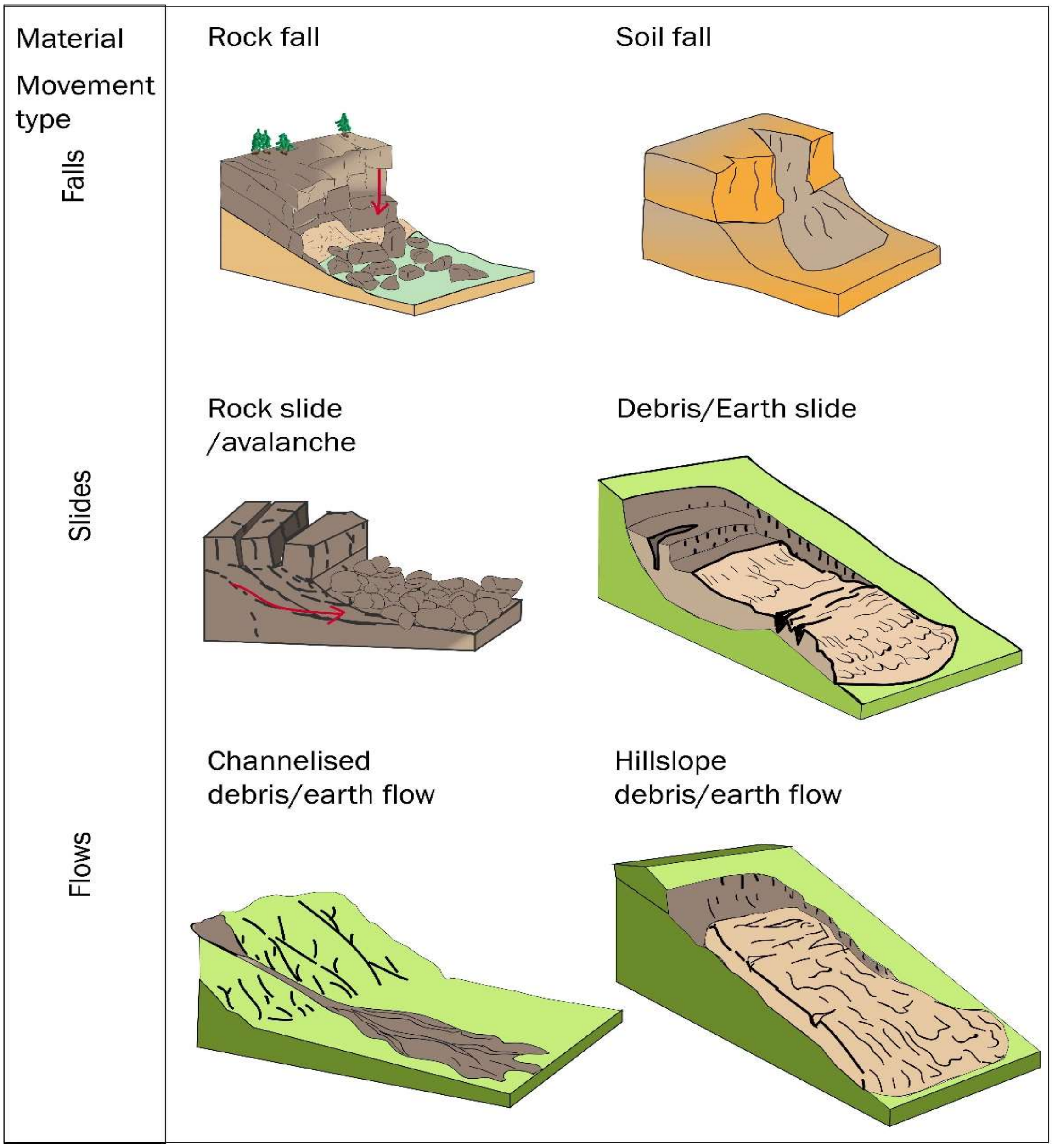


Figure 8. Landslide classification after Varnes et al. (1978) adjusted for practitioners on regional map scale. Slope deformations (complex landslides) are not part of the GreenRisk4Alps project, as well as spreads and the differentiation of movement mechanisms such as rotational and planar/translational). In this report we concentrate on landslide processes relevant for the GreenRisk4Alps project: falls, slides and flows.

Table 4. Overview of landslide terminology in the different Alpine languages

Landslides definitions GreenRisk4Alps					
	German	Italian	French	Slovenian	Norwegian
Rock slope failures					
Rockfall (<5 m^3)	Steinschlag	Caduta massi, frana di crollo	Chute de pierres et de blocs	skalni podor	steinsprang
Rockfall (>100 m^3, in blocks)	Felssturz	Crollo di roccia	Eboulement	skalni podor	steinskred
Rockfall / Rock avalanche (>1Mio m^3 large volume rock mass and 150 km/h)	Bergsturz	Grande frana	Ecroulement rocheux	skalni podor	fjellskred
Rock slides	Felsrutschung, Felsgleitung	Scivolamento di roccia	Masse rocheuse en glissement	kamninski zdrs/ skalni zdrs	steinskred
	Berggleitung				fjellskred
Rock avalanche	Sturzstrom/ Berggleitung	Valanghe di roccia	Masse rocheuse en glissement	kamninski plaz	fjellskred
Rock slope spread	Gesteinsdrift	Espansione laterale di roccia	Etalement de roches	skalni razmik	
Slope deformations					
	Talzuschub/ tiefgründige Massenbewegung/ Bergzerreissung	Deformazione profonda di versante; diversione	Déformations gravitaire	sesedanje pobočja; polzenje pobočja	Ustabil fjellside
Soil slope failures					
Soil Fall (Debris / Earth fall)	Erdfall	Crollo (di detrito/terra)	Ecroulement de terrain	padanje drobirja ; padanje preperine	Jordskred
Debris slide	Schuttstrom	Scivolamenti di detrito	Débris en glissement	drobirski plaz	Jordskred
Earth slide	Erdrutsch	Scivolamenti di terra	Glissement de terrain	zemljinski plaz/preperinski plaz	Jordskred
Earth spread	Fliessmasse	Espansione laterale di terra	Glissement de terrain	preperinski razmik	
Sensitive clay spread	Quicktonrutschung	Scorrimenti di flusso di terra	Glissements d'argile sensible	plaz mokre ilovice	kvikkleireskred
Channelised Debris flow	Mure / Murgang	Colate detritica/ Debris flow	Lave torrentielle	drobirski tok	Flaumskred
Hillslope Debris/Earth flow	Erdstrom / Hangmure	Colate di fango/detrica	Coulée de boue/terrain	preperinski tok	Jordskred
Debris / Earth flood	Mure / Murgang		Lave torrentielle	murasti tok	Flaumskred

5.2.1.1 *Rockfall - Steinschlag/Felssturz/Bergsturz (AUT/GER) – Chute de pierres et de blocs/Eboulement/Ecroulement (FRA) - Caduta massi/Crollo di roccia/Grande frana (ITA) - skalni podor (SLO) – steinsprang/steinskred/fjellskred (N)*

Rockfall describes the falling off of rocky components from a release area. Rock engineering terminology has been included in the Hungr et al. (2014) classification that is based on the kinematic analysis of rockfall release processes: falling, toppling, planar and wedge sliding failure. A rockfall may occur as single or multiple block detachment, falling, rolling and bouncing process.

In German, Italian, French and Norwegian terminology the size of the rockfall event determines the use of different definitions: Steinschlag (A/D), caduta massi (I), chute de pierres et de blocs (F), steinsprang (N) is defined as spontaneous fall of isolated rock components of a size (<5 m^3), while a Felssturz (D), Crollo di roccia (I), eboulement (F), steinskred (N) is defined as >100m^3 (Hungr et al., 2014). A Felssturz is defined as a larger mass released "en bloc" from the rock wall that is deposited as boulder rich talus (Stein-Bichler et al., 2019). This block is fragmented into boulders and stones during the fall and impact and it is characterized by a high degree of fractionation which has no decisive influence on the process. In a Bergsturz (D), Grande frana (I), Ecroulement (F), fjellskred (N) large-volume rock masses with a minimum volume of >1Mio m^3 might reach velocities of 150 km/h moving towards the valley. In general, a Felssturz might destroy infrastructure, but a Bergsturz is changing the entire landscape morphology. In Slovenian and English there is no terminological differences between different sizes of rockfall: skalni podor (SLO), rockfall (E).

Figure 9. Example of a rockfall event in the Alpine region on an orthophoto.

5.2.1.2 Rock slide - Felsrutschung/Berggleitung/Felsgleitung (AUT/GER) – masse rocheuse en glissement (FRA) – Scivolamento di roccia (ITA) – kamninski zrds/skalni zdrs (SLO) –steinskred (N)

In the Hungr et al. (2014) classification, rock slides are differentiated as rock rotational slides, planar slides, wedge slides, compound slides and irregular slides. A rock slide occurs when a moderately to steeply inclined slope loses its cohesion and, pulled by gravity, moves sliding or gliding down the slope. Rock slides tend to move slowly or moderately. The kinematic failure can be caused by planar, topple or wedge failure. Planar slides are often conditioned by erosion or undercutting along dipping planar surfaces. It is important to notice that the boundaries between the mechanisms falling and sliding are fluid. A rockfall can develop into a rock slide and, with sufficient water saturation further into a rock avalanche.

5.2.1.3 Rock avalanche – Sturzstrom/Berggleitung (AUT/GER) – masse rocheuse en glissement (FRA) – Valanghe di roccia (ITA) – kamninski plaz (SLO) –– fjellskred (N)

A rock avalanche is a very large rock failure with high fragmentation processes and motion modes of falling, rolling, bouncing and flowing with high velocities and strong interactions between the components. A rock avalanche is defined as a mass movement that is transported very rapidly and behaves like a fluid mass, and preceded by a strong air pressure wave. Its velocity exceeds by far what could be expected from a frictional perspective (Hungr et al. 2014). During a Bergsturz fall, the individual blocks collide within the mass like billiard balls, this turns the Bergsturz into an actual rock avalanche (Sturzstrom) (Heim, 1932). It was noticed that sometimes also in the English literature rock avalanches were defined by volume: therefore, the translation of rock avalanche could be Sturzstrom as well as Berggleitung.

In GreenRisk4Alps we focus on the simulation of rockfall and rock slides on a regional scale. Rock avalanches, rock slope spreads and big rock slides are not part of our investigations as these are rather landscape changing and cannot be simulated with the same type of models than those used in GreenRisk4Alps.

5.2.1.4 Soil fall - Erdfall (AUT/GER) – écroulement de terrain (FRA) - crollo di detrito/terra (ITA) - padanje drobirja/padanje preperine (SLO)

Soil falls are caused by fall mechanisms in unconsolidated sediments and are of importance along road cuts, coastal cliffs and excavations. They might also be caused where rocks fall into more fine-grained material, such as earth pyramids or glacial and landslide deposits with a wide range of grain sizes.(Highland and Bobrowsky, 2008; Hungr et al., 2014). We might expect an increase in soil falls along hiking paths in the vicinity of shrinking glaciers where glacial deposits might become more unstable due to pressure relief. However, soil falls are of rather subordinate importance for larger infrastructure like settlements and critical infrastructure. In Austria the term “Erdfall” is often used in karst terrain where dissolved gypsum leads to cavities and the surrounding soil falls down.

5.2.1.5 Debris slide – Schuttstrom (AUT/GER) – débris en glissement (FRA) – scivolamento di detrito (ITA) – drobirski plaz (SLO)

The term debris slide is used to describe imperceptibly slow movements of rock debris masses in slope depressions as precursors or intermediate stages of flow movements. At moderate movement speeds (1 m a^{-1}) the more or less treeless vegetation cover is preserved. Rotational rupture leaves a prominent main scarp and back-tilted landslide head (Hungr et al., 2014). Planar slides are indicated by a rather inclined planar rupture surface that is formed by an underlying weaker sediment layer or discontinuity with an inclination angle that exceeds the friction angle (Hungr et al., 2014).

Spontaneous soil slides (13 m/month –5 m/s) are in motion for a single period relatively fast during or after triggering events, such as extreme precipitation events and are usually shallow (less than 2 m deep). In steeper terrain, the material is almost entirely removed from the release area, exposing the gliding surface afterwards (Cruden and Varnes, 1996; Hungr et al., 2014).

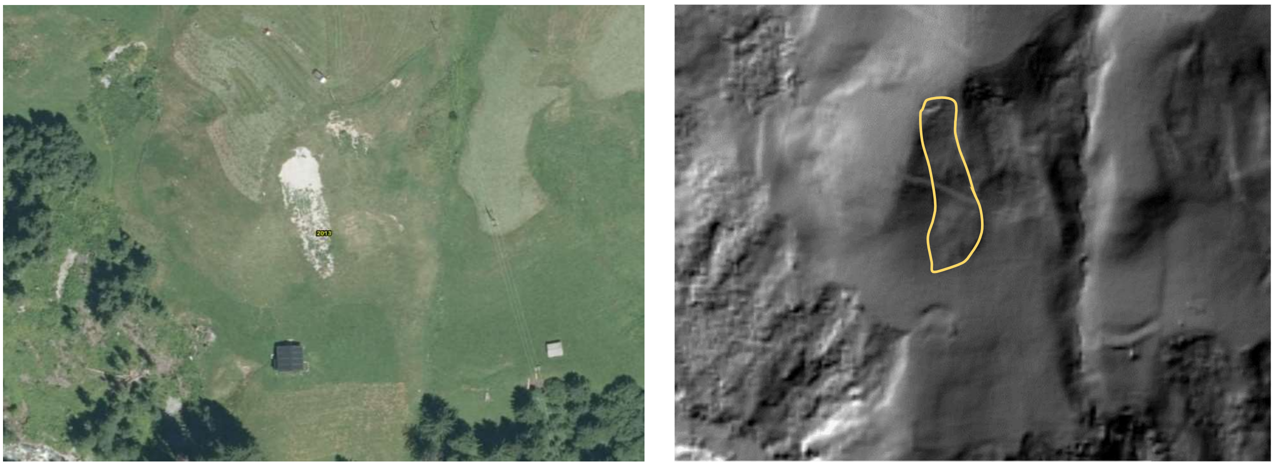


Figure 10. Example of debris/earth slide on orthophoto and digital elevation model hillshade. A debris slide leaves a clear negative imprint on the hillshade in the release area and positive imprint of the deposit, while debris/earth flows are often not recognizable on hillshades.

5.2.1.6 Earth slide – Erdrutsch (AUT/GER) – glissement de terrain (FRA) – scivolamento di terra (ITA) – zemlijinski plaz/preperinski plaz (SLO)

Earth slides with finer grain sizes usually rupture on several planes and not a single planar surface. The basal sliding plane is often a weaker horizon in the soil stratigraphy or a horizon with increased pore water pressure. Spontaneous soil slides occur in the Alpine space in two main forms (Perzl et al., 2017): (1) spontaneous without debris flows and (2) with debris flow. In spontaneous soil slides without debris flow, the material remains in the coherent composite (the "slides" or "slumps", Varnes, 1978) and it is deposited immediately below the release surface. With strong slope water leakage, the material liquefies and flows like a murmur over the slope - the so-called debris flow (Varnes, 1978). The British Geological survey differentiates hillslope debris flows and channelized debris flows. Also, in German these phenomena are differentiated with the terms Mure (channelized debris flow) and Hangmure/Erdstrom (hillslope debris flow). We decided to differentiate in channelized debris/earth flows with linear erosion channels and hillslope debris flows.

