



# Assessing the protective role of alpine forests against rockfall at regional scale

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## Abstract

Worldwide, mountain forests represent a significant factor in reducing rockfall risk over long periods of time on large potential disposition areas. While the economic value of technical protection measures against rockfall can be clearly determined and their benefits indicated, there is no general consensus on the quantification of the protective effect of forests. Experience shows that wherever there is forest, the implementation of technical measures to reduce risk of rockfall might often be dispensable or cheaper, and large deforestations (e.g. after windthrows, forest fires, clear-cuts) often show an increased incidence of rockfall events. This study focussed on how the protective effect of a forest against rockfall can be quantified on an alpine transregional scale. We therefore estimated the runout length, in terms of the angle of reach, of 700 individual rockfall trajectories from 39 release areas from Austria, Germany, Italy and Slovenia. All recorded rockfall events passed through forests which were classified either as coppice forests or, according to the CORINE classification of land cover, as mixed, coniferous or broadleaved dominated high forest stands. For each individual rockfall trajectory, we measured the forest structural parameters stem number, basal area, top height, ratio of shrub to high forest and share of coniferous trees. To quantify the protective effect of forests on rockfall, a hazard reduction factor is introduced, defined as the ratio between an expected angle of reach without forest and the back-calculated forest-influenced angles of reach. The results show that forests significantly reduce the runout length of rockfall. The highest reduction was observed for mixed high forest stands, while the lowest hazard reduction was observed for high forest stands dominated either by coniferous or broadleaved tree species. This implies that as soon as one tree species dominates, the risk reduction factor becomes lower. Coppice forests showed the lowest variability in hazard reduction. Hazard reduction due to forests increases, on average, by 7% for an increase in the stem number by 100 stems per hectare. The proposed concept allows a global view of the effectiveness of protective forests against rockfall processes and thus enable to value forest ecosystem services for future transregional assessments on a European level. Based on our results, general cost–benefit considerations of nature-based solutions against rockfall, such as protective forests as well as first-order evaluations of rockfall hazard reduction effects of silvicultural measures within the different forest types, can be supported.

**Keywords** Protection forests · Rockfall · European Alps · Reliability of forest protective effects on rockfall hazard

## Introduction

Rockfall poses a serious hazard to human welfare all over the world. In addition to personal damage, rockfall events can cause considerable economic loss due to their impact on infrastructural facilities such as roads, railways or various supply networks. In Austria, approx. 9 million € is spent for technical protection against rockfall and erosion per year (Sinabell et al. 2008) and comparable expenditures can also be expected in most European alpine countries. However,

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technical protection measures against rockfall can only be installed in identified, highly exposed and endangered areas, whereby special attention is paid to the surrounding forests where available. This is because such protection forests represent a significant factor in reducing the risk from rockfall events over long periods of time on large potential disposition areas (Dorren et al. 2007; Brang et al. 2008; Bigot et al. 2009; Alpine-Convention 2016). Thus, protection against rockfall in the alpine region, but also worldwide, is provided mainly by forests and their maintenance.

Basically, the occurrence of rockfall events depends mainly on the slope, geology, weathering, local climate and vegetation as well as on the exposure to human activities or earthquakes. The influence of forest cover on the occurrence of a rockfall event is usually within the transit zone, where bouncing heights and velocities of rocks reach their maximum (Flageollet and Weber 1996; Leine et al. 2014; Dorren 2016; Yan et al. 2018). However, the runout distance of a rockfall event depends on the total energy dissipation of one or multiple particles. Energy dissipation mainly occurs due to collision which reduces the kinetic energy (which can be translational and/or rotational)—and it is caused by deformation work on soil surface and/or vegetation structure (including destruction of trees). The loss of kinetic energy depends generally on the rock mass (size of the rock), slope inclination, damping conditions and, regarding the protective role of forests, by collision with trees. In both the transit and the deposit zones, a protective forest is effective in reducing the velocity and hence the bouncing heights of falling rocks (Dorren et al. 2004b; Wang and Lee 2010; Corona et al. 2017).

