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The protective role of forests to reduce rockfall risks and impacts in the Alps under a climate change perspective

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Corresponding Author	Family Name	<b>Lingua</b>
	Particle	
	Given Name	<b>Emanuele</b>
	Prefix	
	Suffix	
	Role	
	Division	
	Organization	TESAF, University of Padova
	Address	Viale dell'Università, 16, 35020, Legnaro, Italy
	Email	emanuele.lingua@unipd.it
Author	Family Name	<b>Bettella</b>
	Particle	
	Given Name	<b>Francesco</b>
	Prefix	
	Suffix	
	Role	
	Division	
	Organization	TESAF, University of Padova
	Address	Viale dell'Università, 16, 35020, Legnaro, Italy
	Email	francesco.bettella@unipd.it
Author	Family Name	<b>Pividori</b>
	Particle	
	Given Name	<b>Mario</b>
	Prefix	
	Suffix	
	Role	
	Division	
	Organization	TESAF, University of Padova
	Address	Viale dell'Università, 16, 35020, Legnaro, Italy
	Email	mario.pividori@unipd.it
Author	Family Name	<b>Marzano</b>
	Particle	
	Given Name	<b>Raffaella</b>
	Prefix	
	Suffix	

Role  
Division  
Organization DISAFA, University of Torino  
Address L.go Braccini, 2, 10095, Grugliasco, Italy  
Email raffaella.marzano@unito.it

---

Author Family Name **Garbarino**  
Particle  
Given Name **Matteo**  
Prefix  
Suffix  
Role  
Division  
Organization DISAFA, University of Torino  
Address L.go Braccini, 2, 10095, Grugliasco, Italy  
Email matteo.garbarino@unito.it

---

Author Family Name **Piras**  
Particle  
Given Name **Marco**  
Prefix  
Suffix  
Role  
Division  
Organization DIATI, Politecnico di Torino  
Address C.so Duca degli Abruzzi, 24, 10129, Turin, Italy  
Email marco.piras@polito.it

---

Author Family Name **Kobal**  
Particle  
Given Name **Milan**  
Prefix  
Suffix  
Role  
Division Department of Forestry and Renewable Forest Resources  
Organization University of Ljubljana  
Address Večna pot 83, 1000, Ljubljana, Slovenia  
Email milan.kobal@bf.uni-lj.si

---

Author Family Name **Berger**  
Particle  
Given Name **Frédéric**  
Prefix  
Suffix  
Role  
Division Mountain Ecosystems Research Unit  
Organization IRSTEA—National Research Institute of Science and Technology for Environment and Agriculture  
Address rue de la Papeterie, 2, BP 76, 38402, Saint-Martin-d'Hères Cedex, France

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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.

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Keywords  
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Protection forests - Alps - Rockfall - Forest management - Climate change

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



Emanuele Lingua, Francesco Bettella, Mario Pividori, Raffaella Marzano, Matteo Garbarino, Marco Piras, Milan Kobal and Frédéric Berger

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2 considered one of the preeminent in mountain areas. In order to fulfil, maximize, and  
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E. Lingua (✉) · F. Bettella · M. Pividori  
TESAF, University of Padova, Viale dell'Università, 16, 35020 Legnaro, Italy  
e-mail: [emanuele.lingua@unipd.it](mailto:emanuele.lingua@unipd.it)

F. Bettella  
e-mail: [francesco.bettella@unipd.it](mailto:francesco.bettella@unipd.it)

M. Pividori  
e-mail: [mario.pividori@unipd.it](mailto:mario.pividori@unipd.it)

R. Marzano · M. Garbarino  
DISAFA, University of Torino, L.go Braccini, 2, 10095 Grugliasco, Italy  
e-mail: [raffaella.marzano@unito.it](mailto:raffaella.marzano@unito.it)

M. Garbarino  
e-mail: [matteo.garbarino@unito.it](mailto:matteo.garbarino@unito.it)

M. Piras  
DIATI, Politecnico di Torino, C.so Duca degli Abruzzi, 24, 10129 Turin, Italy  
e-mail: [marco.piras@polito.it](mailto:marco.piras@polito.it)

M. Kobal  
Department of Forestry and Renewable Forest Resources, University of Ljubljana, Večna pot 83,  
1000 Ljubljana, Slovenia  
e-mail: [milan.kobal@bf.uni-lj.si](mailto:milan.kobal@bf.uni-lj.si)

F. Berger  
Mountain Ecosystems Research Unit, IRSTEA—National Research Institute of Science and  
Technology for Environment and Agriculture, rue de la Papeterie, 2, BP 76, 38402  
Saint-Martin-d'Hères Cedex, France

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14 recent research studies and specifically the results obtained in the RockTheAlps  
15 project (ASP462), dealing with the assessment of protection forests against rockfall  
16 in the Alps.