GreenRisk4Alps concentrates on hillslope debris/earth flows, while channelized debris flows/earth flows/floods are not included in the modeling effort as the processes along torrents with highly liquified material need other algorithms than used in Flow-Py (D.T.1.2.3). In the Hungr classification we can also find a further differentiation of debris/earth flows and floods, instead in the project this differentiation is not considered because the water saturation and process are difficult to determine on regional orthophotos from past events. Therefore, in GreenRisk4Alps we understand that the terminology of debris/earth flows include the phenomena of debris/earth floods with a higher water content during the landslide process

5.2.1.7 *Channelised Debris/Earth flows – Mure/Murgang/Erdstrom (AUT/GER) – lave torrentielle (FRA) – flusso detritico canalizzato (ITA) – murasti tok / drobirski tok (SLO)*

We might understand debris flows as classical periodical Mure that are less saturated with water then debris floods. The term flow slide is designated to the engineering term for water saturated sand or sensitive clay that fails extremely rapidly (Casagrande, 1940). Rapid flow slides fully or partially liquefy and can show large displacements. Debris-charged floods are flood events in torrents that unfold a destructive force beyond the boundaries of a steep torrent channel, as so much debris is transported within the water masses (Stini, 1910). Debris/earth flows/floods are continuous, irreversible deformation of debris or soil masses where the velocity within the moving mass is equal to that of viscous liquids and the ratio of water and solid mass is high, but not over 1:1 (Stein-Bichler et al., 2019).

Channelized debris/earth flows/floods occur mainly in non- or weakly cohesive soils in the area of zero or first order runoff. Therefore, they are common on forest sites. They are also referred to as “Rinnenanbrüche” in Austria (Benda and Dunne, 1997; Dietrich and Dunne, 1978; Moser, 1980). Strong flow pressure in the coarse pore system of this discharge funnel leads to a wedge-shaped breakthrough of the opening downwards, which then erodes the flow path channel-shaped (Varnes 1978, Hungr et al., 2001). “Rinnenanbrüche” or debris flows in torrents often lead to a considerable bedload in receiving rivers, which leads to debris floods with the mortar mobilization from the sole, due to side erosion and riverbank ruptures, causing significant damage in the Alpine region every year (Benda and Dunne, 1997). Subsequent debris flows might deposit outside former channels and form debris cones (Schirmer, 1988). They move very rapid to extremely rapid and consist of saturated debris in a steep channel.

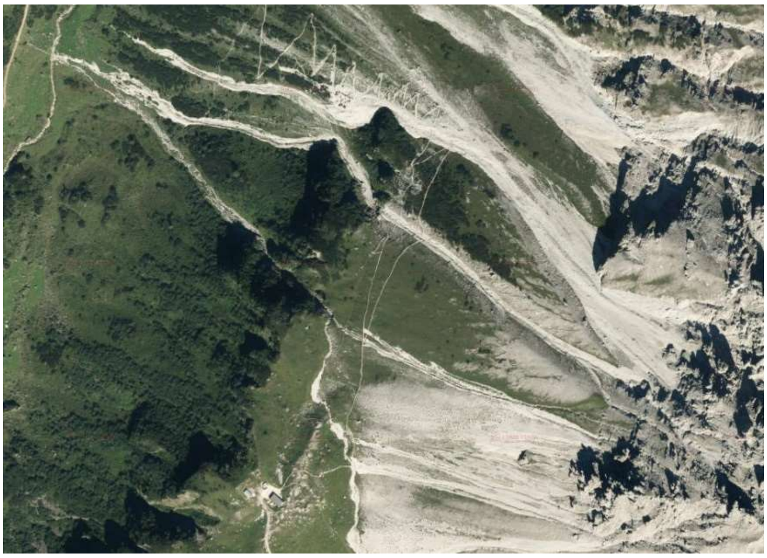


Figure 11. Example of channelized debris flows.

With remote sensing or laser scan mapping the differentiation between debris flow and earth flow is often difficult without outcrops or boreholes needed for the differentiation of dominant grain sizes. Debris flows occur periodically on established paths when the accumulation funnels have been filled after a couple of years and often occur simultaneously with floods (Schirmer, 1988).

5.2.1.8 Hillslope debris/earth flow – Hangmure/Erdstrom (AUT/GER) – coulée de boue/terrain (FRA) – colata di detrito/terra (ITA) – preperinski tok (SLO)

Hillslope debris flows without channel erosion develop as "slides" (translational slides) or "slumps" (rotational slides) from shear fractures in cohesive loose rock (Cruden and Varnes, 1996; Highland and Bobrowsky, 2008; Hungr et al., 2014). Strong water ingress liquefies the landslide body, which subsequently flows over the slope as a debris flow without further erosion. The open areas are mostly flat-skinned, shell-shaped to spoon-shaped rotational infiltrations. Debris flows show dominance in coarse grain sizes (gravel, stones, and boulders) compared to fine grain size in earth flows.

5.2.2 Forest effect on Rock Slope Failure

Forest plays an important role as mitigation for rock slope failure events. These phenomena are particularly widespread in mountain areas where rock fracture is favored by climatic (rainfall and temperature) and topographic (exposition, altitude and steepness) agents (Dorren et al., 2005). In the European Alps, the majority of rockfall events happen primarily in spring season due to freeze-thaw cycles and abundant rainfall (Dorren et al., 2005) and these involve low magnitude/high frequency events regarding only one or few blocks (Berger et al., 2006; Stoffel et al., 2005, D.T.1.1.1). Dorren et al. (2005) showed that, for the studied test site, the residual rockfall hazard on a very steep slope, expressed in terms of the number of rocks that surpass a certain zone, decreases by 63% when forest cover is present. The effect of forest on rock slope failure depends on the volume, shape and energy of the falling blocks and on the structure and conditions of a stand (Bigot et al., 2009; Dupire et al., 2016). The main forest factors affecting rockfall dynamics are tree density, diameter distribution, horizontal distribution of trees across a slope, species composition and forested slope length from the release area to the element at risk (Dupire et al., 2016; Moos et al., 2017). The basal area, associated to the stem mean diameter or stem density, is a very robust indicator for providing a quick overview on the protective capacity of a forested slope against rockfall.

Each species has a different protective capacity that depends on their energy reduction capacity (Dorren et al., 2005). At the same time, species influence the characteristics of forest structure as diameter distribution, tree density and spatial arrangement (Moos et al., 2019). Various authors (Dorren and Berger, 2006; Stokes et al., 2005; Dorren et al., 2006; Bertrand et al., 2013) analyzed the energy reduction capacity of different species through the winching test, dynamic impact test and in-situ rockfall experiments. These studies showed a strong relationship between stem diameter (assimilated to an almost square power relationship) and maximum amount of block energy reduction based on experimental data. In general, broadleaves are more resistant to failure than conifers and in many cases, they just report bark wounds (Dorren and Berger, 2005). Another advantage of the former is their resprouting and regeneration capacity after damages, producing large quantities of scar tissues (Stokes et al., 2005). The presence of the forest may only mitigate the effect of rock slope failure but cannot avoid the trigger. Rather, the presence of the trees close to cliffs can facilitate detachment due to the pressure of the roots penetrating the micro-fractures of the rocks. Moreover, the movements of the plants caused by wind or weight of the snow can worsen the activity of the roots. At the same time, the root system can create a dense network containing the rocks (Dorren et al., 2005).

After the release of the rock (Figure 12), the presence of a forest cover influences the evolution of the event and damage it can cause. Trees mitigate rockfall events stopping or decreasing the velocity and the height of rebound of boulders (Dorren et al., 2007). This effect of the forest, compared to non-forested scenarios for a French test site, results in a reduction in the speed of falling blocks of 26% and in a decrease of the mean rebound height by 33%. Speed reduction and rebounding height depend on kinetic energy reduction caused by the rocks hitting the trees (Dorren et al., 2005). For this reason, stem density in terms of trees per hectare and the basal area are the main forest parameters which determine the effectiveness of the protective effect of a stand. Moreover, we need to consider the dimensions of the rocks because as bigger the rock is, as bigger are the chances of tree impacts but also the energy developed by the boulder. According to this, the length of the forest slope is also a very important parameter. Although, some guidelines (e.g. Wasser and Frehner, 1996) provide indications about minimum stand density (400 trees/ha) without considering blocks dimensions.

For example, the NaiS guidelines (Frehner et al., 2005) for Switzerland's foresters indicate at least 200 trees/ha with a mean DBH larger than 36 cm in optimal conditions and at least 150 trees/ha for the worst conditions. These guidelines also mention that distances between trees in the fall direction should be less than 20 m because falling blocks reach their maximal speed within 40 m, if no impact occurs (Dorren et al., 2005). Of course, stand density and maximum stem number are factors that must be related to tree species, age distribution and environmental factors (Perret et al., 2004) as well as soil type, fertility and environmental limits. The most effective age range of protection forests against rock slope failure is still unknown, but in uneven-aged stands mature trees provide protection against falling rocks for younger trees (under DBH 35 cm) growing downslope.

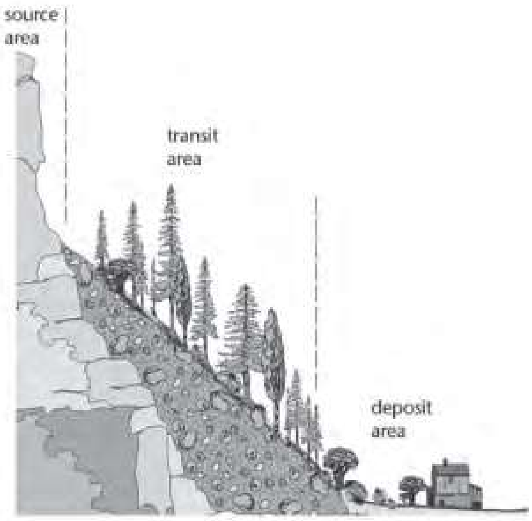


Figure 12. Generalization of the three main areas on an active forested rockfall slope (Dorren et al., 2007).

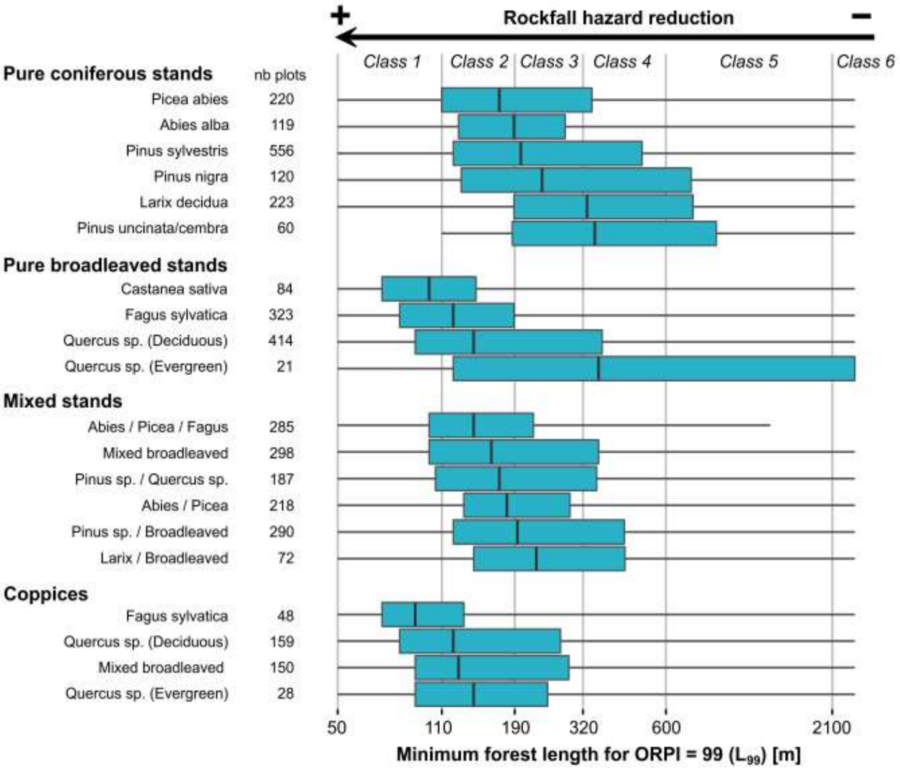


Figure 13. Distribution of the minimum forest length observed for each forest type of French Alps (logarithmic scale) (Dupire et al., 2016).

Non-mature forests, characterized by dense crown cover (>50%), high density (>400 stems/ha), and an absence or large forest gaps (>15 m width), commonly show a good protection potential from rockfall (Dorren et al., 2004a). Instead, mature forests with large trees in the senescence phase of development with large gaps do not provide the optimal protective effect (Fuhr et al., 2015). One study demonstrated that coppice stands provide a better protective effect than high forests, but their protective capacity has not been quantified (Jancke et al., 2009). A recent study in the French Alps (Dupire et al. 2016) showed that a coppice forest had the highest protection capabilities followed by high forest stands of three types: pure broadleaves, mixed and pure conifer forest.

Coppices are composed of a high density of small stems which is very effective for rockfall protection (Jancke et al., 2009). Figure 13 shows that the gradient of protection capabilities decrease from broadleave-dominated forest types to conifer-dominated ones. Young dense stands with more than 8000 trees/ha offer the best protection against small rocks (diameter 20 cm), while only few coppice stands offer a good protection against medium-size rocks (diameter 50 cm) (Jancke et al., 2009). Foresters suggest to cut coppice forests at least every 25 years on steep slopes to maintain high stem densities for good rockfall protection (Autonome Provinz Bozen-Südtirol, 2010). Moreover, dense coppice prevents soil erosion, stabilizes the ground surface, and prevents smaller rocks from rolling off and trap small rocks between the different stems of a single stool. Impacts on large-diameter stems can result in large reductions in the kinetic energy of rocks, however large rocks can be stopped by subsequent impacts on different small trees. Therefore, coppice with standards is to be preferred over simple coppices when is needed for a protective function (Radtke et al., 2014). Radtke et al. (2014) suggested a different guideline for small rocks (0,25-0.50 m^3) events by considering the DBH and the basal area more important than only the stand density. Following this rationale, coppices older than 20 years offer a better protection against rockfall than younger ones.

Similar as for avalanches, dead wood plays an important role in the mitigation of rockfall events. Downed stems can stop falling rocks and can be used for controlling the falling direction modifying it and channeling the blocks away from a "sensitive" area (human infrastructures) or with a more suitable forest structure to mitigate the event (Dorren et al., 2004a). This action is limited by wood decay rates, where some species are more resistant than others. For example, European beech and silver birch are significantly less durable than Norway spruce or silver fir, with more than 20% of wood decaying in only two years (Stokes et al., 2006). Anyway, for the large part of the species, protection is provided in the first 30 years (Dorren et al., 2005). Another limit related to wood decay is that the rocks stopped by the trunks when they rot could give rise to a secondary starting zone by releasing the material accumulated so far (AA. VV., 2006). This capacity of felled trunks can be taken advantage of in protection forest management. Indeed, some plants can be cut and released on the slope to act as a barrier, if the felled trunks are carefully positioned along the slope to deviate all the rocks away from a channel into areas with a high stand density or high surface roughness like depressions where many large rocks have been deposited. Another option is to deviate the rocks into the channel, if an adequate protection (e.g. a rockfall net or dam) is established at the end of it (Dorren et al., 2005; Schönenberger et al., 2005; Wehrli et al., 2006). In addition to this, lying deadwood provide a good seedbed for seedlings (Figure 14), which could stimulate forest regeneration (Dorren et al., 2004b).