An effect of forests on rockfall was first systematically analysed by Jahn (1988) who moved rocks downhill along forest-covered and unstocked slopes. He found about 60% of the stones in covered sections stopped as a result of tree contacts and 3–10 times more stones were deposited in covered than in uncovered areas. Based on real-size experiments, Dorren et al. (2005) confirmed the protective effect of forests against rockfall. They found residual rockfall hazard, expressed as the number of rocks that surpass a specified zone, to be decreased by 63% at the forested site. They also observed that the number of impacts against a tree is more important than the dissipated energy created by the impact. For this reason, they concluded that a high stand density in forests is more important than the presence of large diameter stems. A quantitative estimation of the rockfall risk reduction due to forests is often investigated with the use of simulations, especially under a plot size-scale consideration. Stoffel et al. (2006) applied RockyFor3D on three different forest stands in Switzerland. They found the number of rocks passing through a specific evaluation zone to be 1.7–8.5 times higher for simulation scenarios without accounting for forest stands. Dupire et al. (2016) analysed typical forest

structures and compositions of France, regarding their protective effect. Based on multiple rockfall simulations, they found that coppices dominated by beech (*Fagus sylvatica*) and oak (*Quercus* sp.) showed the best rockfall hazard reduction. Instead, the coniferous stands of pine (*Pinus* sp.) and larch (*Larix decidua*) had the least impact on minimizing the risk of rockfall. A decreasing gradient of the protective effect from forest types dominated by broadleaved species to forest types dominated by coniferous species was found, whereas mixed stands represented in most cases the highest risk reduction. In addition, forest stands dominated by shade-tolerant tree species such as beech (*Fagus sylvatica*), fir (*Abies alba*) and spruce (*Picea abies*) seem to have a better protection potential than stands dominated by light demanding species such as oak (*Quercus* sp.), pine (*Pinus* sp.) or larch (*Larix decidua*). Their results also suggest that forests with a high stem density and high basal area had the greatest impact on protection against rockfall. Moos et al. (2017) quantified the effect of forests on frequency and intensity of rockfall on a local-scale approach and applied multiple rockfall simulations for different forest and non-forest scenarios under varying forest stand and terrain conditions. They found that rockfall frequency can be reduced between approximately 10 and 90% and rockfall intensity between 10 and 70%, compared to non-forested conditions. Rockfall risk reduction decreases with lower stem numbers, tree diameters and increasing rock volume but also depends on the horizontal forest structure.

Wehrli et al. (2006) simulated long-term effects of forest dynamics on the protective effect against rockfall by combining the forest patch model ForClim (Bugmann 1996) with the rockfall model RockFor<sup>NET</sup> (Berger and Dorren 2006). They found key parameters for an effective protection to be a high initial stand density and low mortality rates. Similarly, Woltjer et al. (2008) embedded a 3D rockfall module in the patch-based forest simulator PICUS (Lexer and Hönninger 2001; Seidl et al. 2005). Based on this approach, Rammer et al. (2015) analysed the effects of four management scenarios on rockfall protection and timber production on a 38-hectare forest over 100 years. Overall, they found that 30–70% of the simulated rocks, depending on rock size and forest characteristics, were stopped by the forest with the least effect caused by a business as usual age class shelterwood management approach and the highest effect due to forest management scenarios with slit-shaped gaps.

Nevertheless, knowledge about the protective effect of technical measures against rockfall is much higher than knowledge about the protective effect of forests. For example, rockfall nets, the preferred protection measure in the alpine region, are usually certified according to the size of the potential design event (Peila and Ronco 2009; ETAG-027 2013; Arndt et al. 2015; De Biagi et al. 2020). This allows a quantitative assessment of rockfall risk reduction based

on technical mitigation measures, supporting cost–benefit analysis. In contrast, quantifying rockfall hazard reduction offered by protection forests depends on regional and temporal characteristics and varies from local scale (“tree-based”) up to plot size scale (“area-based”). For this reason, the protective effect of the forest can rarely be directly included in a cost–benefit-oriented risk analysis and certainly not on an alpine-wide or European-based standard. However, following a risk-based protection forest strategy for ensuring its protective effect against natural hazards, one can assume that the financial expenses of such nature-based mitigations are lower than conservative mitigation concepts (Olschewski et al. 2012). Dorren and Berger (2006) reported about 50 million euros which are spent each year on preserving or improving the protection service provided by mountain forests—which is still roughly three to six times less than the expenditures for technical mitigations regarding torrents and avalanche protection (c.f. Andres and Badoux, 2019).

