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Abstract	Among the functions provided by forests, protection has always been considered one of the preeminent in mountain areas. In order to fulfil, maximize, and sustain this function, specific forest structures should be obtained and maintained through properly designed forest management. A specific management goal should be defined with a well-defined forest target against each natural hazard, based on the protection potentially provided by the forest stands, in either an active (e.g. against avalanches) or passive way (e.g. against rockfall). Climate change is forecast to affect both disturbance regimes and forest ecosystems, leading to new challenging issues concerning protection forest management. This paper describes how a forest stand exerts its protective role against rockfalls and the target profile to be reached for sustaining this function. Potential consequences of climate change on forest ecosystems that management will have to face in the near future are also addressed. New perspectives are provided taking into account the knowledge coming from recent research studies and specifically the results obtained in the RockTheAlps project (ASP462), dealing with the assessment of protection forests against rockfall in the Alps.
Keywords (separated by '-')	Protection forests - Alps - Rockfall - Forest management - Climate change

The Protective Role of Forests to Reduce Rockfall Risks and Impacts in the Alps Under a Climate Change Perspective

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Abstract Among the functions provided by forests, protection has always been considered one of the preeminent in mountain areas. In order to fulfil, maximize, and sustain this function, specific forest structures should be obtained and maintained through properly designed forest management. A specific management goal should be defined with a well-defined forest target against each natural hazard, based on the protection potentially provided by the forest stands, in either an active (e.g. against avalanches) or passive way (e.g. against rockfall). Climate change is forecast to affect both disturbance regimes and forest ecosystems, leading to new challenging issues concerning protection forest management. This paper describes how a forest stand exerts its protective role against rockfalls and the target profile to be reached

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Protection Forests

In mountainous areas, forest stands have always played an important role in maintaining valleys safe for living in and transiting. This importance is increasing, since in the last decades settlements have also been built in remote mountain areas and there is the need to access them throughout the year, mostly for tourism (Wehrli and Dorren 2013; Lingua et al. 2017).

The protective role is considered among one of the most important functions provided by a forest stand. All forests, regardless of their location, can accomplish this, for instance protecting the soil from surface erosion and taking part directly and indirectly in the hydrological cycle. However, despite this general protective role, we do not define all forests as protection forests. A protection forest is instead characterized and defined due to the existence of a specific natural hazard against which it offers protection in an active or passive way. It might also fulfil other functions, but its protective role is preeminent. Protection forests are particularly effective against some types of abiotic disturbances, like snow avalanches, rockfalls, debris flows, shallow landslides, surface erosion and floods. Since these are mostly gravity-driven hazards, it is clear that the protective role provided by forests can became fundamental in mountain areas, where steep slopes increase the risk of occurrence (Lingua et al. 2017). By definition, active protection is exerted when the forest helps to prevent the occurrence of a natural hazard. Passive protection occurs instead in those situations in which the presence of the forest contributes to mitigating the effects produced by the disturbance. The distinction between these two kinds of protective roles mostly depends on the characteristics of the considered process. For instance, forests play an important protective role against snow avalanches in the starting zone, preventing their release. For rocks falling down a slope, forests can instead reduce the speed and number of rocks reaching the bottom of the slope.

We can further classify stands based on the presence of a specific object to be protected into direct and indirect protection forests (Brang et al. 2006). A direct protection forest is defined as such when it grows in close proximity to an endangered asset to which it offers protection against natural hazards. This direct protection is generally offered to people, buildings and any other infrastructure that might be exposed to a specific hazard in a mountain area. The direct protective function is usually provided over an area, which is limited in size and located below, and close to the protection forest. A typical example of a direct protection forest is represented by a stand located above a group of houses or a road, which are threatened by snow avalanches.

The indirect protective function is instead exerted by forests, independently of their exact location, simply by their presence at a broader scale (e.g. the landscape level). This could be the case for stands in mountain catchments where they can potentially reduce soil erosion and flooding at the closing section.

Almost any forest can offer some indirect protection, for instance through its effect in intercepting precipitation or affecting the local climate. Only some forests affected by gravitational hazards have a direct protective function.