Figure 14. Rockfall protection by obstacles consisting of logs positioned on the slope (Photo: Bernhard Maier) (Dorren et al., 2007).

In Table 5, a summary of recommendations found in the literature for optimal forest structure that offers the best protection against rockfall is provided. A specific tool dedicated to a rapid assessment of forest effects of different structures on rockfall hazard (slope scale) is freely available at https://www.ecorisq.org/rockfor-net-en.

Table 5. Most relevant forest characteristics that influence onset probability, propagation probability and intensity of rockfalls.

PROTECTION FOREST CHARACTERISTICS AGAINST ROCKFALLS FOR BOULDERS < 10 m³				
FOREST CHARACTERISTICS	Release area	Source	Transit and run out zone	Source
canopy cover	Remove unstable trees (leverage effect due to wind and roots development) at the top of cliffs or outcrops On talus and scree slopes: ≥ 70%	*Berger et al., 2013*	≥ 70%	*Berger, 1991*
species composition	With equivalent diameter, deciduous trees are more resistant than evergreen ones. Promote deciduous or mixed forest. Deciduous trees among the largest trees > 30%.	*Berger et al., 2013; Dorren et al., 2015*	With equivalent diameter, deciduous trees are more resistant than evergreen ones. Promote deciduous or mixed forest. Deciduous trees among the largest trees > 30%	*Berger et al., 2013; Dorren et al., 2015*
terrain roughness	Leave ≥ 1.3 m stumps after cutting or completely level the stump parallel to the slope in order to avoid a trampoline effect. Snags, stumps, root plates, lying logs promotes roughness but could be dangerous if they can be set in motion or by capturing and releasing boulders due to the kinematic of the wood decay.	*Dorren et al., 2005; Berger et al., 2013; Dorren et al., 2015*	Leave 1.3 m high stumps after cutting completely level the stump parallel to the slope in order to avoid a trampoline effect. Snags, stumps, root plates, lying logs promotes roughness but could be dangerous if they can be set in motion. The maximal distance (along the slope) between two lying logs should be ≤ 10 m and the diameter of the logs should at least be equal to the diameter of the boulder. The orientation of the lying logs must be 70° from the line of the steepest slope.	*Dorren et al., 2005; Berger et al., 2013; Dorren et al., 2015*
tree size	Even if all the compartments of a tree intervene in the dissipation of the energy of a falling rock, a tree is effective, if the rock impacts the first third of its height.	*Dorren, 2016*	Even if all the compartments of a tree intervene in the dissipation of the energy of a falling rock, a tree is effective, if the rock impacts the first third of its height.	*Dorren, 2016*
gap length[α]	< 40 m if high forest < 20 m if coppice In all cases, recommended value: ≤ 1.3 × average height of trees, with a wooden strip below the gap > 2 × average height of trees	*Frehner et al., 2005; Berger et al., 2013*	<40 m if high forest <20 m if coppice In all cases, recommended value: ≤ 1.3 × average height of trees, with a wooden strip below the gap > 2 × average height of trees	*Frehner et al., 2005; Berger et al., 2013*
gap width	No information in the literature		No information in the literature	
diameter distribution	On screes and talus slopes: maintain a high basal area compatible with the sustainability of the stand. For cliffs	*Berger et al., 2013; Dorren et al., 2015*	General recommendation can be provided : The basal area of trees with a DBH ≥ 15 cm is required to be ≥ 25	*Berger et al., 2013; Dorren et al., 2015*

	and outcrops: maintain at the foot of the release area a wooded strip with a high basal area compatible with the sustainability of the stand.		m²/ha in the transit zone, and ≥20 m²/ha in the runout zone. However, the diameter distribution depends on many factors such as the volume of the boulder, the initial fall heigth, the length of the forested slope, the slope gradient etc. In the case of a corridor, maintain a high tree density in a band of 25 m on either side of a corridor.	
Crown size	No information in the literature		No information in the literature, but it can be recomended to promote trees with crowns to their base, especially on the edge of gaps and corridors for their frictionnal effect.	
Coefficient of stability value (H/D)[β]	coniferous: H/D ≤ 65 broadleaves: H/D ≤ 80	*Berger et al., 2013*	coniferous: H/D ≤ 65 broadleaves: H/D ≤ 80	*Berger et al., 2013*

[α] Measured along the line of the steepest slope from trunk to trunk. Gap lengths indicated as maximal requirements.

[β] H/D = Height/DBH (diameter at breast height)

5.2.3 Soil Slope Failure

Soil slope failure is one of the major disturbances occurring in the Alps and it is probably the natural hazard that tends to cause the majority of damages to human infrastructures and buildings. In forests, its frequency is often underestimated because its scars and deposition areas are less detectable. Slope steepness is one of the most important factors for slope stability. If a slope angle is less than 20°, the driving forces are compared to soil strength so the risk of landslide detachment is negligible. On steeper slopes (>45°) in most cases only a thin layer of till covers the bedrock and erosion and rockfall processes prevail. Rickli and Graf (2009) found the role of slope steepness in landslide starting zones showed significant differences between forests and open lands, where soil slope failure in forests were triggered on steeper slopes than on non-vegetated slopes (Rickli and Graf, 2009). This is also confirmed by the analysis of hazard inventories in which landslide density was lower in forested areas compared to non-vegetated areas (Figure 15) (Rickli et al., 2019). Several studies in the Alpine region showed that flow paths are longer in open areas than in forests of a magnitude ranging from 50% to more than 100% (Ketcheson and Froehlich, 1978; May, 2002; Lancaster et al., 2003).

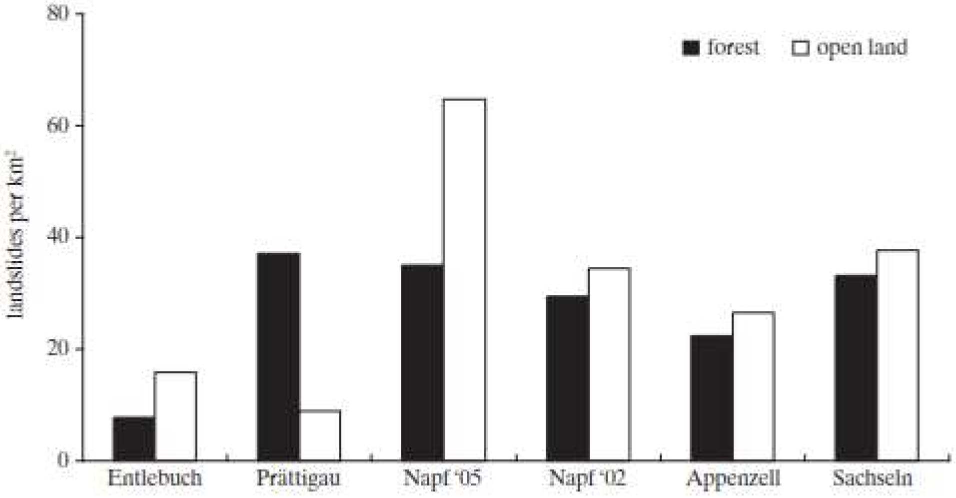


Figure 15. Landslide density in forests and in open land of six study areas in Switzerland. Only slope areas with slope inclination of 20° to 50° were considered for the calculation of the landslide densities (Rickli and Graf, 2009).

Similar to avalanches, protection forests for soil slope failure are important but their effectiveness depend on stand structure characteristics within the release area. The degree of stabilization depends on forest characteristics: spatial distribution of the trees and of their roots system (Schwarz et al., 2012). Many events were found to occur in forest stands with poor structure like unstocked, mono-layered, young stand/thickets, comprised of conifer trees (>80%) and partial (40%) or sparse (20%) cover (Rickli et al., 2019). An increase in landslide frequency was also found in areas of deforestation and intense harvesting activity when the root systems of harvested trees began to decay. (Rickli and Graf, 2009).

At the same time, the effect of forest structure depends on the steepness and the hydrological conditions of a slope (Moos et al., 2016). Vegetation is recognized to be a stabilizing element on hillslopes due to its reduction of runoff, erosion, and triggering and magnitude of the mass movements. Moreover, forest stands increase flow resistance, promote deposition and reduce runout distance. The presence of high-density trees promotes sediment deposition. Michelini et al. (2017) showed for their study area in Western Italian Alps (province of Bolzano and Belluno) that in the first part of a deposition area, larger trees in sparse stands produced larger deposit thicknesses. In the last part of the deposition area, the deposition was favored by small-diameter trees in high-density stands. Referring to the final part of deposit zone, groups of trees and shrubs can induce the formation of stable piles of debris, intercepting parts of the solid material and contributing to the reduction of the energy flow. For this reason, forest management should aim to encourage denser forests across depositional zones (Michelini et al., 2017).

Forest affects also the slope material, its physical properties and the hillslope hydrology. Hydrological regulation mostly acts at the catchment scale (Dazio et al.,2018) and its main benefits (see Figure 16) are (Dorren and Schwarz, 2016):

- Intercepting rainfall;
- Altering hydraulic conductivity through physical transformation of the soil by roots;
- Enhanced evapotranspiration.

Figure 16. Soil stabilizing functions of plants, e.g. interception, evapotranspiration, and root reinforcement (Graf et al., 2019).

Precipitation interception by canopies sums up to 10-40%, though this value varies spatially and depends on rainfall rate as well as on forest type and structure. Each tree species has different interception potential rate, but it is positively correlated with leaf area and strongly related to plant growth performance. In general, interception tends to be higher in coniferous dominated stands than in broadleaved forests (Graf et al., 2019).

Moos et al. (2016) confirmed the key role of management and maintenance of forests in landslide prone areas and highlighted the importance of not only canopy cover but also the small-scale spatial structure of forests and arrangement of trees that affect slope stability. A study in the French Alps indicates effective root reinforcement with a horizontal distance of 4 m between clusters, also named tree islands (Mao et al., 2014). In any case, the stabilizing effect of a small tree distance is considerably reduced on slopes steeper than 38°. On the other hand, the presence of gaps in the stand structure longer than 20 m are negative characteristics for slope stability, especially for slopes steeper than 36°. In temperate montane forests, despite the abundance of understory species, soil reinforcement by roots in gaps was significantly lower than in tree island, especially in the first few centimeters of the soil (0.0-0.4 m) (Mao et al., 2013).

Today the importance of the mechanical effects of roots for the protection against soil slope failure is widely recognized (Sidle and Ochiai, 2006). Root reinforcement is strongly related to tree species composition, stand origin (gamic or agamic), structure and health conditions (Schwarz et al., 2012). Plant roots strongly affect the morphology and the triggering mechanisms of shallow landslide in vegetated slopes (Schmidt et al.,2001). The root system acts on slope stability through a mechanical action that can be summarized as follows (Sidle and Ochiai, 2006):

- Soil reinforcement by roots;
- Buttressing and arching;
- Surcharge: locally tree weight increases the normal force components as well as the tangential force components, but in general plays a minimal role on the overall stability of a slope (Stokes et al., 2008).

Soil reinforcement by roots has three main components (Schwarz et al., 2012; Giadrossich et al., 2013; Mattli, 2015; Cohen and Schwarz, 2017):

- Basal root reinforcement (Figure 17.1): anchorage of unstable soil mantle into more stable substrate. This is the most effective mechanism but is absent in many cases, because the failure surface is deeper than the rooting zone;
- Stiffening the unstable soil mantle, increasing stability through buttressing and arching by trees (Stokes et al., 2008) (Figure 17.2). This mechanism increases the effects of the other two components and is relevant when there is a strong interaction between neighboring root systems (Schwarz et al., 2010; Schwarz et al., 2015);
- Lateral root reinforcement (Figure 17.3: reinforce the potential unstable soil mantle by roots under shearing, tension and compression acting the lateral edge of the landslide body). The effect of lateral root reinforcement decreases with increasing slope angle implying higher tree densities for the same stabilization effect. The contribution of this mechanism depends on the type of deformation and on the spatial distribution of the root network.

Lateral root reinforcement, as shown in Figure 18, is a function of stem diameter (DBH) and of the distance from the stem. Reinforce effects increase with increasing tree DBH and decrease with increasing distance to the stem (Dazio et al., 2018).

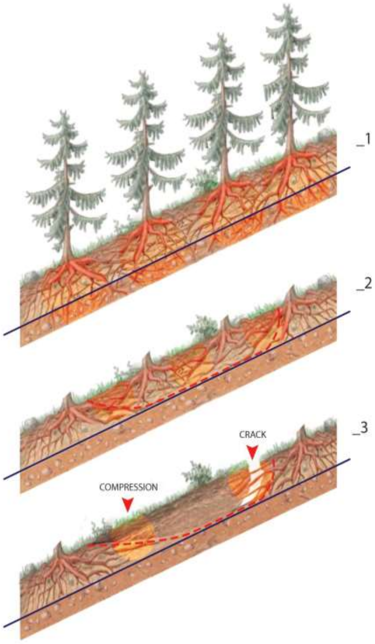


Figure 17. Illustration of three different mechanism of root reinforcement (modified from Giadrossich et al., 2013).

A large proportion of roots in forest is confined in the first meter of soil and, only occasionally, vertical roots reach the depth of potential shear planes of shallow landslide (1-2 m) (Schwarz et al., 2012). The potential protective effect of root reinforcement on soil slope failure is limited by (Cohen et al., 2017):

- Magnitude of root reinforcement that is a function of species composition and forest structure;
- The heterogeneity of root distribution;
- The depth of the landslide shear surface (basal reinforcement);

- The length and the volume of the mass movement (lateral reinforcement, buttressing/arching mechanism and stiffening effects).

Topographic location strongly influences the root strength. In convex locations the tensile strength and the mean root cohesion is higher than in concave locations (Hales et al., 2009).