## 17 **Protection Forests**

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

23 The protective role is considered among one of the most important functions pro-  
24 vided by a forest stand. All forests, regardless of their location, can accomplish this,  
25 for instance protecting the soil from surface erosion and taking part directly and indi-  
26 rectly in the hydrological cycle. However, despite this general protective role, we do  
27 not define all forests as protection forests. A protection forest is instead characterized  
28 and defined due to the existence of a specific natural hazard against which it offers  
29 protection in an active or passive way. It might also fulfil other functions, but its pro-  
30 tective role is preeminent. Protection forests are particularly effective against some  
31 types of abiotic disturbances, like snow avalanches, rockfalls, debris flows, shallow  
32 landslides, surface erosion and floods. Since these are mostly gravity-driven haz-  
33 ards, it is clear that the protective role provided by forests can become fundamental  
34 in mountain areas, where steep slopes increase the risk of occurrence (Lingua et al.  
35 2017). By definition, active protection is exerted when the forest helps to prevent the  
36 occurrence of a natural hazard. Passive protection occurs instead in those situations  
37 in which the presence of the forest contributes to mitigating the effects produced by  
38 the disturbance. The distinction between these two kinds of protective roles mostly  
39 depends on the characteristics of the considered process. For instance, forests play  
40 an important protective role against snow avalanches in the starting zone, preventing  
41 their release. For rocks falling down a slope, forests can instead reduce the speed and  
42 number of rocks reaching the bottom of the slope.

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

51 by a stand located above a group of houses or a road, which are threatened by snow  
52 avalanches.

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

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

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

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

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

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

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

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

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

89 In this context, proper management of protection forests should be oriented  
90 towards the maintenance of forest structures with a high degree of resistance and  
91 resilience to disturbances, as well as capable of providing effective protection to  
92 people and structures at risk. To reach this objective may sometimes require making  
93 compromises, since the characteristics needed to increase resistance to a certain dis-  
94 turbance might not necessarily be those that maximise the protective function of the  
95 same stand against some specific hazard. For instance, to decrease the probability

96 of a crown fire spreading in the forest canopy, we could decide to reduce the stand  
97 density, but this management decision might consequently diminish the protection  
98 effectiveness of that same forest against rockfall.

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

## 104 **Managing Protection Forests Against Rockfall Hazard**

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

113 Current management of protection forests adopts the term target profile to describe  
114 the characteristics of the stand that we want to obtain through silvicultural interven-  
115 tions, according to the natural hazards involved and local site conditions (Brang et al.  
116 2006). A target profile thus describes the state of the forest that is expected to have  
117 an effective protective action against natural hazards and that can be permanently  
118 maintained with minimum effort.

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

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

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



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

142 When rocks start moving down the slope, they enter the transit zone. In this zone,  
143 rocks can slide, roll and bounce (if the incline exceeds  $35^\circ$ ). The potential contribution  
144 of the forest in mitigating the impact of rockfall (considering blocks up to a size of  
145  $5 \text{ m}^3$ ) can be significant. Trees act as energy-dissipating elements, making falling  
146 rocks lose part of their kinetic energy with each impact on stems, lying deadwood  
147 logs and root plates. In addition to dissipating energy, the collision against a tree can  
148 cause a falling rock to deviate its trajectory or even to stop (Fig. 1).