The distinction between direct and indirect protection forests is particularly important in the context of forest planning, specifically in the definition of intervention priorities and management targets (Berger and Rey 2004).

A stand with a direct protective function should be permanently effective (Lingua et al. 2017). This can be achieved if the stand has high resistance to natural hazards and high persistency. The only way to maintain a stand in this efficiency window is with active forest management.

All forests are anyway subject to stand dynamics, which may modify or limit their protection effectiveness. Most of these dynamics are driven by the occurrence of natural disturbances, which often coincide with the hazards they are meant to prevent or mitigate.

Protection forests might be affected by different kinds of disturbances, including wildfires, storms, snow break, bark beetle outbreaks, which can act at both small and large scale. This last category of events can deeply alter the capacity of the stand to maintain its protective function. The degree and temporal extent in the impairment of the protective function produced after the disturbance is strongly related to the severity and spatial extent of the disturbance itself, as well as the recovery process undertaken naturally by the disturbed system.

At this stage, the quality and quantity of biological legacies (e.g. logs, root plates) can affect both the recovery process, for instance favouring the establishment of natural regeneration, and the residual protection function offered by the disturbed stand (Lingua et al. 2017).

A forest can offer a certain degree of protection, being more or less effective in its protective function, based on two main aspects: (1) the type and characteristics of the natural hazards involved; (2) the main features of the stand, together with its conditions when a damaging event occurs (Brang et al. 2008).

Concerning the disturbance regime, intensity and frequency of occurrence are the two most influential attributes affecting the capacity of a forest stand to provide an effective protective function.

In this context, proper management of protection forests should be oriented towards the maintenance of forest structures with a high degree of resistance and resilience to disturbances, as well as capable of providing effective protection to people and structures at risk. To reach this objective may sometimes require making compromises, since the characteristics needed to increase resistance to a certain disturbance might not necessarily be those that maximise the protective function of the same stand against some specific hazard. For instance, to decrease the probability of a crown fire spreading in the forest canopy, we could decide to reduce the stand density, but this management decision might consequently diminish the protection effectiveness of that same forest against rockfall.

Structure and composition of protection forests should thus be designed based on the type of disturbance that might affect the stand, the disturbance regime, the required protection function and the possibility of guaranteeing stand renewal. Obtaining the stand structures required to reach these management goals is a long-term process requiring decades or even centuries.

Managing Protection Forests Against Rockfall Hazard

In natural forest stand dynamics, some stages will not provide a protective effect, since trees are in turn too small, too sparse, or too few (Motta and Haudemand 2000). To be effective, a protection forest should have defined characteristics, especially concerning tree density and average stem size. In order to guarantee the protective function, a certain structure (i.e., combination of tree density and average size) has therefore to be achieved and maintained over time. As previously stated, appropriate silvicultural management can guide a forest towards its highest protection effectiveness and it should thus be designed and pursued to reach this aim.

Current management of protection forests adopts the term target profile to describe the characteristics of the stand that we want to obtain through silvicultural interventions, according to the natural hazards involved and local site conditions (Brang et al. 2006). A target profile thus describes the state of the forest that is expected to have an effective protective action against natural hazards and that can be permanently maintained with minimum effort.

Depending on the hazard type, different attributes of the forest have to be taken into account in terms of their protective effect (Lingua et al. 2017). Considering snow avalanches, for instance, the forest performs an active protective role in the starting zone impeding the release of an avalanche. In this situation, the canopy cover is the key parameter to consider since it plays the important role of snow interception (Frehner et al. 2007). When dealing with a rockfall hazard, forests mainly act in a passive way, limiting its impact by reducing the runout length. In this case, tree density and size are the main stand parameters of interest.

A rockfall process is the movement of falling rocks and their interaction with the environment (Frehner et al. 2007). On a slope characterized by rockfalls, three distinct areas (that often overlap) can be found: the zone of origin, the transit zone and the runout and deposition zone.