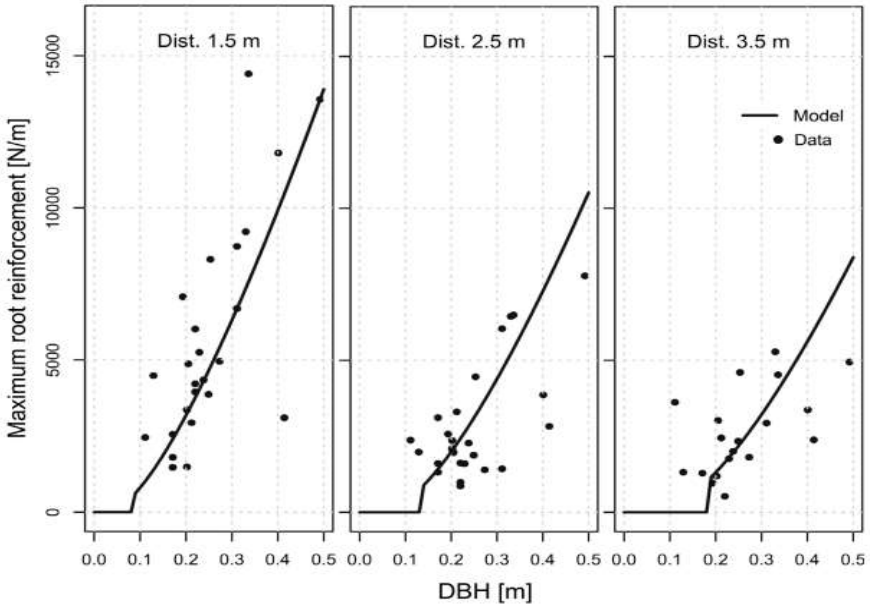


Figure 18. Comparison between calculated and modelled lateral maximum root reinforcement as a function of tree dimension (DBH) and distance from the tree stem (Dazio et al., 2018).

The presence of mycorrhizae fungi is another important element, which indirectly improves soil aggregate stability. In particular, mycorrhizae accelerate the development of the root network of their host plants and serve as a distribution vector for associated microorganisms, which are also soil stabilizing. Moreover, the fungi contribute with their filamentous growth-form and the vast mycelia networks that grow far beyond the rhizosphere enmeshing loose soil particles with soil aggregates and cementing them through the production of metabolites such as polysaccharides and hydrophobines. Lastly, mycorrhized compared to non-mycorrhized plants have a greater access to nutrients, which results in the development and establishment of a protective vegetation cover. This positive feedback is the central key of successful eco-engineering measures aimed at sustainable slope stabilization and protection against shallow soil slope failures (Graf et al., 2019).

Altitude is another important factor that affects soil slope failure because geology, topography and vegetation depending on it. In particular, the effects of elevation are (Tsukamoto, 1990):

- Rainfall increase with altitude;
- Vegetation changing;
- Topography of the relief: drainage density, slope length, sliding area;
- Soil depth;
- Rock characteristics as geological age (older rock at higher altitudes), hardness (harder rocks appear at higher altitudes), fracture (higher altitudes are more fractured).

As consequence of a soil slope failure trees can be pushed over, broken, tilted or wounded. Coarse woody debris (CWD) laying in a hazard track can be transported and compacted into a dam or intercept material favoring the deposition, thus restricting delivery of this material to the valley bottom. CWD pieces and standing trees act as obstacles that can influence the flow direction and, therefore, reduce its velocity and its spatial range (Figures 19-20). CWD's effective influence on surface slope processes is estimated at 100-150 years and depends on the energy of these processes (Matyja, 2007). At the same time, fallen and uprooted trees may be transported into erosion gullies, torrents and rivers by slope failures, intensifying the hazard (Vergani et al., 2017a). Finally, in addition to root damages, landslide movements can change underground and surface water distribution causing problems of hydric balance, like dry conditions or extreme humidity, to the forest stand. In some cases, this can result in tree death (Šilhán, 2015).

Stem elasticity also decreases with the age and plants lose their ability to react to tilting caused by landslide movements. Inclined younger trees return to vertical positions faster than older trees due to better annual eccentric growth or reaction wood creation. This process creates S-shaped stems that are typical of trees growing in landslide tracks. However, inclined old trees are better indicators since their tilted stems reflect landslide movements over a longer period of time (Figure 21). Similarly, tree root system depth plays an important role, where plants with deeper roots are less affected by surface movements and are more reliable indictors of deeper soil movements (Šilhán, 2015).

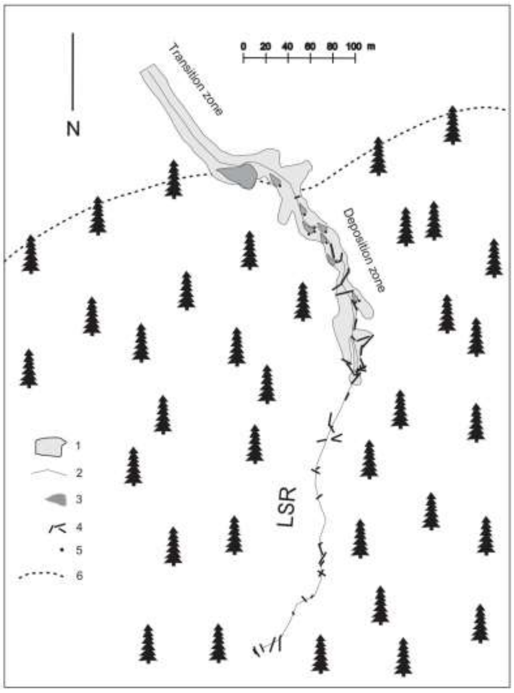


Figure 19. Sketch map of the transitional and deposition zones of debris-flows and the linear slope runoff (LSR) track with the locations of CWD (Matyia, 2007). 1- debris flows deposits; 2- axis of the debris flow and LSR track; 3- piles of debris of height >1m; 4- CWD item; 5- standing trees; 6- timberline.

Figure 20. Boulder trapped in the root system of a fallen tree in an advanced stage of decomposition, which can be a potential future rockfall realease area. An example found in the lower belt forest of the Karkonosze Mts, Sudety, SW Polond (Lukasz Pawlik, 2013).

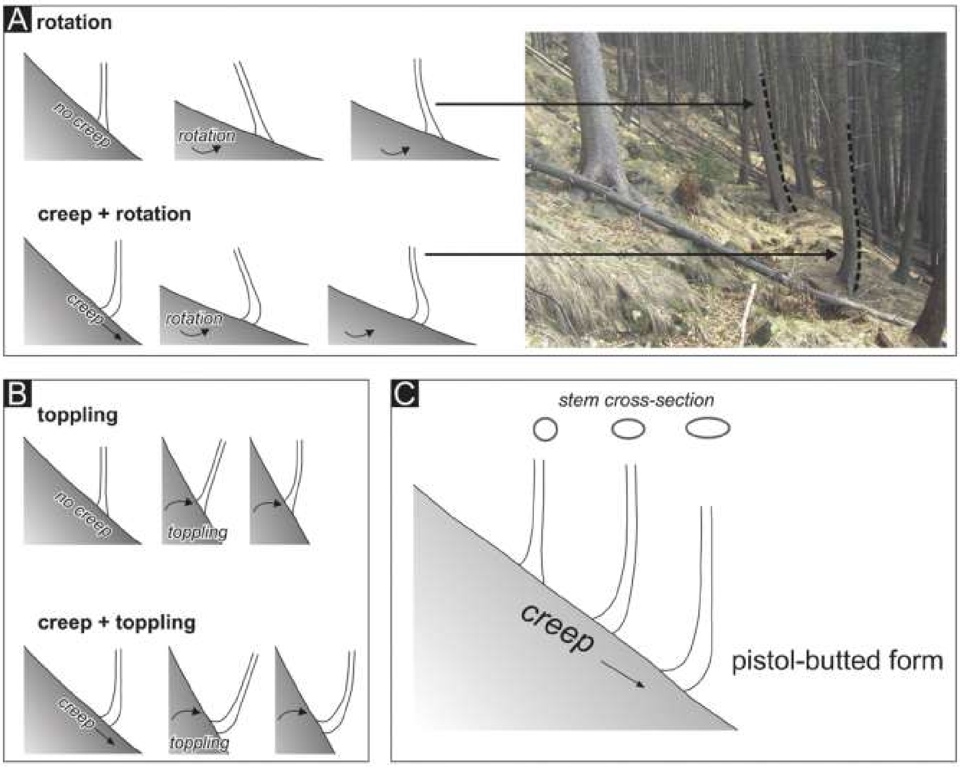


Figure 21. Tree tilting due to various processes. A — reaction of tree growth to rotation mechanism of landslide, and to the combination of preceding creep and subsequent rotation movement; B — reaction of tree growth to landslide movements based on the toppling mechanism (flexural and block toppling) as well as the tree growth response to the combination of preceding shallow creep and subsequent toppling; C – deformation of tree stem as a response to shallow creep movements (Karel Šilhán, 2015).

Root regeneration after disturbances highly differs among tree species. European conifers do not resprout from stool and do not regenerate at the roots; on the contrary deciduous species have a very different resprouting ability and root regeneration capacity, which usually decrease with age (Dazio et al., 2018).

Other important elements for root regeneration disturbance and reinforcement are harvesting activities (Vergani et al., 2016) or forest fires (Vergani et al., 2017b). In this context, coppice stands seem to offer an improved protective effect, in fact they present a very interesting regrowth ability, even if greatly varying among species, coppicing techniques and stand age (Dazio et al., 2018). This is demonstrated also in a study of Dazio et al. (2018) where they found that young coppices in rotation display lateral root reinforcement estimated of 5 kN/m independently of the silvicultural management applied. Instead, an overaged stand has a value 2 times higher (10kN/m). In this sense, chestnut coppices are a good example, because, after a disturbance to root systems, this species gradually tends to completely replace the root system when it is subject to coppicing. In a long-term perspective, this characteristic gives chestnut a strong root reinforcement but in the short-term could have a negative impact on slope stability, because the root system is weaker in the early period after the coppice (Dazio et al., 2018).

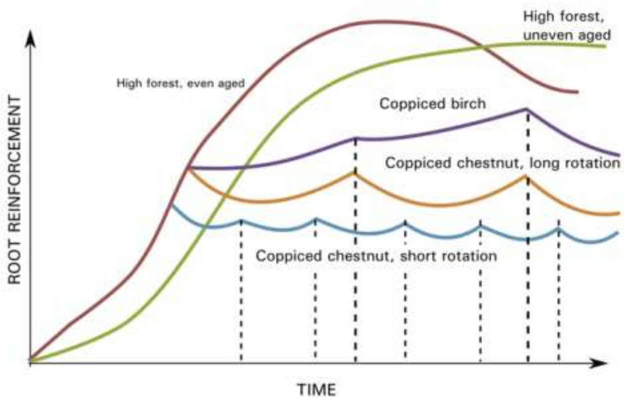


Figure 22. Conceptual illustration of the long-term development of root reinforcement at the stand scale as function of the silvicultural system and the species (Vergani et al., 2017).

However, on one side overaged chestnut coppices are one of the best solutions for soil stabilization (Figure 22), on the other side these stands are very difficult to manage because old stumps lose their sprouting ability and become unstable. This situation often causes stool uprooting, which turns into soil erosion, increased fuel for forest fires and the risk of log jamming and consequent triggering of woody debris in torrents (Vogt et al., 2006).

Selected thinning has the advantages of improving both shoot and stool stability in the long-term and an increase in wood quality, which is beneficial for the overall sustainability of the coppice system (Manetti et al., 2014). Finally, the role of shrub species and regeneration is a key factor for the management strategies devoted to preserve the resilience of protection forests. Indeed, they can guarantee almost 30% of the root reinforcement of alive trees after 15 years from harvesting (Vergani et al., 2016).

A summary of recommendations for optimal forest structure that offers the best protection against shallow landslides is provided in Table 6. An online tool dedicated to a rapid assessment of forest effects on shallow landslides at the entire slope scale is freely available at: https://www.ecorisq.org/slidefor-net-en.

Table 6. Most relevant forest characteristics that influence onset probability, propagation probability and intensity of shallow landslides (depth ≤ 2 m).

FOREST CHARACTERISTICS	Water infiltration area	Source	Sliding area	Source
canopy cover	Remove unstable trees (leverage effect due to wind and roots development) in areas of preferential water infiltration. Promote permanent vegetation cover (including the forest) ≥ 30%, recommended ≥ 70%	*Frehner et al., 2005; Gauquelin et al., 2006*	Promote permanent vegetation cover (including the forest) ≥ 40%, recommended ≥ 70%,	*Frehner et al., 2005; Gauquelin et al., 2006*
species composition	Species adapted to wet sites, mixed forests	*Frehner et al., 2005; Gauquelin et al., 2006*	Species adapted to wet sites, mixed forests	*Frehner et al., 2005; Gauquelin et al., 2006*
terrain roughness	No information in the literature		No information in the literature	
tree size	Locally avoid the presence of heavy trees and trees with a strong wind grip	*Frehner et al., 2005*	Locally avoid the presence of heavy trees and trees with a strong wind grip	*Frehner et al., 2005*
gap length [α]	No information in the literature		If the forest regeneration is not established: gap area ≤ 600 m² If the forest regeneration is established: gap area ≤ 1200 m²	*Frehner et al., 2005*
gap width				
diameter distribution	No information in the literature		The most effective diameter distribution depends on many factors such as the slope, the effective friction angle of the soil, the soil cohesion etc.	*Cohen et al., 2017*
Crown size	No information in the literature, but it can be recommended to promote trees with crowns to their base for optimizing the rainfall interception and evapotranspiration effects. Due to the relation existing between the size of the root plate and the crown size, it can be recommended to promote trees with the biggest crown diameter as possible.			
Coefficient of stability value (H/D)[a]	No information in the literature, but the same recommendations as for the other natural hazards can be applied: coniferous: H/D ≤ 65 broadleaves: H/D ≤ 80	*Gauquelin et al., 2006*	No information in the literature, but the same recommendations as for the other natural hazards can be applied: coniferous: H/D ≤ 65 broadleaves: H/D ≤ 80	*Gauquelin et al., 2006*

[a] H/D = Height/DBH (diameter at breast height)

5.3 FLUVIAL PROCESSES

Natural hazards linked to fluvial processes interact differently with forests compared to the natural hazards discussed above. Riparian forests have peculiar ecological characteristics such as soil conditions and vegetation, but at the same time aquatic ecosystems are modified by the presence of the forest, which influences their structure, biodiversity and dynamics (Naiman et al., 2000). Until recently, only few studies have examined responses of riparian vegetation to floods in mountain streams (Johnson et al., 2000).

In high gradient mountain streams, physical processes dominate riparian forest dynamics, whereas in low gradient streams, forests are often more influenced by physiological responses to protracted inundation (Johnson et al., 2000). Floods act on riparian vegetation in a hydrological and a geomorphological way. Hydrological effects are mechanical damages, saturation and propagule transport. Geomorphological impacts include the destruction and creation of substrate. Floods are the first geomorphological agents modelling fluvial environment, and have an important role in controlling the pattern of riparian vegetation along channels (Figure 23). The mosaic of riparian forests is the result of a complex interaction among vegetation, geomorphological processes and time. Interaction between floods and vegetation is complex, both influencing and influenced by the structure and composition of streamside forests. The high energy of the flow can erode streambanks and undercut, topple and remove standing vegetation. Streamside vegetation physically constrains flows and traps floating debris, and its root systems increase the erosion resistance of streambanks (Johnson et al., 2000).

Figure 23. Example of landscape modeled by fluvial dynamic (A.A. V.V., 2008).