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

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

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

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

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

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

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

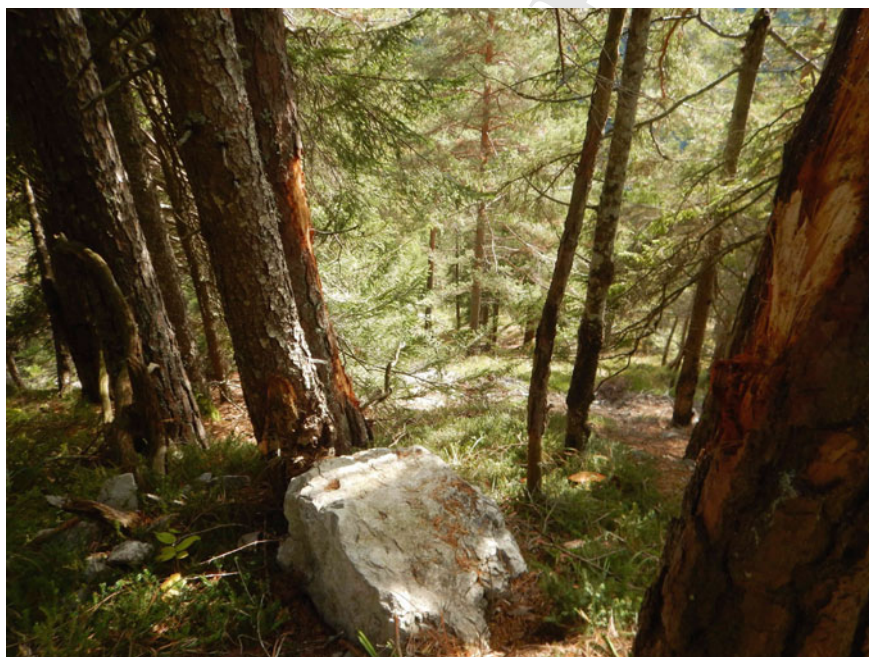
**Table 1** Silvicultural guidelines for rockfall mitigation by forest stands. Modified from Berger et al. (2017), Frehner et al. (2007)

	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 <sup>2</sup> /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 <sup>2</sup> /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 $\leq 80$

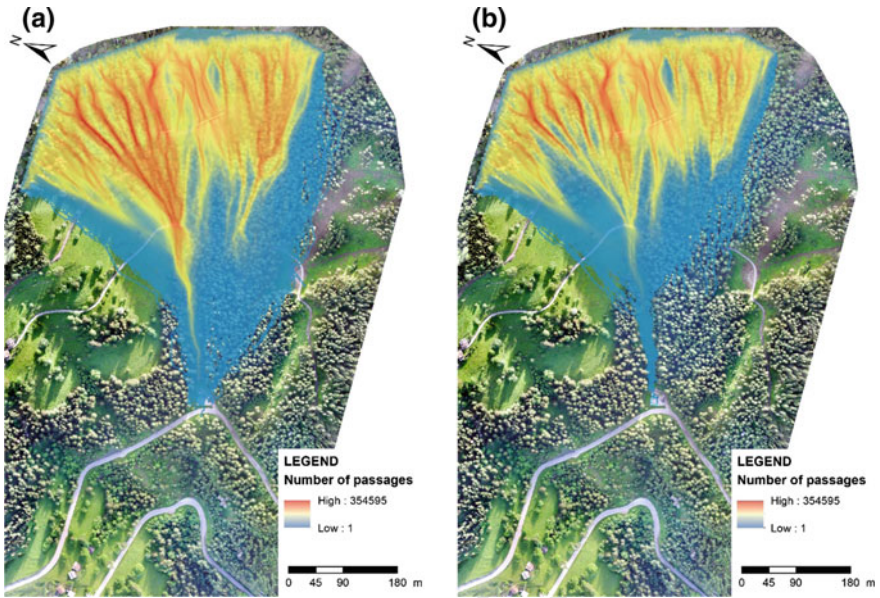


**Fig. 1** Rock stopped by trees in a protection forest (Auronzo di Cadore, BL, Italy). The stems show evidence of recent wounds produced by bouncing rocks

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

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

201 In the Alps, several studies provided detailed maps of protection forests in single  
202 municipalities or valleys (see for example Motta and Haudemand 2000), and some  
203 maps are also available at the regional or country level. However, the coverage is not  
204 complete and the methodologies and spatial scales adopted are not harmonized. The  
205 project RockTheAlps (ASP462), carried out in the framework of the Interreg Alpine  
206 Space (2014–2020), aimed at filling this gap, identifying and applying innovative  
207 methodologies to detect and map rockfall risk and protection forests, providing deci-  
208 sion makers and policy makers with harmonized information for the whole Alpine  
209 Space. At the broader scale, a model (ROCK-EU) based on more than 10,000 real  
210 cases collected from the Alps has been implemented to map the potential runout  
211 zone (Fig. 2). The forests located in this area are thus considered protection forests.  
212 In order to define protection forests with direct protective function, the presence of  
213 endangered assets has been taken into account and added to the model. The effective-  
214 ness of the identified protection forests will be assessed by means of TORRID  
215 (Toolbox for assessing the protective effect of forests against rockfall and expressing  
216 the protective role in a Risk Reduction InDex), a new toolbox developed for the entire  
217 Alpine Space. The rockfall risk reduction provided by forest stands will be defined  
218 and the gap between optimal characteristics and current situation will be identified,  
219 guiding forest managers in the crucial phase of prioritization according to an adap-  
220 tive management approach. The preliminary map of the protective function obtained  
221 after the first version of the model shows that around 20% of forests in the Alpine  
222 Space are potentially providing this important ecosystem service. The analyses have  
223 been conducted on a 25 m DEM, since this is the resolution available for the entire  
224 Alpine Space, but the methodologies applied are flexible and can easily be re-run as  
225 soon as a better resolution becomes available for the whole area. Furthermore the  
226 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  $1.2 \text{ m}^3$ ; 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