In the zone of origin, where rocks are released (generally corresponding to steep slopes exceeding 30°), the forest does not play a relevant protective role, other than general water regimentation and root holding functions. In some cases trees can actually act as triggering factors. Roots can penetrate into cracks, increasing frost wedging effects. Moreover, roots can produce acid exudates that, together with litter (in the case of conifers), can corrode and weather rocks, and they can release rocks

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they were previously holding when trees sway or are uprooted by strong winds. Forest management in the zone of origin should aim to avoid the presence of unstable trees potentially prone to uprooting, and perhaps even tall trees, since they are more subjected to wind load (Table 1). If suitable for the site and species, coppicing can be applied, to maintain stands at lower height.

When rocks start moving down the slope, they enter the transit zone. In this zone, rocks can slide, roll and bounce (if the incline exceeds 35°). The potential contribution of the forest in mitigating the impact of rockfall (considering blocks up to a size of 5 m^3) can be significant. Trees act as energy-dissipating elements, making falling rocks lose part of their kinetic energy with each impact on stems, lying deadwood logs and root plates. In addition to dissipating energy, the collision against a tree can cause a falling rock to deviate its trajectory or even to stop (Fig. 1).

The diameter of the stems in relation to the size of the rocks strongly determines the energy reduction efficiency. The larger the trees, the more effective they can be in dissipating energy or stopping rocks. However, big trees usually belong to older age classes, being more prone to falling as a consequence of senescence dynamics, with subsequent short-lived protection effects.

A high density of trees is supposedly desirable since it increases the probability for a falling rock to hit a stem. However, from an ecological point of view, a stand with a high density of large trees is not sustainable. The self-thinning rule explains why in the presence of a large number of stems, their average size will be smaller compared to a stand with lower tree density where trees can grow bigger.

The desired target profile against rockfall can be obtained by silvicultural management, focusing on prominent stand parameters such as basal area and mean diameter at breast height (DBH; corresponding to the diameter at 1.30 m) or stem density.

It has been proven that, to be effective against rockfall, a protection forest should have a minimal length of 250 m along the slope. Moreover, attention should be given not to create gaps between stems larger than 40 m along the maximum slope. In this short distance, rocks can in fact regain high speed, depleting all the protective role of the upslope forest.

Rocks start decreasing their speed when the slope diminishes to less than 30°; they then stop rapidly if the slope reaches less than 25°. In this last area, known as the runout and deposition zone, the forest can play an important role in reducing the length of the rock path, contributing to slowing down the rocks in the same manner as in the transit zone. Here, however, the forest stand can be even more effective, since the rock energy (i.e. its speed) is already reducing because of the diminishing slope steepness. Consequently, in the runout and deposition zone even small trees can stop big rocks.

To increase the protection function against rockfall, silvicultural management can also act on species composition, where possible, favouring the presence of broadleaves (hardwood species), since they are usually more resistant than conifers.

The importance of the protective function of a forest stand against rockfall should be considered looking at the residual hazard, considering the risk reduction (Dorren and Berger 2007). The ability to dissipate the rocks kinetic energy and thus their speed can effectively reduce the intensity of the hazard, leading, if the element

Table 1 Silvicultural guidelines for rockfall mitigation by forest stands. Modified from Berger et al. (2017), Frehner et al. (2007)

	Recommendations	Thresholds
Zone of origin (release zone)	Remove unstable trees (leverage effect due to the wind) at the top of cliffs or outcrops and in the release area	Coefficient of stability value (height/diameter at breast height = H/DBH) Conifers: H/DBH $\leq$ 65 Broadleaves: H/DBH $\leq$ 80
	Maintain a high basal area compatible with stand sustainability at the foot of the release area	
	Whenever possible, limit boulder's distance to the beginning of the stand	
	Promote broadleaved trees that are more resistant than conifers with equivalent diameter Maintain more than 30% of broadleaved trees among the largest trees. Depending on site conditions, a certain amount of conifers is needed for stand stability	
	Limit the size of gaps (same thresholds as for transit and runout zones)	
	Harvest trees leaving stumps with a min. height of 1.30 m or, if rockfall can occur, completely remove stump to ground-level (or screed in order to avoid a trampoline effect)	
	Fell/cut trees at an oblique angle to the slope leaving felled trees on the ground in a position from which they cannot be easily moved	
Transit and run out zones	If possible, increase the planimetric length of the forested slope	Recommended horizontal length of forested slope >200 m (ideal >250 m)
	Limit the size of gaps	Length of gap along the steepest slope: High forest <40 m Coppice <20 m, In all cases, recommended value (H = average height of trees): length $\leq$1.3H with a wooded strip below the gap >2H (recommended >4H)
	Promote broadleaved trees, which are more resistant than conifers with equivalent diameter Maintain more than 30% of broadleaved trees among the largest trees. Depending on the site conditions, a certain amount of conifers is needed for increasing the stand stability	
	Maintain an appropriate basal area for the efficient trees	In the transit zone: the basal area of trees with a DBH $\geq$15 cm is required to be $\geq$25 m^2/ha