Heterogeneity in landscape morphology, microclimate gradient, site productivity and disturbance regime play important roles in determining riparian forest structure, species richness, and colonization by invasive plants (Naiman et al., 2000). Flood-forest interaction can have also a negative impact resulting in several types of damage to riparian forests in montane regions. Damages depend on the energy of the flood waters and on the physical impact by material transported by the flow. Some studies suggest that the potential damage is related to the amount of sediment transported, which, particularly in mountain environments, includes floated wood (Wolman and Miller, 1960; Kochel 1988). The types of material transport and disturbance intensity are manifested through increasing disturbance severity, ranging from inundating standing riparian trees to toppled but still partially rooted trees, to complete tree removal.

Until few years ago riparian forests were considered dangerous for hydraulic safety, but more recently a fundamental importance was recognized for fluvial management and ecosystems. For example, the presence of vegetation limits bursting of river banks, decreases velocity of the flow and enhances the deposition of floated materials (A.A.V.V., 2008). Forest act on floods in two different ways: concentrating or dissipating flood energy. The effectiveness depends on tree species, size and location of riparian vegetation. Riparian vegetation can constrict flows and narrow the impact zone. Johnson et al. (2000) demonstrate that forests alone are not able to constrict the flows, but wood and uprooting trees deposited on the banks acted as levees that can deviate the flow and reduce its energy, creating backwater areas and low energy zones. Vegetation mitigates the hazard increasing the roughness (Manning's n) of the channel, which dissipates some of the energy of high flows and decreases the velocity of the flood, resulting in deposition of suspended materials (Johnson et al., 2000). Materials of big dimension such as rocks or wood can also be physically stopped by standing trees (A.A. V.V., 2008). However, forests may increase the potential damage of the flow due to of the wood transported by debris flows or riparian trees that have uprooted and entrained by flood flows, which can impact standing trees and provide leverage for flood water to topple or uproot them (Figure 24). Rivers with high density of floated wood have lower plant regeneration rates and less standing trees than rivers in which floating wood is not a common disturbance.

Figure 24. Solid materials deposition thanks to the vegetation (A.A. V.V., 2008).

Moreover, riparian forests represent an important defense against flooding acting as expanded catchment and retaining high quantities of water (A.A. V.V., 2008). Frequency and magnitude of disturbances in riparian vegetation decreases with distance from the channel. This gradient controls the distribution of riparian vegetation where flood-resistant species and young trees are nearest to or inside the channel and less tolerant species are farther (Johnson et al., 2000). Typical species of these areas such as Populus spp. and Salix spp. are characterized by a high tolerance of submersion and flexibility especially of younger trees. These two species are dominant in banks frequently subject to flooding and high magnitude disturbances in which the stand has been continuously replaced and renewed. Another important characteristic of poplars and willows is their capacity to root also from single plant parts. Where floods are less frequent other species such as Fraxinus spp., Ulmus spp., Prunus spp. and Quercus robur may be present since these species have slower growth rates and are less tolerant to submersion, which are characteristics of mature riparian forests (A.A. V.V., 2008). Riparian management focuses on different directions including (Naiman et al., 2000):

- Emphasize ecological functions and natural riparian forest patterns;
- Adoption of a landscape perspective of river networks;
- Development of restoring riparian ecosystem properties;
- Attention to social needs from riparian resources.

Finally, management of riparian forest also maintaining the stability of herbaceous and shrub layers can avoid some management problem of smaller streams. Stability is given by multilayered stands with flexible shrubs that limit erosion and young trees with DBH decreasing towards the channel (A.A.V.V., 2008).

6 PROTECTION FORESTS COMPARED TO ARTIFICIAL PROTECTION MEASURES

In areas where protective effects of forests against natural hazards are not sufficient, e.g. if the damage potential or residual risk is high, the forested slope is too short or protective effects need to be re-established following disturbance, artificial protection measures should be applied (Brang et al., 2006). However, artificial protection measures can never replace all the functions and effects that forests with a protective function provide (Baral et al., 2017); moreover, construction and management of artificial protection measures is often financially exhausting (Brang, 2001). In some cases (e.g. Switzerland), long-term artificial protection measures are estimated to be about thousand times more expensive than the financial costs for silvicultural interventions that maintain effective protection (Altwegg, 1991). Therefore, from an ecological and financial standpoint, silvicultural measures should aim to facilitate the best protective effect of forest as possible, and artificial protection measures should only be constructed in areas of insufficient protective effects of forest. However, in order to compare the protective effects of forest to the effectiveness of artificial protection measures, we must first quantify the protective effects.

6.1 QUANTIFICATION OF FOREST'S PROTECTIVE EFFECTS

Research on protective effects of the forest is mainly related to maintaining optimal stand structure (see Chapter 5 for references). Gap size, stand dimension, tree density, diameter distribution and tree species composition are considered to be most relevant parameters that can be used to quantify protective effects (e.g. Bauerhansl et al., 2010). However, among the Alpine countries there are still differences between the criteria and parameters that define protective effects of forests (Bauerhansl et al., 2010), e.g. concerning the relevance of particular stand characteristics and values (Berger et al., 2013). This is probably the result of insufficient comparative studies, the use of different methodologies to quantify protective effects and also varying forest and process characteristics, which are related to the impact of climate, disturbances or past silvicultural activities in different countries of the Alpine Space (Bauerhansl et al., 2010). Therefore, the debate on assessing optimal forest characteristics that provide optimal protective effects is still underway (Berger et al., 2013; for further information see also GR4A report D.T1.3.2).

The two main methodologies that were developed to quantify the protective effects of forests are:

- Models, both deterministic or stochastics;
- Expert systems (e.g. silvicultural guidelines).

In Austria, France, Italy, Germany and Switzerland guidelines and/or recommendations for managing protection forests are already available (BMLFUW, 2008; Gauquelin et al., 2006; Berretti et al., 2006; Bayerisches Staatsministerium für Ernährung, Landwirtschaft und Forsten, 2016; BaySF, 2018a, b; Frehner et al., 2005, 2007). In contrast, in Slovenia they are still missing (Bauerhansl et al., 2010), although some authors provided instructions for maintaining optimal forest protective effects (Pintar, 1968; Horvat and Zemljič, 1998).

Moreover, another relevant aspect for quantifying protective effects of the forest against natural hazards is regarding information on different scales (Moos et al., 2017):

- Each relevant tree compartment (root system, the stem, and the crown);
- Individual tree as a whole;

- Forest stand;
- Forest complex.

Usually, information on experimental data of individual trees (e.g. tree kinetic energy dissipation of a rockfall) is applied to a larger scale, e.g. forest complex. In that way, information on experimental data become operational and an assessment of protective effects of the forest is possible (Moos et al., 2017). Protective effects of forests can be even compared to protective effects of artificial structures in monetary terms (Moos et al., 2017).

6.2 QUANTIFICATION OF PROTECTIVE EFFECTS OF ARTIFICIAL PROTECTION MEASURES

Mitigation measures can be divided by intervention, design and duration to provide integral hazard protection. Active and passive measures are distinguished in terms of intervention: active mitigation measures influence initiation, transport and deposition of mass movement. In this way, the potential consequences of the hazard are reduced by influencing its probability of occurrence or by manipulating the hazardous process itself in order to change its characteristics of magnitude and frequency (Hübl and Fiebinger, 2005; Holub and Hübl, 2008). In contrast, spatial separation of endangered people and objects from hazardous area are defined as passive mitigation measures (Wilhelm, 1996). A reduction of potential loss and decrease of vulnerability could be achieved by preventive measures in terms of spatial planning, and land-use and event response in terms of immediate actions (Holub and Hübl, 2008).

By design passive measures can be classified in structural and non-structural measures: structural mitigation measures include all physical measures used to mitigate natural hazards, while non-structural measures typically concentrate on identifying hazard prone areas by limiting their use temporarily or permanently (forest measures can be seen as non-structural measures) (Holub and Hübl, 2008). For this reason, non-structural measures strongly depend on legal structures of each individual country (Holub and Hübl, 2008). Finally, about their duration: durable technical measures, forest measures and land-use planning are considered as permanent mitigation measures, while temporary measures are adjusted to a certain point of time and hazard potential of a location (Holub and Hübl, 2008). In order to achieve an optimized and cost-efficient damage prevention, the framework of integral risk management requires a combination of active and passive measures, as well as both permanent and temporal measures (Table 7) (Holub and Hübl, 2008).

Table 7. Integral natural hazard protection in terms of intervention, design and duration; combinations of all attributes are possible (McClung and Schaerer, 2006; Holub and Hübl, 2008).

Intervention	Design	Duration
Active	Structural	Temporary
Passive	Non-structural	Permanent

Considering different indicators (Table 8), protection measures can be generally divided in 'green' and 'grey' protection measures. Hereafter, we will focus only on 'grey' infrastructure. Since there are different terms describing 'grey' infrastructure, we will first focus on its explanation:

Grey infrastructures are predominantly made out of concrete and steel (Tavakol-Davani et al., 2015). Numerous studies evaluating the role of green and grey infrastructure have been conducted. Results suggest that a combination of green and grey protection measures is more cost-efficient and effective than a grey-only option (Dong et al., 2017).

Artificial measures are measures made or produced by human beings rather than occurring naturally, especially as a copy of something natural (Cambridge Dictionary, 2019).

Technical measures are active permanent (Table 8) conventional mitigation structures that influence natural hazard processes (Holub and Hübl, 2008). According to their location of implementation, they can have stabilizing, consolidating, deflecting, breaking, filtering, retaining and other roles. Forest-biological and soil-bio engineering measures can supplement technical structures (Holub and Hübl, 2008). Conventional technical measures are cost-intensive in construction, and can interfere with the adjacent landscape and its ecology (e.g. Mayer, 2004; Rudolf-Miklau and Patek, 2004). In addition, the complexity of their maintenance and their limited lifetime are major problems (Holub and Hübl, 2008).

Table 8. Categories of mitigation measures (Holub and Hübl, 2008).

	Active	Passive
Permanent	Soil bio-engineering Forestry measures Technical measures	Spatial planning and land-use Hazard mapping Local structural measures
Temporary	Immediate measures	Information and warning Exclusion zones and evacuation

In the Alpine Space there are few (potential) settlement areas that are uninfluenced by natural hazards, therefore structural mitigation measures are essential in order to allow protection and extension of settlement areas. The effect of mitigation measures against natural hazards such as snow avalanches, rockfall, landslides and fluvial processes should be considered to ensure a minimal level of quality, safety and sustainability. When the basic standards are met, the effect of mitigation measures is analyzed based on the following questions (Margreth and Romang, 2010):

- Whether the mitigation measures may be relevant in any way to the hazard assessment;
- Whether mitigation measures are assessed technically by determining their reliability in terms of structural safety, serviceability and durability;
- Whether structural measures are quantified in terms of effect, with respect to their reliability (Table 9).

Table 9. Adjustment to potential natural hazards (Alexander, 2017; Spang, 1998).

Type of hazard	Modification of event	Modification of human vulnerability	Distribution of losses
Avalanche	Artificial triggering	Snow tunnels and barriers	Emergency relief
Rock-fall	Cliff stabilization	Galleries and nets	Emergency relief
Landslide	Drainage of the head scarp area	Land-use regulation	Loans and insurance
Fluvial process	Upstream water impoundment	Flood-proofing	Loans and insurance

Furthermore, the analysis of cost-effect is a crucial point in mitigation measures planning process. When planning protection measures, the effect of mitigation measures is estimated by intensity and probability of hazardous processes. Based on the quantification of hazardous processes, the effect of mitigation measures has to be higher than the uncertainties related to hazard and risk management, has to be analyzed for different scenarios (e.g. scenarios for hazard maps, extreme scenarios) and for different scales, e.g. focusing on the single area with respect to the whole system (Margreth and Romang, 2010). Mitigation measures as well as natural hazard processes change over time, thus the consideration of mitigation measures implies on one hand maintenance and, if necessary, renovation and renewal of each measure and of the whole system of measures, and on the other hand a periodic verification of the risk situation (Margreth and Romang, 2010).

Assessment and quantification of the effects of mitigation measures are crucial, so that mitigation measures can be optimally selected, evaluated and compared (Margreth and Romang, 2010). Artificial protection measures in general experience different failure modes: geometrical failure happens when the structure is jumped over (rockfall) or overran (avalanches, landslides, torrents), because the height may be insufficient; structural failure happens when the structure is not strong enough to withstand the impact. Although the knowledge for certain structural measures has improved in recent years, there are still important knowledge gaps during extreme events (Margreth and Romang, 2010).

6.3 PROTECTIVE EFFECT OF FOREST AND GREY MEASURES AGAINST AVALANCHES

6.3.1 Protective effects of the forest against snow avalanches

The amount of scientific literature regarding the effects of forest on avalanche release is increasing (e.g. Schneebeli and Meyer-Grass, 1992; Bebi et al., 2001; Scnheebeli and Bebi, 2004; Viglietti et al., 2010). Based on forest characteristics (see Chapter 5), different levels of forest's protective effects can be distinguished (Bauerhansl et al., 2010). Methodologies for evaluating forests' protective effects on avalanche release are usually based on binary decisions (sufficient/insufficient protective effect), or a qualitative or quantitative ranking (Bauerhansl et al., 2010).

However, forests can also influence the length of the avalanche runout by affecting avalanche velocity, flow heights and snow deposition patterns (e.g. Feistl et al., 2014a). Forest presents obstacles to avalanche flow, and where snow mass impacts trees, flow energy is dissipated (braking effect). The mechanism of depositing snow mass behind a tree or groups of trees is called detrainment effect (Feistl et al., 2014a). The braking effect of forest on avalanche flow can be simulated with avalanche dynamics models based on either friction or the detrainment approaches (e.g. Teich et al., 2012; 2014; Feistl et al., 2014a). The friction approach accounts for tree breakage or debris entrainment by increasing turbulent friction (Voellmy friction coefficients; e.g. Wichmann, 2017; Gruber and Bartelt, 2007; Christen et al., 2010). This approach is often applied in Voellmy-type models for extreme avalanches (Voellmy, 1955; Bartelt and Stöckli, 2001, Christen et al., 2010). However, the friction approach poorly represents the braking effect of forest for smaller avalanches (Teich et al., 2012). Therefore, the detrainment approach was developed, which calculates the mass (and consequently momentum) that is extracted from an avalanche when impacting trees (Feistl et al., 2014a). The detrainment approach is valid only for events where forest is not destroyed, and is not suitable for simulating complex flows with woody debris (Feistl et al., 2014a).

Forest's protective capacity to reduce avalanche velocities and shorten runout distances of smaller avalanches is mainly related to stand structure (e.g. Teich et al., 2012); however, there are only few physical or statistical models to quantitatively calculate the protective effect of forest based on forest structure. Forest's protective capacity differs if the tree is broken or if the tree sustains avalanche loading pressure. Therefore, avalanche dynamics models should include tree-breaking and avalanche loading (avalanche flow density, velocity and height) when predicting avalanche runouts (Feistl et al., 2015). Moreover, there are only few measurements of avalanche velocities in forested terrain (Feistl et al., 2015). One of the few avalanche dynamics models that accounts for forest effects on avalanche runout is RAMMS::AVALANCHE (Christen et al., 2010). In the future, quantifying protective effects of forests against avalanches by applying avalanche dynamics models should include forest parameters such as forest type, stem density,diameter distribution, surface roughness and vertical structure of the forest (Teich et al., 2014).