The results of our study allow a first-order evaluation of the hazard minimization of rockfall in protection forests on a transnational (alpine-wide) scale and might be considered as a pre-certification of the rockfall protection effect of different forest types—which is a first step towards a comprehensive cost–benefit analysis. For this purpose, we focussed explicitly on the rockfall hazard reduction of forest stands on a regional-scale approach, i.e. being transnational applicable, and present a comprehensive and empirically based reliability model to predict hazard reduction of rockfall. To this end, we applied our model to four different forest types which can be identified throughout Europe, according to the standardized CORINE land-use data. Based on rockfall events in protection forests of Austria, Germany, Italy and Slovenia, we first present variations of compiled forest parameters according to different forest types considered in this study. Finally, differences of hazard reduction of rockfall for the considered forest types resulting in specific reliability models are shown and their application to value forest protection services as a basis for evaluating benefit or supporting a sustainable forest management is discussed.

## Methods

### Data

Since the forest has its greatest influence in the transit and depositional path of rockfall events, our analyses focus exclusively on the runout, i.e. on the influence of different forest types within the transit and depositional path of a rockfall event.

The protective effect of a forest against rockfall and thus its hazard reduction potential depend, however, on several parameters. For this study, we considered stem number,

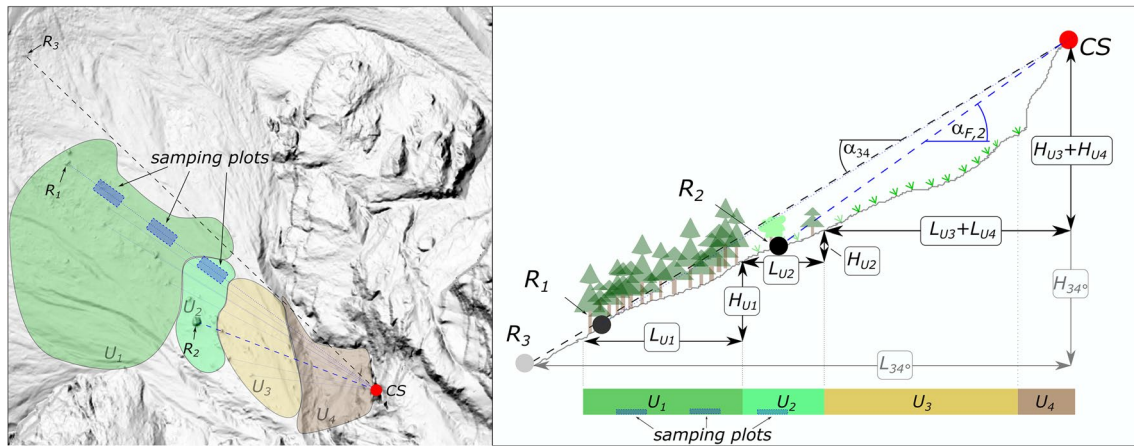
basal area, top height, the ratio of high forest to brush forest as well as dominant tree species to be essential characteristics. The choice of the forest parameters was guided by their influence on rockfall hazard based on previous studies (Frehner et al. 2005; Ancelin et al. 2006; Brang et al. 2006; Perzl 2008), the requirements of expert systems for assessing the protective effect of mountain forests against rockfall at regional alpine level (Berger et al. 2013; Cerbu et al. 2013; Accastello et al. 2019) and their possible investigation by remote sensing techniques (e.g. Sarro et al. 2018; Schardt et al. 2018). The study is based on a rockfall catalogue of 730 individual rockfall trajectories from 39 different release areas from Austria, Germany, Italy and Slovenia, which was compiled in the framework of the Alpine Space Interreg project “Rock the Alps” (ASP462).