(continued)

Table 1 (continued)

	Recommendations	Thresholds
		In the run out zone, the basal area of trees with a DBH $\geq$15 cm is required to be $\geq$20 m^2/ha
	Maintain an appropriate stem density for the efficient trees Maintain a high density in a band of 25 m on either side of a corridor	In all cases the stem density for trees with a diameter of $\geq$20 cm is required to be $\geq$350 stems/ha
	Remove unstable trees along corridors	Value of the coefficient of stability (height/diameter at breast height = H/DBH) Conifers: H/DBH $\leq$ 65 Broadleaves: H/DBH $\leq$ 80

Fig. 1 Rock stopped by trees in a protection forest (Auronzo di Cadore, BL, Italy). The stems show evidence of recent wounds produced by bouncing rocks

to be protected requires no marginal risk, to fewer and less impacting permanent infrastructures being built. We should remember that a forest stand provides several ecosystem services besides the protective function (i.e. habitat provision, recreation, aesthetic value), while a rockfall net is only a passive protection.

Managing stands to perform a protective function requires accurate knowledge of their spatial location. The availability of accurate maps with a good resolution is thus highly desirable. When rock sources are known, the area affected by the rockfall processes can be defined by modelling the path of the rocks. Rockfall trajectories modelling is frequently implemented via simulation models with different spatial dimensions (2D, 2.5D, or 3D), normally using topographic layers that are created in most GIS programs (Volkwein et al. 2011; Pradhan and Fanos 2017). The reliability of the results mostly depends on the input data; the accuracy of Digital Elevation Models (DEM) is therefore crucial for a correct rockfall assessment (Žabota et al. 2019). The availability of new remote sensing tools, particularly LiDAR (Light Detection and Ranging), and platforms (i.e. UAV—Unmanned Aerial Vehicle), provides enhanced information that renders the simulation closer to reality, at least concerning slope profile. Forest parameters can be also extracted from remote sensing data with good accuracy (Eysn et al. 2015), but the goodness of the results is still strongly affected by the forest stand complexity (e.g. structural diversity, species composition).

In the Alps, several studies provided detailed maps of protection forests in single municipalities or valleys (see for example Motta and Haudemand 2000), and some maps are also available at the regional or country level. However, the coverage is not complete and the methodologies and spatial scales adopted are not harmonized. The project RockTheAlps (ASP462), carried out in the framework of the Interreg Alpine Space (2014–2020), aimed at filling this gap, identifying and applying innovative methodologies to detect and map rockfall risk and protection forests, providing decision makers and policy makers with harmonized information for the whole Alpine Space. At the broader scale, a model (ROCK-EU) based on more than 10,000 real cases collected from the Alps has been implemented to map the potential runout zone (Fig. 2). The forests located in this area are thus considered protection forests. In order to define protection forests with direct protective function, the presence of endangered assets has been taken into account and added to the model. The effectiveness of the identified protection forests will be assessed by means of TORRID (Toolbox for assessing the protective effect of forests against rockfall and expressing the protective role in a Risk Reduction InDex), a new toolbox developed for the entire Alpine Space. The rockfall risk reduction provided by forest stands will be defined and the gap between optimal characteristics and current situation will be identified, guiding forest managers in the crucial phase of prioritization according to an adaptive management approach. The preliminary map of the protective function obtained after the first version of the model shows that around 20% of forests in the Alpine Space are potentially providing this important ecosystem service. The analyses have been conducted on a 25 m DEM, since this is the resolution available for the entire Alpine Space, but the methodologies applied are flexible and can easily be re-run as soon as a better resolution becomes available for the whole area. Furthermore the results of the simulation at 25 m spatial resolution have proven to be comparable