Due to the assumption, that forest's ability to stop avalanches is limited, especially for extremely large fast-moving avalanches (De Quervain, 1978; Margreth, 2004), forests were rarely included into calculating avalanche dynamics. Forests influence was mainly expressed as minor changes to the flow friction (Gruber and Bartelt, 2007). However, the need for understanding avalanche dynamics in forested terrain is increasing, and the attention is especially given to smaller and medium avalanches which are most affected by the forest, and consequently are important in providing protection for infrastructure and in ski areas (e.g. Teich et al., 2012; 2014; Feistl et al., 2014a, b; 2015).

6.3.2 Protective effect of artificial measures against snow avalanches

Artificial protection measures can be constructed in snow avalanche release and deposition zones to reduce hazard and risk (Perla and Martinelli, 1976). That is, a protection measure can absorb or dissipate the kinetic energy of snow avalanche impact by catching and stopping snow mass. When designing and planning avalanche protection structures, information on snow mechanics and avalanche dynamics is most crucial. The parameters, influencing avalanche release and dynamics, therefore, the construction of protection measures are:

- exposition (orientation to wind and sun);
- slope characteristics (such as surface roughness, dimension, configuration and elevation);
- snow characteristics (such as flow regime, mass, depth of accumulated snow);
- kinematics (velocity and impact angle) and the layer of absorbing material (thickness, compaction degree) (Stethem et al., 2003; Thibert and Baroudi, 2010).

Avalanche protection structures differ based on their function, material and placement. Massive earth, stone or concrete walls, terraces, and mounds requiring little or no detailed design have been used for more than a century. Avalanche defense structures can be classified in four groups (Table 10; Perla and Martinelli, 1976):

- supporting structures in the starting zone;
- deflecting and retarding structures in the track and runout zones;
- direct protection structures in the runout zone;
- snow fences and wind baffles.

Table 10. Integral avalanche protection in terms of intervention and duration (McClung and Schaerer, 2006).

	Active	Passive
Temporary	Avalanche control by explosives Road closures Precautionary evacuation	Avalanche forecasting Seasonal occupation Seasonal road closures Organizational measures Warning signs
Permanent	Supporting structures Snow fences	Hazard mapping Land-use planning

	Deviation, retarding and catching dams Splitting wedges Reinforced construction Snow sheds (galleries) Reforestation, forest protection/management	

Supporting structures are built in the starting zone (upper part of the avalanche path) to prevent avalanches from forming and releasing. The common snow avalanche structures are snow bridges, snow rakes, snow fences, combined with earth walls or terraces to gain height in areas of deep snow (Perla and Martinelli, 1976). Snow supporting structures are expensive to install and maintain, especially because of the material used and their placement in hard-to-reach terrain. Deflecting and retarding structures are massive structures, usually made of earth, rock or concrete and located in or near avalanche tracks or runout zones, intended to keep the moving snow of an avalanche away from valuable objects. The common structures are usually earth mounds, which are typically inexpensive to build and relatively easy to maintain or dams built on benches (Perla and Martinelli, 1976). Direct-protection structures built immediately adjacent to the protected object can be a part of the object itself. Their construction is more economical for narrow roads than for multi-lane highways. Snow fences and wind baffles are in most cases used to reduce the number and size of avalanches and to prevent the formation of cornices (Perla and Martinelli, 1976).

Table 11. Structural countermeasures against snow avalanches (Catalogue …, 2008).

Process	Counter measure	Type
Snow avalanches	Snow drift regulation	Snow fence
		Jet roof
		Wind baffle
	Stabilizing constructions	Snow bridge / rake
		Snow net
		Tripod
	Braking constructions	Avalanche breaker
	Deflecting and catching constructions	Deflecting and catching dam
		Gallery
		Tunnel
	Artificial release	Aerial cableway
		Preplaced explosives
		Gas exploders
		Guns
	Afforestation	

The occurrence of snow avalanches with greatest magnitude is often related to non-forested areas above the timberline (Bartelt and Stöckli, 2001; Teich et al., 2012). In such areas only technical protection measures are constructed to reduce onset probabilities of avalanches (Perla and Martinelli, 1976). Another artificial protection structure against snow avalanches and rockfall are wooden tripods, which prevent snow gliding and disrupt the propagation of smaller rocks (Brang et al., 2006; Catalogue …, 2008). Wooden tripods can be used as protection of seedlings in avalanche afforestation programs (Frey and Thee, 2006; Catalogue …, 2008) and, therefore, can be also seen as part of silvicultural measures. The lifetime of wooden tripods depends on the type of wood used. They are usually designed to serve their purpose for about 50 years. Compared to steel structures timber structures are less expensive, but their effect in the long term depends on the success of the afforestation (Catalogue ..., 2008).

6.4 PROTECTIVE EFFECT OF FOREST AND ARTIFICIAL STRUCTURES ON ROCK SLOPE FAILURES

6.4.1 Protective effect of the forest against rock slope failures

In the case of rock slope failures, the protective effect of the forest is mainly mitigative in reducing the propagation probability of the mass movements. However, forests that grow in release areas of rockfall can either increase or have no effect on onset probability.

In rockfall areas where forests don’t provide sufficient protective effects due to negative forest effects in or close proximity of elements at risk to the release area, artificial technical structures should be constructed. Technical measures in the rockfall source areas provide the best protective effect against rockfall activity. Unstable rocks and cliff faces can be supported by nets, wires, rock anchors or concrete sprayed directly onto the rockfall source areas (Figure 25). Such technical measures are often located above infrastructure objects (Chen et al., 2013). The constraints of artificial measures is that the construction can be challenging due to inaccessible or difficult terrain.

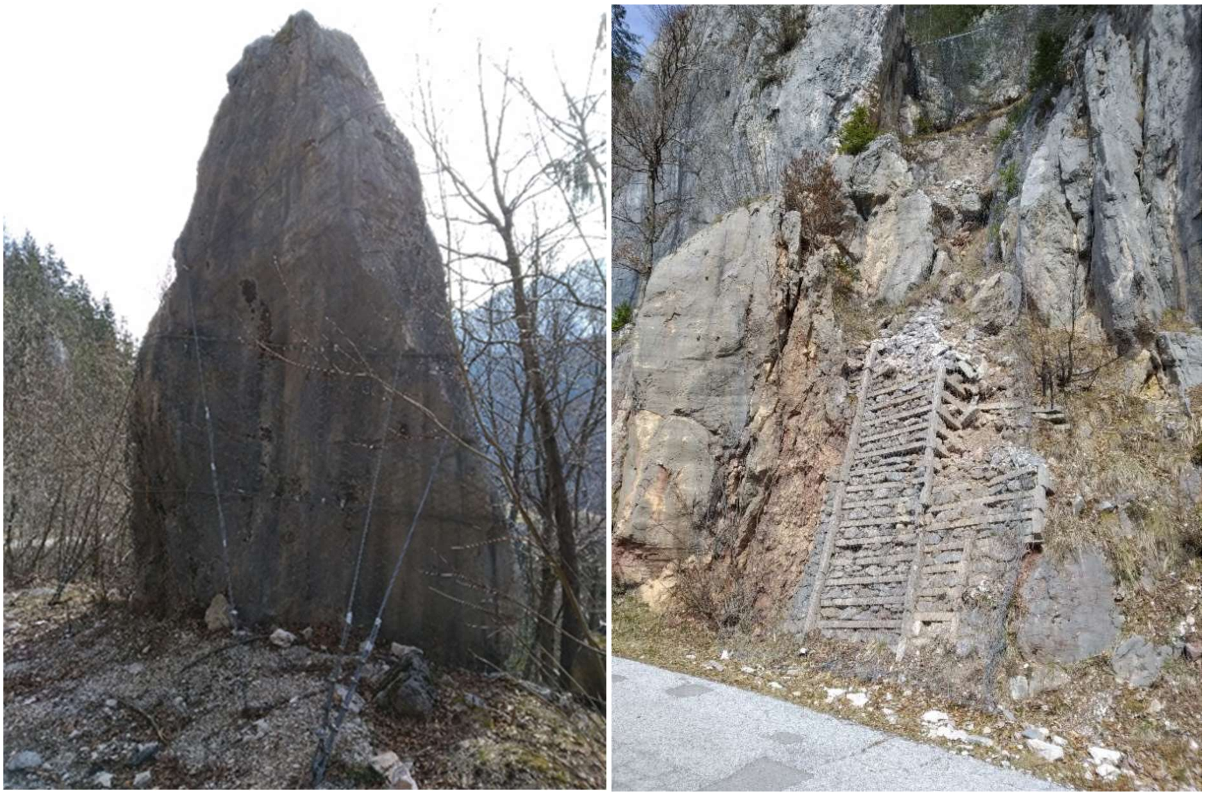


Figure 25. An example of secured rockfall release area by nets and anchored wires. Location of photo – Gozd Martuljek (Photo: Domen Oven, 2019).

Forest’s protective effect is greatest in reducing the propagation probability of rockfall (e.g. Dupire et al., 2016). These protection forests with direct protective function are located in rockfall transit and runout areas where they can act as protective barriers, i.e. individual trees absorb and dissipate kinetic energy of rockfall (e.g. Perret et al., 2004; Brang et al., 2006; Dorren et al., 2005; Dorren and Berger, 2006). By measuring dissipated kinetic energy, the mechanical resistance of a tree can be quantified (Bartelt and Stöckli, 2001; Stokes et al., 2005; 2006; Dorren et al., 2005; Dorren and Berger, 2006; Jonsson et al., 2007). Although there exist three methods for quantifying mechanical resistance of trees to slope processes (static tree-pulling tests, dynamic impact tests on wood samples, dynamic impacts tests on living trees) (Dorren and Berger, 2006), the information on biomechanical behavior of individual trees under the effects of rockfall is still lacking (Stokes et al., 2006). In fact, a tree can absorb or dissipate the kinetic energy of a rock impact in several different ways: through the translation and rotation of the root system, deformation and oscillation of the stem, or local penetration at the point of impact of the rock mass (Foetzki et al., 2004; Brauner et al., 2005; Dorren and Berger, 2006). Because an individual tree absorbs energy in different ways, quantitative assessments of the absorbed kinetic energy of trees are extremely challenging (Dorren et al. 2007). Dorren et al. (2005) calculated the ability to absorb the energy for individual tree species on the basis of field testing, thus determining the scale of which tree species are more or less resistant to mechanical pressures (Order of tree species from most resistant to least is: *Quercus robur* > *Fagus sylvatica* > *Acer pseudoplatanus* > *Abies alba* > *Larix decidua / Picea abies*; Figure 26). Based on the scale of resistance, deciduous trees are more effective in providing a protective function against rockfall (Dorren and Berger, 2006; Stokes, 2006).

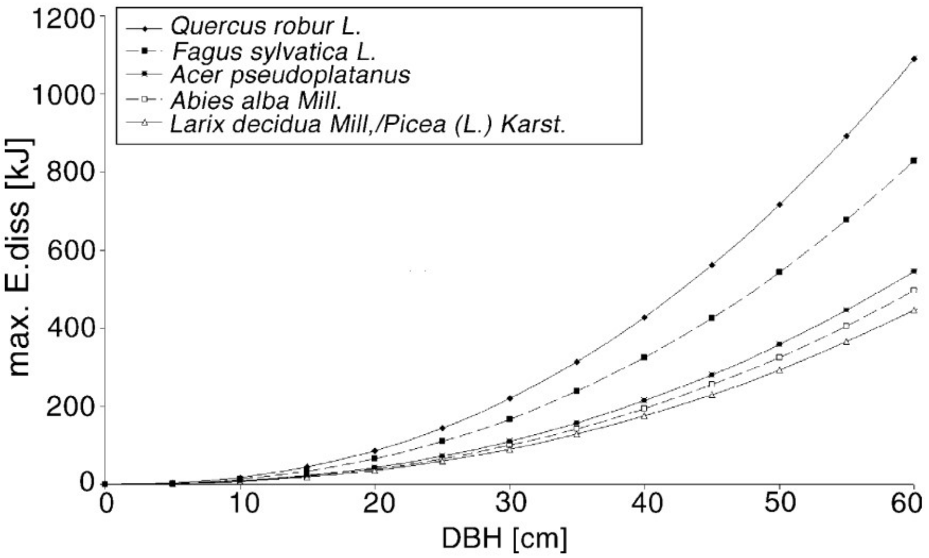


Figure 26. Ratio of diameter of breast height and maximum energy dissipation that can be transmitted by a single tree species (From Dorren et al., 2005).

Furthermore, European beech and broadleaves in general are more resistant to rockfall compared to Norway spruce because of the bending and splitting characteristics of their wood (Dorren and Berger, 2006), better anchorage and quicker healing (Stokes et al., 2006). Tree anchorage is mainly the result of root characteristics, especially root depth, topology and biomass (Stokes et al., 2006). Trees with shallow plate-root system (e.g. Norway spruce) are less resistant to overturning (e.g. Fourcaud et al., 2008).

Besides tree's characteristics, the impact position on a tree and the size of the block also influence the probability that a rock will be stopped by a tree (Wehrli et al., 2006; Toe, 2016), especially the frontal impact of a rock is more likely to be stopped by a trunk, compared to lateral impacts of rocks (Dorren and

Berger, 2006). The effect of the forest on risk reduction is strongly related to the magnitude of the event, which is in the case of rockfall related to volume of the block (Figure 27).

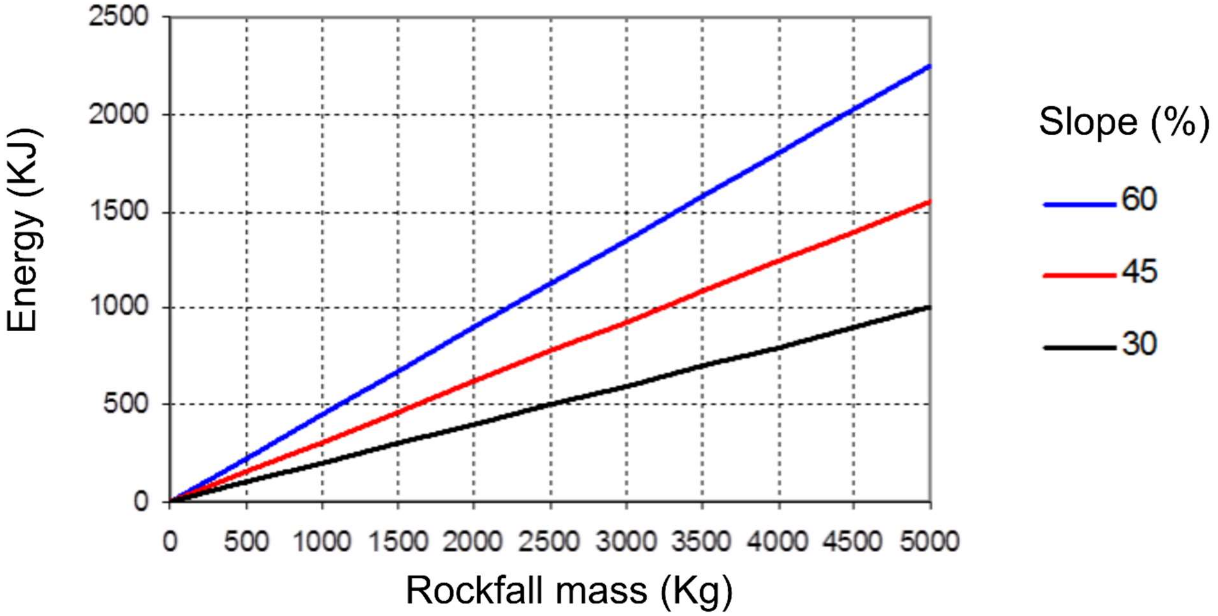


Figure 27. Kinetic energy of rockfall in relation to slope angle and mass of the rock (Papež, 2012).