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

230 Several case studies distributed over the Alps have been used to test the large-  
 231 scale model locally, as well as to evaluate the economic value of the protective  
 232 function (Bianchi et al. 2018). Some of the case studies were also selected among  
 233 forest stands recently affected by high severity disturbances, which consequently  
 234 altered their ability to sustain the provision of ecosystem services and particularly  
 235 their potential protective function. In the western Alps, during autumn 2017, almost  
 236 10,000 ha of forests were affected by large wildfires, and some of these stands were  
 237 protection forests. In the post-disturbance silvicultural intervention plan, priorities  
 238 were assigned to the protection forests characterized by high burn severity. The  
 239 recent storm Vaia, in late October 2018, which affected more than 40,000 ha of  
 240 forests in the central and eastern Italian Alps, resulted in more than 8.6 M cubic  
 241 meters of windthrown trees. Several of these forest stands had provided, among  
 242 other ecosystem services, a relevant protective function.



## 243 **Managing Protection Forests Under Climate Change**

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

247 Forest ecosystems in mountain regions will be greatly affected by climate change.  
248 Tree species compositions, forest cover and growth rate are among the parameters of  
249 great importance for the fulfilment of the protective function that could be altered in  
250 the mid- and long-term perspective (Albrich et al. 2018). Not only rising mean tem-  
251 peratures and changes in precipitation patterns will shape future forests by selecting  
252 species more adapted to the new conditions, but also the alteration of natural dis-  
253 turbance regimes will have a crucial role. Disturbance regimes are forecast to be  
254 altered by climate change in several parts of the world (Dale et al. 2001; Seidl et al.  
255 2017). Both abiotic and biotic disturbance agents will be affected and their cumula-  
256 tive impacts can result in unprecedented negative effects on forests (Temperli et al.  
257 2013). Appropriate disturbance regimes are in equilibrium with species composition  
258 and forest structure that are thus able to resist or persist after disturbances since they  
259 are adapted to their occurrence with a specific intensity and return interval. Altering  
260 the disturbance regime can instead lead to changes in species arrangement, and the  
261 creation of degraded structures.

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

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

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

286 insect outbreaks, and standing dead trees killed by pests and diseases can potentially  
287 increase fire risk.

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

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

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

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

313 Given the expected alteration of disturbance regimes within mountain areas, par-  
314 ticular attention should be paid to the assessment of the most suitable post-disturbance  
315 management decisions. After a disturbance affecting a protection forest, management  
316 practices to be adopted should be carefully considered. In the Alps the most common  
317 post-disturbance management practice is salvage logging (i.e. the felling and removal  
318 of affected trees), followed or not by plantation. This practice has proven to act as an  
319 additional disturbance on the already disturbed environment, with several negative  
320 effects on the ecosystem processes and services (Leverkus et al. 2018; Marzano et al.  
321 2013). Furthermore, removing these deadwood elements from forests that had a pro-  
322 tective function can further deplete the residual protection they can still offer after the  
323 disturbance. Lying deadwood, especially if formed of large logs, greatly increases  
324 the surface roughness of the forest floor, acting as additional obstacles for the rocks  
325 (Fuhr et al. 2015). Nevertheless, its role is still generally underestimated, and not con-  
326 sidered reliable. After a stand replacing disturbance, if the area is not salvaged, lying  
327 logs can exert a protective function for a very long time, despite decaying processes.  
328 The long-lasting and beneficial effect produced by the presence of large amounts of  
329 lying deadwood resulting in greater ground roughness has already been proven after  
330 past high-severity disturbance events. In forests affected by the storm Vivian in 1990,

331 for instance, very few follow-up rockfall events have occurred (Wohlgemuth et al.  
332 2017).

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

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

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



## 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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