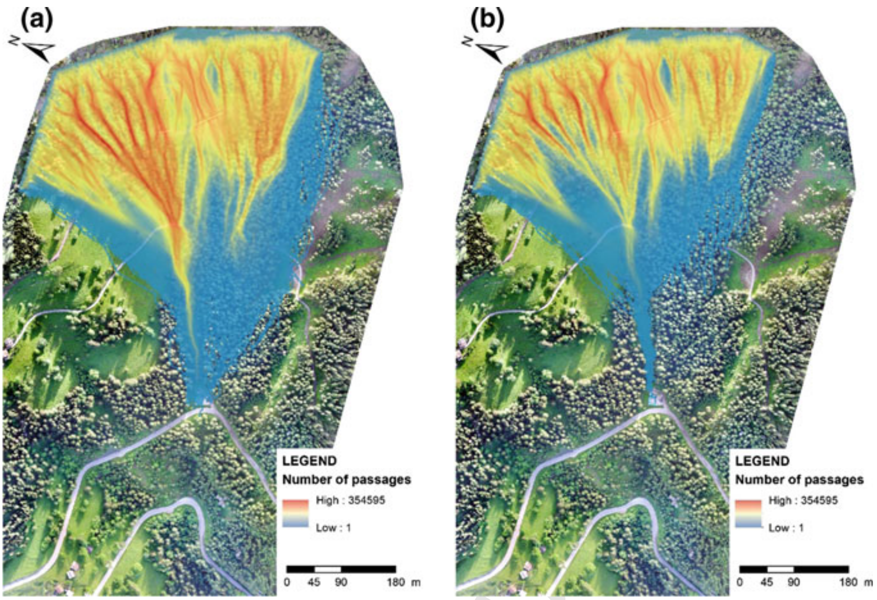

Fig. 2 Simulation of rockfall in the Colcuc study case (Colle Santa Lucia, BL, Italy). The number of passages (size 1.2 m^3; 1000 replication from each source cell) is shown for the scenario without forest (**a**) and with forest (**b**). The reduction in runout length provided by the protection forest is evident

with the results obtained at a finer scale and can therefore be used effectively at the regional level, where only a general overview of the potential risk is needed, and location accuracy is not the main purpose (Žabota et al. 2019).

Several case studies distributed over the Alps have been used to test the large-scale model locally, as well as to evaluate the economic value of the protective function (Bianchi et al. 2018). Some of the case studies were also selected among forest stands recently affected by high severity disturbances, which consequently altered their ability to sustain the provision of ecosystem services and particularly their potential protective function. In the western Alps, during autumn 2017, almost 10,000 ha of forests were affected by large wildfires, and some of these stands were protection forests. In the post-disturbance silvicultural intervention plan, priorities were assigned to the protection forests characterized by high burn severity. The recent storm Vaia, in late October 2018, which affected more than 40,000 ha of forests in the central and eastern Italian Alps, resulted in more than 8.6 M cubic meters of windthrown trees. Several of these forest stands had provided, among other ecosystem services, a relevant protective function.

Managing Protection Forests Under Climate Change

Climate change is predicted to produce important consequences, both direct and indirect, on forest ecosystems and on the disturbance regimes possibly affecting them (Seidl et al. 2017; Seidl and Rammer 2017; Thom et al. 2017).