Currently the only way to quantify the protective effect of the forest against rockfall activity can be achieved by models that simulate individual block trajectories (e.g. Stoffel et al., 2006; Moos et al., 2018). By comparing the frequency of trajectories between forested and non-forested areas protective effects and risk reduction can be calculated for specific cases (Moos et al., 2018). However, case studies that assess risk reduction by forest are rare. Moreover, there are still uncertainties regarding assessing the protective effect with simulation models due to model assumptions that can be too generalized to be applied to a specific case study site (Moos et al., 2018). For example, the RockFor3D model does not consider different tree species when calculating energy dissipative capacity of a tree neither their vitality or anchorage (Moos et al., 2018). Besides modeling constrains, there are also problems determining actual (onset) frequency and magnitude of the specific rockfall site, and therefore validating modeling results (Moos et al., 2018). Although dendro-geo-morphological methods can be applied to validate a model, they are time consuming but provide precise estimation of frequency and magnitude (e.g. Moos et al., 2018). Nevertheless, deterministic or stochastic models such as RockyFor3D, RAMMS, Zingeller GEOTEST and RockFor.net (e.g. Perret et al., 2004; Stoffel, et al., 2006, Berger and Dorren, 2007; Dorren et al., 2015; Sellmeier, 2015) can be used for quantitative risk assessment with inclusion of forest parameters and thus provide an objective method to compare protective effects of forest with artificial protection measures, both in terms of effectiveness and cost-efficiency (Moos et al., 2018). Since 2019 a new application for helping experts to characterize and quantify rockfall hazards and forests' protective effect is available: PLATROCK. It's the first online and freely accessible rockfall multi-model platform (https://www.alpine-space.eu/projects/rockthealps/en/results-and-download/platrock).

Figure 28. Individual trees with relatively small DBH can stop enormous rocks, although tree's capacity to dissipate all kinetic energy of the rock is also influenced by the velocity of the rock (Photo: Barbara Žabota, 2017, 2019).

6.4.2 Protective effect of artificial measures against rockfall

Before identifying potential places for building rockfall protection measures, a systematic mapping should be carried out on the slope to identify high risk areas and by avoiding such areas, if possible, by moving intended structures to safer areas (Spang, 1998). When designing rockfall protection measures, detailed geotechnical mapping is required to determine size, volume and location of unstable rocks. Furthermore, features prone to cause rockfall should be identified, and parameters of slope surface should be analyzed (Spang, 1998). Based on case-specific input parameters rockfall simulation models should be used for hazard assessment and different mitigation scenarios (e.g. ditches, dams, galleries, etc.). The appropriate structure is selected according to the required energy dissipation and, later on, dimensions are optimized by applying probabilistic safety concepts (Spang, 1998). In addition, when selecting appropriate mitigation measures, ecological impacts should be avoided, minimized or compensated (Spang, 1998). Linear, inconspicuous, light and transparent structures with high specific strengths should be installed, instead of bulky systems (Spang, 1998). Furthermore, economic solutions with low construction cost, short construction time, long life-time and low maintenance requirements, but high safety should be considered as well (Spang, 1998).

Table 12. Integral rockfall protection in terms of intervention and duration (Spang, 1998; Volkwein et al., 2009; Volkwein et al., 2011).

	Active	Passive
Temporary	Rockfall control by explosives Road closures Precautionary evacuation	Rockfall forecasting Seasonal occupation Seasonal road closures

		Organizational measures Warning signs
Permanent	Supporting structures Deviation, retarding and catching dams Rockfall nets Galleries Reforestation, forest protection/management	Hazard mapping Land-use planning

According to the terrain topography above the endangered zones and the kinetic energy and bounce heights distribution along the slope profile obtained from rockfall simulations, suitable protection measures are suggested in order to divert or stop rockfall (e.g. Spang, 1998; Volkwein et al., 2009, 2011). While diversion is done by galleries, stopping can be done by several types of structures, mainly depending on the required energy dissipation (Spang, 1998). Energies > 2,500 kJ require (earth) dams and ditches, while energies < 2,500 kJ can be dissipated by barriers (rigid steel, wood and concrete structures are completely replaced by different types and strong flexible wire rope nets of different types and strengths) (Spang, 1998). Most effective are embankments and ditches, especially embankments which are able to withstand high impact energies of 20 MJ (Volkwein et al., 2011), although their construction is more spatially demanding (Baumann, 2008; Lambert and Bourrier, 2011). Another type of protection measure is galleries, which are effective for small and well-defined endangered zones with a high rate of medium magnitude events (Volkwein et al., 2011). The galleries can provide protection up to 5000 kJ (Vogel and Masuva, 2009). One of the most common protection measures against rockfall protection is the use of flexible protection systems (fences), installed along infrastructure and buildings to stop moving blocks (Volkwein et al., 2011). The type of system and height are most important characteristics that influence the maximum energy dissipation capacity.

Figure 29. Wooden technical measures that reduces propagation probability of rockfall (Photo: Barbara Žabota, 2019).

Finally, also wooden technical measures can be quite effective against rocks of smaller diameter, especially in combination with forest's protective effect (Figure 29). However, wood is susceptible to decay and, therefore, the durability of wooden technical measures is limited (Foliente et al., 2002), but such structures are cost-efficient and can be viewed as sustainable due to their low carbon footprint.

Considering safety concepts, protection measures may experience two different failure modes; geometrical failure happens when the structure is jumped over, due to insufficient height; structural failure happens when the structure is not strong enough to withstand the impact (Spang, 1998). According to Stocker (1997) there are three different possibilities to define safety factors against failure modes:

- safety factors as a lump sum on the load (structural safety) and the bounce height (geometrical safety);
- application of partial safety factors on input data, e.g. rock volume, rock density, friction angles, damping etc.;
- probabilistic approach, using a random number generator to vary all input data during rockfall simulation.

Furthermore, the trajectory analysis provides statistical distributions for the bouncing heights and kinetic energy of the boulder, which are used to identify possible construction sites and to define the main geometrical characteristics of the protection measure (e.g. Volkwein et al., 2009, 2011). Besides kinematics (velocity and impact angle), the parameters influencing bouncing phenomena and protection measures are:

- slope characteristics (such as strength, stiffness, roughness, inclination);
- rock characteristics (such as strength, stiffness, weight, size, shape);
- layer of absorbing characteristics of material (thickness, compaction degree) (e.g. Peila et al., 2007, Volkwein et al., 2009, 2011).

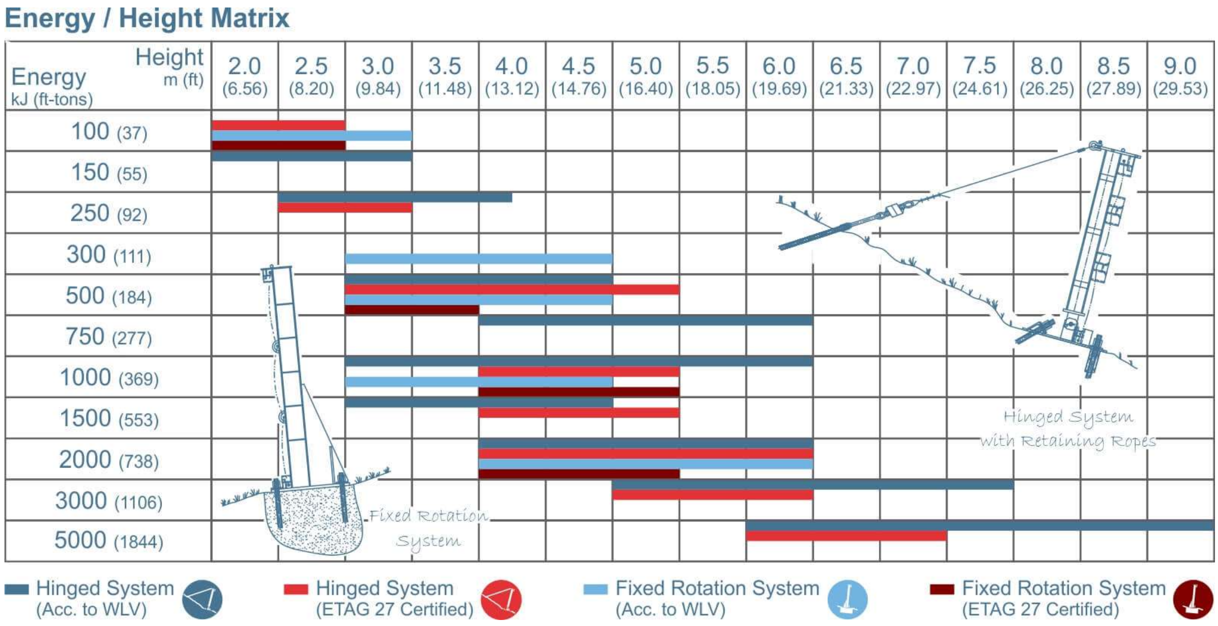


Figure 30. Energy height matrix for rockfall, considering different systems (Trumer, 2019).

Protective effects of artificial rockfall protection measures can also be quantified by the absorbed energy (Figure 30) (e.g. Peila et al., 2007, Volkwein et al., 2009, 2011).

In areas where the protective effect of a forest is inadequate (couloirs, forest gaps), silvicultural measures can be applied besides technical (grey) infrastructure in order to mitigate impacts of mass movements (Berger et al., 2013). Silvicultural measures increase surface roughness and dissipate kinetic energy of rockfall, e.g.:

- leaving tree stumps as high as possible,
- leaving felled trees in the forest, and positioning them diagonally to the slope direction (Figure 31) (Berger et al., 2013).

Criteria for selecting trees to be felled should consider: position in relation to rockfall corridor, tree stability, choosing large diameter trees (or stacking multiple trees), the effect on regeneration, the effect on size of the gaps, shadow effects (trees growing behind each other) (Berger et al., 2013). On average, the energy loss of rocks that hit felled trees is around 30%, and the optimal orientation of the stems is between 45° and 70° (Berger et al., 2013).

A last mixed solution is to use trees as support for rockfall nets. The development of this combined technique has been initially launched in France in 2012, and the first efficient prototype has been successfully tested in 2016 for an impact energy of 100 kJ. Prototypes for higher energy are under development and test. One of the advantages of this combined technique is its low cost of implementation compared to traditional rockfall nets.

Figure 31. Leaving felled trees promotes surface roughness (Photo: Barbara Žabota, 2019).

6.5 PROTECTIVE EFFECT OF FOREST AND ARTIFICIAL STRUCTURES ON SOIL SLOPE FAILURES

6.5.1 Protective effect of forest against soil slope failures

Given the important role that forests can have (as highlighted in chapter 5.2), the range of green measures to increase protective effects is much more limited for soil slope failures than for the other hazards. In most cases the only feasible solution is the adoption of soil-bioengineering measures, which often include vegetation elements such as tree spurs, branch layering, vegetated channels, live brush mattresses, live slope grids, live fascines etc. (Schuster and Lynn, 2001; Hübl and Fiebiger, 2005). Soil bio-engineering methods can be fast and effective solutions in stabilization of a slope (Andreu et al., 2009; 12). Afforestation (and soil-bioengineering) of unstable slopes present financially and logistically viable mitigation measure (Galve et al., 2015), however its protective effect can be delayed in time. In terms of effect, the most effective mitigation measure is the combination of soil-bio engineering and engineering structures (Schuster and Lynn, 2001; Popescu and Sasahara, 2009; Galve et al., 2015). Conventional retaining structures made of steel or concrete are financially exhaustive and their effect decreases over time. Therefore, they are often replaced by biotechnical slope protection (as part of landslide remediation) in order to create more environmentally acceptable solutions (Schuster and Lynn, 2001). Nonetheless, the realization of specific mitigation measures should be done by suitability assessment, which is based on analysis of the stability of the landslide mass and analysis of the geologic and meteorological conditions (Bhasin et al., 2002).

Similarly, concerning debris flow, while there are no available measures to limit the transit of the event, catchment-scale solutions as afforestation, forest cattle grazing and game stock reduction can successfully reduce surface runoff and bedload transport due to the improvement of forest conditions (Hübl and Fiebiger, 2005).

6.5.2 Protective effect of artificial measures against soil slope failures

Technical and biotechnical measures in combination with hazard mapping and land-use planning can effectively reduce landslide risk to accepted levels (Table 13; Amman, 2001; Hübl and Fiebiger, 2005). In general, mitigation measures can be distinguished in active, focusing on the hazard, and passive measures, focusing on the potential damage (Hübl and Steinwendtner, 2000; Kienholz, 2003).

Table 13. Integral landslide protection in terms of intervention and duration (Ribičič, 2006).

	Active	Passive
Temporary	Road closures Precautionary evacuation	Landslide forecasting Seasonal occupation Seasonal road closures Organizational measures Warning signs
Permanent	Supporting structures (walls) Reinforced construction Jet grounding Wells Reforestation, forest protection/management	Hazard mapping Land-use planning

From a practical perspective, the following classification into four groups is also often used (Popescu and Sasahara, 2009):

- modification of slope geometry: e.g. removing/adding material, reducing slope angle;
- drainage: pipes, trenches, wells, boreholes etc.;
- retaining structures: e.g. walls, piers, piles, earth retaining structures;
- internal slope reinforcement: e.g. rock bolts, anchors etc.

Modification of slope geometry and drainage are the most used (and least costly) method of landslide remediation (Popescu and Sasahara, 2009). Often, other measures are possible focusing on the pre-existing structures such as restoration and /or reforestation of abandoned terraces and use of local structural measures over stretches of potentially unstable hillsides (Galve et al., 2015).

In the case of debris flows, active debris-flow mitigation measures can influence the initiation, transport or deposition (Hübl and Fiebiger, 2005). Mitigation measures are classified based on their functionality into watershed management, forest measures, terrain altering, drainage systems, channel-bed stabilization etc. to decrease erosion and runoff, which reduces onset probabilities, and "hard" engineering structures such as barriers, deflection berms and debris basins to reduce the propagation probability (Table 14; Hübl and Fiebiger, 2005). The most common structures are breakers (also check dams), designed as independent structures or combined with dosing and sorting barriers to reduce impact energy and to control discharge (Hübl and Fiebiger, 2005; Popescu and Sasahara, 2009). Deflection structures (dikes, embankments, groins, deflection walls), constructed to direct debris-flow towards an area with low consequences require the existence of an area with low economic value, where debris is allowed to deposit (Hübl and Fiebiger, 2005). Passive mitigation measures are used to reduce the potential loss, e.g. altering the spatial and temporal character either of the damage produced by debris flows or the associated vulnerability (Hübl and Fiebiger, 2005).