As indicated in Fig. 1, rockfall hazards from one release area typically show several different individual rockfall trajectories of the single blocks, passing different portions of forested and non-forested slope segments. To measure the protective effect of forests on such rockfall events, we therefore first identified, for each of the 39 release areas, land-cover units with relatively homogenous composition and structure  $U_i$  either by remote sensing, from existing land-use inventories or local field surveys.

We then registered the distribution of the units  $U_i$  along the individual rockfall trajectory and measured for each  $U_i$ , horizontal length  $L$  and drop height  $H$ . For forest related land-cover units, multiple sampling plots, with a minimum length of 20 m in downslope direction (regarding canopy cover), have been established. The number of plot samples per land-cover unit, required to give a defined degree of accuracy, is difficult to be predicted in advance. We defined a minimum of one sample plot per 60 m length of the considered unit  $U_i$  or at least one plot per unit, respectively. In each sample, plot information on stem number (N/ha), basal area ( $\text{m}^2/\text{ha}$ ), top height (m) of the highest tree within the sample per species, the ratio of high forest to coppices, shrub and young growth (DBH < 12 cm) (%) and the ratio of broadleaved to coniferous trees (%) are selected. Compiled data from multiple sample plots per land-cover unit were averaged. The basal area was estimated either by the angle count sampling (ACS) method (Bitterlich 1984) or, in case of young stands and shrubs below callipering limit of ACS, we used tree diameters at breast height (DBH) from stem surveys on fixed area plots.

### Calculations and statistics

By assuming that every rockfall trajectory is a reproduction of the protective effect of the local composition of  $U_i$  of each release area, we estimated the representative forest parameters for each release area, as the length weighted mean of the rockfall trajectory with the largest runout length:



**Fig. 1** Sampling design adopted to measure the protective role of forests related to several rockfall events from one release area. CS denotes the centre of the scar of the release area, and R denotes the location of the block deposits. Three rockfall event profiles are exemplary shown, passing forested  $R_1$  and  $R_2$ , and mostly non-forested sections  $R_3$ . The forest-related land-cover units  $U_1$  and  $U_2$  differ in their

characteristic parameters (investigated by sampling plots), whereas the characteristic forest parameters for the non-forested units  $U_3$  and  $U_4$  are set to 0. The rockfall event profile  $R_3$  represents the mean critical angle of reach for non-forested rockfall profiles as proposed by Jaboyedoff and Labiouse (2011), which is used in the definition of the hazard reduction factor in Eq. (3)

$$\langle f \rangle = \left( \sum_{i=1}^n f_i * L_i \right) * \left( \sum_{i=1}^n L_i \right)^{-1} \quad (1)$$

where  $f_i$  is a general forest parameter, like stand density, basal area or top height, and  $L_i$  is the horizontal length of unit  $i$ . For non-forested land-cover units,  $f_i = 0$ .

Based on the representative forest parameters, we classified each release into coppice forests (A) and high forests following the CORINE land-cover classification (Kosztra et al. 2019) with share of coniferous species below 25%, above 75% and between 25 and 75% into coniferous dominated (B), broadleaved dominated (C) and mixed (D) high forest stands, respectively.

We measured the impact of forest on the runout of rockfall as the angle of reach that is defined as the arctangent of the ratio between the total fall height  $H$  and the maximum horizontal runout length  $L$ , of a rockfall event, i.e. the angle of the shortest line between the top of the rockfall source scar and the stopping point:

$$\alpha = \tan^{-1} S = \tan^{-1} \left( \frac{H}{L} \right) \quad (2)$$

whereas the tangent of the angle of reach  $S$  refers to the energy slope or “Geometrisches Gefälle” (Heim 1932). Based on Eq. (2), we back-calculated the angles of reach  $\alpha_{F,j}$ , respectively, and energy slopes  $S_{F,j}$  for each rockfall trajectory.