Forest ecosystems in mountain regions will be greatly affected by climate change. Tree species compositions, forest cover and growth rate are among the parameters of great importance for the fulfilment of the protective function that could be altered in the mid- and long-term perspective (Albrich et al. 2018). Not only rising mean temperatures and changes in precipitation patterns will shape future forests by selecting species more adapted to the new conditions, but also the alteration of natural disturbance regimes will have a crucial role. Disturbance regimes are forecast to be altered by climate change in several parts of the world (Dale et al. 2001; Seidl et al. 2017). Both abiotic and biotic disturbance agents will be affected and their cumulative impacts can result in unprecedented negative effects on forests (Temperli et al. 2013). Appropriate disturbance regimes are in equilibrium with species composition and forest structure that are thus able to resist or persist after disturbances since they are adapted to their occurrence with a specific intensity and return interval. Altering the disturbance regime can instead lead to changes in species arrangement, and the creation of degraded structures.

Extreme events have the potential to affect forests much more than gradual changes in temperature (Lindner et al. 2014). Indeed natural disturbances are discrete events that could produce sudden alterations to forests, while changes in climatic conditions can increase stress resulting in a stand decline that can take several years before causing tree death.

From the perspective of forest management, focusing specifically on protection forests, there are two main topics to tackle: the non-permanence issue and species fitness (Dyderski et al. 2019).

When a high severity disturbance affects a protection forest, forest cover will be partially or totally removed, with consequences on the level of protection offered by the disturbed forest, based on the residual structure and composition. In the case of wildfires or insect outbreaks standing dead trees will dominate the landscape immediately after the event; they will persist standing for a variable amount of time, depending mostly on tree species and size (Marzano et al. 2012). In the case of a windthrow there will instead be mostly logs and uprooted trees covering the ground. The rise in temperatures will result in increasing fire risk, particularly in the driest valleys of the Alps. Rather than the gradual increase in temperature, extreme and prolonged droughts may increase the probability of large stand-replacing fires (Zumbrunnen et al. 2009; Eelkin et al. 2013). Biotic agents can also be highly favoured by the presence of trees stressed by water limitation, and even a moderate increase in temperature or drought length has been found to potentially raise the risk of forest pathogens outbreaks (Bentz et al. 2010). Natural disturbances are often interdependent, and the occurrence of one type can promote the occurrence of another one and increase its intensity. Windthrows or severe droughts are generally followed by insect outbreaks, and standing dead trees killed by pests and diseases can potentially increase fire risk.

Forest regeneration will be the most susceptible stage. Mature trees show a sort of biological inertia; they already have a well-developed and larger root system compared to seedlings, and are therefore able to counteract increasing stresses up to a certain threshold.

Concerning rockfall, one of the most probable consequences of climate change will be an increase in occurrence (Berger et al. 2017). Although rockfall is an almost unpredictable phenomenon, triggering factors are generally related to weather conditions, such as freeze-thaw processes (frost wedging) and precipitations. A high variation of temperature over a short period, and long duration and/or high intensity of precipitations generally precede rockfall events. Indeed, some studies already indicated an increase in rockfall occurrences for years with weather anomalies (Berger et al. 2017). Climate change will not only directly affect rocks release, but also and probably to a greater extent the forests that should mitigate this hazard.

Forest management should take into account climate change effect on forest ecosystems, identifying and mitigating potential threats to resistance and resilience traits of the stands.

Thinning can be a correct silvicultural treatment in order to enhance resistance to increasing water stress. Reducing inter-tree competition and providing more growing space for roots in search of water produced encouraging results also in post-drought recovery (Hlásny et al. 2014). However, concerning rockfall mitigation, reducing tree density is not always a good option, since we need to maintain the high probability of impacts between rocks and stems to dissipate the energy, deviate the path, and eventually stop the rolling rocks. In this case, it could be better to focus on manipulating species composition towards the creation of a stand including a mixture more adapted to the new conditions.