Table 14. Structural countermeasures against debris flow (Catalogue …, 2008).

Process	Counter measure	Type
Debris flow	Increase slope stability	Drainage
		Soil-bio engineering
	Consolidation / Stabilization	Sill
		Ramp
		Closed check dam
	Transformation of process	Debris flow breaker
		Drop structure
	Organic debris filtration	Open check dam (rake)
	Permanent debris deposition	Open check dam
		Deposition basin
	Temporary debris deposition	Open check dam
	Protection / Deflection	Protection and deflection walls / dams
	Discharge control	Transport channel
	Afforestation	

6.6 PROTECTIVE EFFECT OF FOREST AND ARTIFICIAL STRUCTURES ON FLUVIAL PROCESSES

6.6.1 Protective effect of the forest against floods

Despite various studies of forest hydrological processes, due to the intricate processes involved the quantification of forest's protective effect against onset probabilities and intensity of floods at larger scale still pose quite a task (Moos et al., 2017). There also exists doubt whether at larger scales forests have any mitigation effect in extreme flood events (Dhakal and Sullivan, 2014; Sidle and Ziegler, 2016; Moos et al., 2017). Instead, it is important to emphasize the possibility of enhancing other measures such as restoring wetlands, increasing groundwater storage, limiting pavements in settlements, planting catch vegetation etc. (Krysanova et al., 2008). Furthermore, functioning ecosystems can have a buffering function on communities, for example impacts of flooding effects (Watson et al., 1999). Current techniques for quantifying water-related ecosystem services can be divided into three categories (e.g. Brody et al., 2006; Ming et al., 2007; Keeler et al., 2012; Watson et al., 1999):

- empirical approaches, used to measures biophysical supply of ecosystem services;
- advanced hydrological models, modified to inform ecosystem service decision;
- models developed as support tools for ecosystem service decision making.

Empirical approaches are used to measure the water capacity of wetland soil or the development of wetlands to flooding frequency, while advanced hydrological models do not tend to produce results, but evaluate benefits to specific stakeholders (Watson et al., 1999).

6.6.2 Protective effect of artificial measures against floods

In areas where the protective effect of the forest against onset and propagation probabilities of floods is not sufficient, artificial protection measures should be constructed, especially in areas of high torrent activity. Flood protection measures can be divided into structural or technical measures and non-structural measures, which include social measures and measures taken in watersheds (e.g. bioengineering solutions) (Krysanova et al., 2008). Structural mitigation measures can be transverse or longitudinal. Transverse structures mainly prevent stream bed erosion, while longitudinal structure prevent bank erosion. Structural measures such as barriers, check dams and flood-control reservoirs are used to mitigate the effect of floods (Hübl and Fiebiger, 2005). Barriers are constructed across the path of debris flows to encourage the deposition by presenting a physical obstruction to the flow. Check dams are structures placed transversally to the torrent, from one bank to another and permanently backfilled. The height of a check dam is defined according to the designed slope, and based on a hydraulic study (Catalogue…, 2008).

The response strategies for preventing flood events include different protection measures. Focusing on structural measures, it is clear that physical protection, including dams, storage reservoirs and embankments (e.g. polders, levees etc.), alone cannot completely protect against floods (Kundzewicz and Takeuchi 1999).

6.7 PROTECTIVE EFFECT: FORESTS VS. ARTIFICIAL MEASURES

A comparison of protective effects of forest and artificial measures is presented in Table 15, where a distinction was made by mass movement process. The presented weighing of protective effects of forest was adapted after Bauerhansl et al. (2010). Protection measures are presented only for the mass movement processes considered in this report (see Chapter 5). Artificial protection measures are combined for all types of soil slope failures defined in Chapter 5, although different types of artificial protection measures are applied for different natural hazards.

The comparison of protective effects of different protection measures was done for different parts of their process area (e.g. release, transit and runout area). Four types of protection measures were identified: protection forest, artificial protection measures, soil-bioengineering and silvicultural measures. The protective effect of forest was evaluated only for four types of forest (coniferous mature, deciduous mature, coniferous young, deciduous young), because tree species and DBH are relevant stand parameters in terms of protection against mass movements. The protective effect of artificial protection measures was evaluated only for well-established structures, and dimensions and type of material were not acknowledged. Furthermore, the condition of protection measures was not accounted for. Therefore, Table 15 presents only a rough estimation of protective effects of individual protection measures since it is difficult to quantify and compare protective effects of forest to other (artificial) protection measures due to complex variables that affect the resistance of individual trees against mass movement processes. In the case of indirect protection forest, the quantification of protective effects is even more challenging. Therefore, the comparison of protective effects between different protection measures should be viewed as a generalization. Protective effects of protection measures were quantified based on three levels of effect (low, medium, high).

Table 15. A comparison of protective effect of forest and artificial measures: - negative protective effect, / not used, o - no effect, + low protective effect, ++ medium protective effect, +++ high protective effect. In cases where multiple symbols occur various effect can be observed.

Natural hazards / Protection measures	AVALANCHES		ROCK SLOPE FAILURES		SOIL SLOPE FAILURES		FLUVIAL PROCESSES
Part or type of natural hazard	Release area	Transit and runout area	Release area	Transit and runout area	Release area	Transit and runout area	Floods
1 PROTECTION FOREST							
1.1 Coniferous mature forest	+++	o, +, ++	+, -	+++	+++	o, ++	o, ++
1.2 Deciduous mature forest	+	o, +	+, -	+++	+++	o, ++	o, ++
1.3 Coniferous young forest	++	o, +, ++	+, -	+++	+, ++	o, +	o, ++
1.4 Deciduous young forest	++	o, +	+, -	+++	+, ++	o, +	o, +++
2 ARTIFICIAL PROTECTION MEASURES							
2.1 Fences	+++	+++	/	++	/	/	/
2.2 Walls	+++	+++	+++	+++	+++	/	/
2.3 Breakers	/	+++	/	/	/	+++*	/
2.4 Barriers	/	+++	/	+++	/	+++	+++
2.5 Galleries	/	+++	/	+++	/	/	/
2.6 Dams	+++	/	/	/	/	+++	+++
2.7 Nets	+++	/	+++	+++	/	++*	/
2.8 Embankment/ retaining structures	/	/	/	+++	++	++	/
2.9 'Jet grounding' / slope reinforcement	/	/	/	/	++	++	/
2.10 Drainage	/	/	/	/	++	++	++
2.11 Sill	/	/	/	/	/	++*	++
2.12 River training	/	/	/	/	/	+*	+++
3 SOIL-BIO ENGINEERING							
3.1 Groin	/	/	/	/	/	++*	+
3.2 Live crib wall	/	/	/	/	/	+*	+++
4 SILVICULTURAL MEASURES							
4.1 High stumps	++	+	/	++	+	/	/
4.2 Leaving felled trees	++	+	/	++	/	/	/
4.3 Afforestation	+++	+	+	++	+++	+	+++

*Protective effect of artificial protection measures described only for debris flows.

Forest (especially coniferous) was identified as the most cost-effective protection measure in snow avalanche release areas. However, avalanche release areas can be located above the tree line and, therefore, artificial protection measures should be constructed in such areas where appropriate. The effect of artificial measures in release areas varies based on their height, material and position (McClung and Schaerer, 2006). Protective effects of forest in transit and runout zones of avalanches is low or even non-existent in the case of large avalanches. In these zones, artificial protection measures are the most effective, especially massive structures such as galleries. Soil bio-engineering and silvicultural measures are the most effective in the release areas since they increase surface roughness and prevent snow gliding.

In rockfall release areas the protective effect of forest is debatable, while artificial protection measure can sufficiently prevent rockfall initiation. In the case of rock slope failures, protective effects of forest are the highest in transit and runout zones. High-density broadleaf stands are especially highly resistant against rockfall. Artificial protection measures can be even more effective in rockfall transit and runout zones in comparison to forests, although they should be constructed in appropriate dimensions. The effectiveness of silvicultural measures to increase protection against rockfall is strongly time dependent. Directly after the silvicultural intervention, the effectiveness of the protection forest could be reduced. Therefore, the integration of both technical and silvicultural measures can guarantee an effective protection in the short as well as in the long-term.

Forest seems to be most effective in preventing soil slope failures due to root reinforcement of the slope. Mature trees with tap root system are most effective in slope stabilization while young trees, areas with shrubs and grasses and forest gaps are prone to soil slope failures. Artificial protection can be, in comparison to the forest's protective effect, even more effective in the case of deep landslides, where the effect of root reinforcement can be negligible. In the case of debris flows, forest can have direct or indirect protective effects, although its effect varies. In general, forested slopes reduce onset probabilities of debris flows, whereas, if the debris flow occurs and flows into a torrent channel, the effect of forest is non-existent. Therefore, the only solution in terms of protection is to construct artificial protection measures. The purpose of soil-bioengineering and silvicultural measures is mainly to reduce onset probabilities. Bioengineering methods (in combination with technical structures) can also be used to prevent bank erosion.

The protective effect of forest on floods is indirect since forests can generally reduce the onset probability; however, in the case of extreme precipitation the effect of forest can be limited. Young forest stands are in general better suited for mitigating peak flows due to higher water demands. The protective effect of artificial protection measure cannot be fully replaced with forest, because the protective effect of forest is non-existent once water is in the (torrent) channel. Protective effects of artificial structures can be high, although they need to be kept in sufficient condition. Moreover, monitoring and maintenance of artificial measures should be one of the more important management priorities. If maintenance is neglected for a longer period, the protective effect of the measures drops due to the devastating mechanical forces and material disintegration (Figure 32). However, maintenance of artificial protection measures is of high financial demands (Piton et al., 2017).

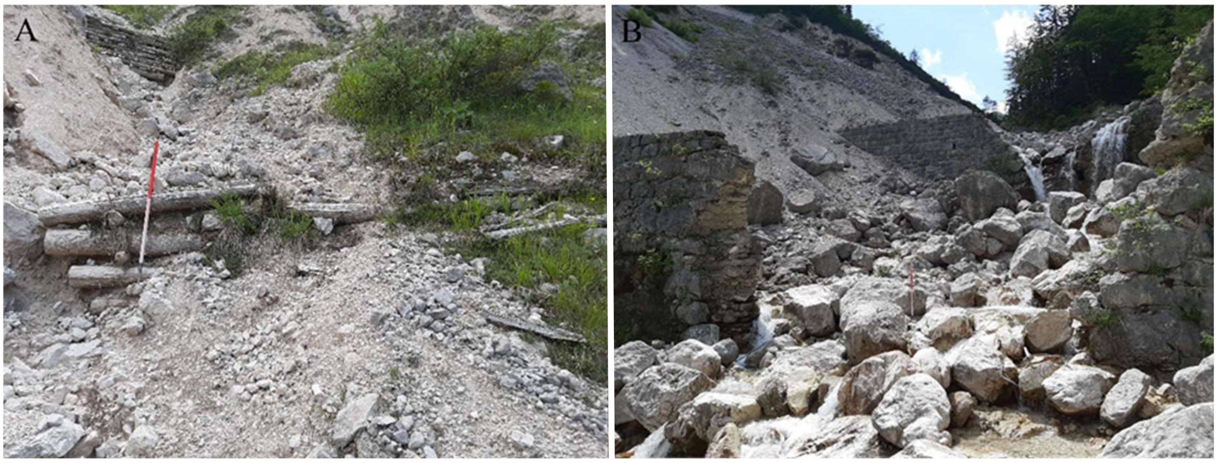


Figure 32. Completely destroyed torrent control measures that provide no protective function. Location: Kranjska Gora. (Photo: Domen Oven).

In conclusion, the choice of a protection measure should be based on the characteristics of the protection measure such as resistance, cost, durability and sustainability (Table 16). Construction costs of artificial protection measures are generally high, because construction demands large quantities of material and especially in the case of high transportation costs or in the case of demand for new infrastructure. Soil bioengineering is a cost-effective solution for stabilizing embankments and their protective effect can be prolonged until higher vegetation develops. Soil bioengineering is usually used in combination with technical measures. Afforestation as a protection measure against floods is mainly applied indirectly to limit surface runoff and surface erosion and on the watershed scale. In terms of sustainability, protection forest, silvicultural measures and soil bioengineering are considered to be less disruptive for environment due to their cost-effectiveness and multi-functionality.

Table 16. Characteristics of protection measures: + low, ++ medium, +++ high. Resistance is the capability of the protection measure to withstand mass movement impacts. Cost can be divided into construction and maintenance. Construction cost depends on the material, logistics, and number of working hours. Cost of maintenance consist of monitoring, and repairs. Durability is related to the life expectancy of the protection measure. Sustainability of the protection measure is related to the maintaining of the ecological balance.

Protection measure\Characteristics	Resistance	Construction cost	Maintenance cost	Durability	Sustainability
PROTECTION FOREST	+/+++	+	++	+	+++
ARTIFICIAL PROTECTION MEASURES	+++	+++	+++	++	+
SOIL-BIO ENGINEERING	++	+	+	++	+++
SILVICULTURAL MEASURES	+	+	+	+	+++

7 CONCLUSIONS

Forests are fundamental for human activity thanks to their numerous functions (ecosystem services) such as the protection from different natural hazards in the Alpine Space. In this report, we analyzed the main natural hazards that can affect settlements and infrastructures in mountain areas and the role of forests in mitigating their intensity or limiting their frequency.

Effectiveness of protection depends on resistance and resilience of each stand, which, in turn, depend on forest structure. It is not possible to give a whole, comprehensive and absolute description of the best structure that a stand should have to mitigate or avoid natural hazards, because each hazard requires specific characteristics connected not only to the hazard itself, but also to the intrinsic characteristics of each site such as topography, climate, stand structure and type of plant association. It is, however, possible to provide general recommendations: for example, uneven-aged stands provide a better protective function compared to even-aged stands due to their multilayered structure and their wide range of DBHs and age classes. This also helps stands to be more resilient when affected by a disturbance and ultimately to maintain some form of protective effect over a longer time scale. Another important factor is roughness of the forest floor, which depends partly on soil and topography and in large part on deadwood volume and spatial distribution (lying trunks, stumps, uprooting trees…). Roughness is very important in particular in case of rockfall, creating a barrier, and avalanches, by interrupting the homogeneity of the snowpack. Furthermore, a high stand density is important, because it creates a uniform and continuous system of roots that stabilize the soil and provides an uninterrupted forest cover, which improves the probability of rockfall impacts and, like roughness, disrupts the formation of a homogeneous snow layers reducing the likelihood of slab avalanche formation. Density should be intended for both stem density and absence of large dimension gaps in the forest cover.

Another important point is related to tree species and, therefore, to forest species composition. Each species has a different root system, stem resistance/elasticity, crown shape, etc. All these characteristics make each species more suitable against some hazards than others. In general, conifers provide better protection in avalanches prevention than broadleaves, which reduce their canopy surface in the winter. However, broadleaf stands are more suitable against rockfall due to their better stem resistance. Other advantage of broadleaves is the ability of some species to resprout, creating a faster recovery after disturbance. When forest stands are subject to more than one disturbance, the best forest structure is a multi-aged mixed forest, but ecological limits to the development of broadleaves at higher altitudes and conifers at lower altitudes make this solution not always feasible.

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