To express the effect of forests on the observed total runout distances, we estimate an individual dimensionless hazard reduction factor  $x_j$ :

$$x_j = 1 - \frac{S_{34}}{S_{F,j}} = 1 - \frac{\tan(34^\circ)}{\tan(\alpha_{F,j})} \quad (3)$$

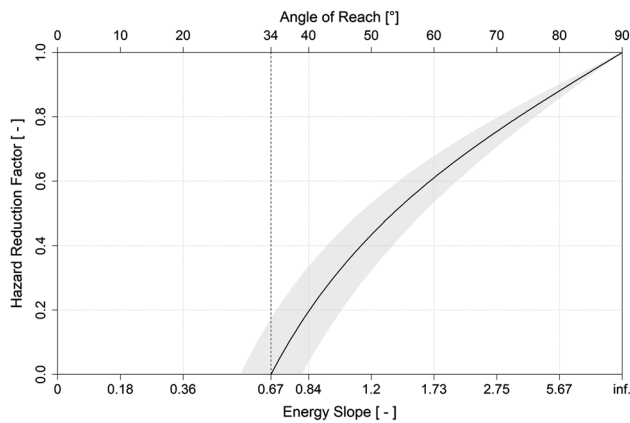
The hazard reduction factor relates the back-calculated forest-influenced energy slopes  $S_{F,j}$  to a mean critical energy slope for non-forested rockfall profiles  $S_{34} = 0.67 \pm 0.03$ , i.e.  $\alpha_{34} = 34^\circ \pm 1.62^\circ$ , proposed by Jaboyedoff and Labiouse (2011). Figure 2 shows the theoretical progression of the hazard reduction factor  $x$  considering a fixed critical energy slope for non-forested rockfall profiles (Eq. 3). Assuming normality, also the range of uncertainty is indicated—estimated by varying  $S_{34}$  between  $0.67 \pm 3 * 0.03$ . It includes 99.73% of all hazard reduction factors  $x_j$  for applying the fixed critical energy slope  $S_{34}$ .

It must be noted that even low hazard reduction factors, for example 20%, might represent a significant reduction in the maximum runout length, as they relate to the total horizontal runout distance of the rockfall event. According to Eq. (3), a 20% hazard reduction ( $x_j = 0.2$ ) would then correspond to an angle of reach of  $40.14^\circ$ . Based on Eq. (4), this results in an average reduction of the horizontal runout length  $\Delta L$  by 30% of the considered fall height:

$$\Delta L = L - L_j = \left( \frac{1}{\tan(34^\circ)} - \frac{1}{\tan(\alpha_{F,j})} \right) H_j \quad (4)$$

For a 50% hazard reduction ( $x_j = 0.5$ ), the individual reach angle corresponds to  $53.45^\circ$  and the horizontal runout length would thus be shortened by more than 70% of the considered fall height.





**Fig. 2** The black line shows the average progression of the hazard reduction factor (Eq. 3) with  $S_{34}=0.67$ . Uncertainty, given by the shaded area, was estimated by varying  $S_{34}$  between  $0.67 \pm 3 \cdot 0.03$ , which includes, by assuming normality of  $S_{34}$ , 99.73% of all hazard reduction factors for a fixed energy slope. For example, a rockfall event on a forested slope with a  $S_F=1.43$  or  $\alpha_F=55^\circ$  corresponds to a hazard reduction factor, between 0.32 and 0.53, while a  $S_F=0.84$  or  $\alpha_F$  of  $40^\circ$  corresponds to a hazard reduction factor, between 0.04 and 0.33. Hence, the impact of uncertainty in  $S_{34}$  decreases with increasing energy slope values

Statistical reliability considerations help to quantify the expected lifetime of several systems (Crowder 2017). Here, we apply this approach to indicate the probability (expected lifetime) of a certain hazard reduction factor for each forest type, which we indicate based on the individual empirical cumulative distribution.

## Results

A summary of the representative forest parameters for each major forest type is provided in Table 1. Here, coppice forests and shrublands (forest type A) differ significantly from the high forest stand types (B–D). The number of rockfall trajectories corresponds to Coppice stands, as expected, showed the highest stem density and the lowest basal area as well as average top height. High forest stands showed a higher density in the mixed stands (753 stems per hectare) compared to pure coniferous (616 stems per hectare) and broadleaved (441 stems per hectare) stands,

while the highest basal area was found in the pure coniferous forests (Table 1).