Given the expected alteration of disturbance regimes within mountain areas, particular attention should be paid to the assessment of the most suitable post-disturbance management decisions. After a disturbance affecting a protection forest, management practices to be adopted should be carefully considered. In the Alps the most common post-disturbance management practice is salvage logging (i.e. the felling and removal of affected trees), followed or not by plantation. This practice has proven to act as an additional disturbance on the already disturbed environment, with several negative effects on the ecosystem processes and services (Leverkus et al. 2018; Marzano et al. 2013). Furthermore, removing these deadwood elements from forests that had a protective function can further deplete the residual protection they can still offer after the disturbance. Lying deadwood, especially if formed of large logs, greatly increases the surface roughness of the forest floor, acting as additional obstacles for the rocks (Fuhr et al. 2015). Nevertheless, its role is still generally underestimated, and not considered reliable. After a stand replacing disturbance, if the area is not salvaged, lying logs can exert a protective function for a very long time, despite decaying processes. The long-lasting and beneficial effect produced by the presence of large amounts of lying deadwood resulting in greater ground roughness has already be proven after past high-severity disturbance events. In forests affected by the storm Vivian in 1990, for instance, very few follow-up rockfall events have occurred (Wohlgemuth et al. 2017).

Moreover, deadwood elements can result in enhanced microsite conditions facilitating regeneration establishment and survival, particularly in sites affected by severe disturbances, where the disturbance might have exacerbated already harsh conditions (Marzano et al. 2013; Leverkus et al. 2018). Preferential recruitment is in fact particularly evident in climatically stressed sites. Within areas characterized by high insolation and low precipitation, fallen trees and uprooted stumps create microsites where more shade and moisture are available for seedlings, stabilizing microclimatic conditions (Beghin et al. 2010). The sheltering effects of deadwood elements directly protecting tree regeneration against high radiation, high temperature and high transpiration rates were found to be determinant in arid environments (Callaway 2007; Marzano et al. 2013). These nurse objects can also act as traps for wind-dispersed seeds. In areas with low winter temperatures, the beneficial effect of deadwood material could also result in maintaining higher soil temperatures during the night, positively affecting winter seedling survival, as found by Castro et al. (2011). At the same time, similar results can be obtained in cold environments where deadwood protects seedlings from snow gliding and favours snow melting, locally increasing the length of the growing season.

Leaving standing and lying deadwood after a disturbance can thus produce a double positive effect in the management of protection forests, providing both enhanced microsites for regeneration, and eco-engineering structures. Even if deadwood undergoes natural decaying processes, reducing its protective effects over time, during its permanence standing or lying on the ground it may still perform an important function for the time lapse required by the natural or planted regeneration to establish (Wohlgemuth et al. 2017).

With specific reference to rockfall activities, it could be even more appropriate to discuss global change rather than just climate change. Including land-use and land cover changes will in fact provide a better overview on the foreseen scenarios for this natural hazard (Lopez-Saez et al. 2016) for the Alpine area. Since temperature is rising and land use is shifting from crops or pastures to forests due to the abandonment of marginal lands, forest cover in mountain areas will increase, theoretically providing increased protection against rockfall propagations (Berger et al. 2017). Forests will potentially cover more land at the upper elevations, tree growth will increase, broadleaves will gain a higher share. The increase in lengths of forested slopes, basal area, and broadleaves percentage are all consequences leading to a generic increase in the protective effect against rockfall. In two French Alpine departments (Haute-Savoie and Isère), this expansion of protection forests has been forecast to reach around 20% of the current area (Berger et al. 2017). However, rockfall is a site-specific phenomenon, involving local lithological, geomorphological, climate and forest issues, so we cannot excessively generalize the possible effects of global change.

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Conclusions

The management of protection forests under climate change is a challenging task. Unfortunately, there is no "one size fits all" management approach, but it is advisable to adopt a site and case specific tailor-made solution. Forests in the Alps will probably grow better and increase their range in the next decades, but uncertainty related to natural disturbances calls for a more careful assessment of their potential protective role. Since site conditions are changing, and therefore so are species performances, we should also change the forest management approach. Adaptive management, considering both climate and land-use changes, should be promoted. The inclusion of natural hazards and protection function assessment in forest management plans should be supported by guidelines providing factual information derived from scientific knowledge acquired in the recent research projects. Specific attention should be paid to finding evidence from research studies focusing on monitoring protection forests affected by severe natural disturbances in order to define proper post-disturbance management considering their preeminent protection function.

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Chapter 18

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