The four forest types, however, differ not only in their characteristics—which are considered essential for the protection against rockfall—but also show clear differences in their contribution regarding the resistance to the rockfall dynamics. Figure 3 provides information about the distribution of the reach angle and energy slope, respectively, for each forest type.

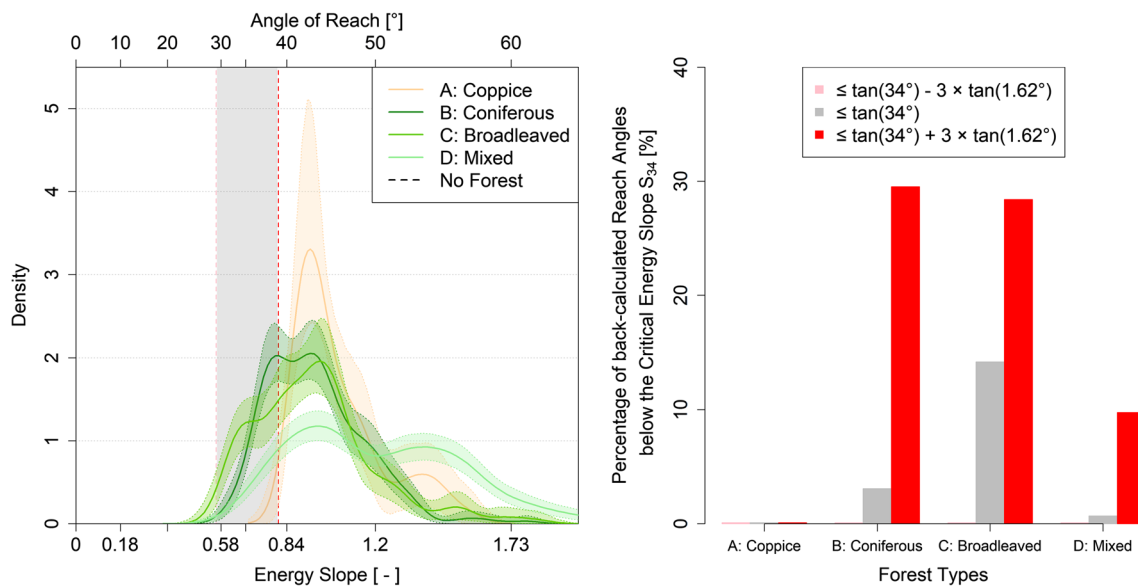
All rockfall trajectories of the coppice forest stands analysed in this study started from the same release area. This is the reason why the back-calculated reach angles or energy slopes for the coppice forest type (A) are closely distributed around  $43^\circ$  corresponding to an energy slope of 0.93. However, similar typical reach angles or energy slopes can be observed for the other three high stand forests. For the coniferous dominated high forest type (B), the most frequent angle of reach amounts to  $43^\circ$ . Both broadleaved dominated and mixed forest types (C and D) show the most frequent reach angle at  $44^\circ$  and energy slope of 0.97, respectively. Yet, it shows that structural differences exist within the coniferous dominated and mixed forest stands. This is indicated by a bi-modal density distribution (Fig. 3, left panel), which has a first peak (mode) for the forest type B (coniferous dominated high forests) at an angle of reach of  $38^\circ$  and an energy slope of 0.97 and a second peak (mode) for the forest type D (mixed high forests) at an angle of reach of  $54^\circ$  and energy slope of 1.38. Compared to non-forested rockfall profiles, no back-calculated reach angles of forest type A (coppice stands), less than 30% of all back-calculated reach angles for the forest types B and C and about 10% of all back-calculated reach angles for the forest type D (mixed stands), exceed the uncertainty range of the pre-assumed critical reach angle or energy slope of rockfalls on non-forested slopes (Fig. 3, right panel).

In Fig. 4, additionally to the probability density function of the hazard reduction factor (left panel), the corresponding reliability plots (right panel), estimated as 1 minus the empirical cumulative distribution, are shown for each forest type.

Again, the bi-modal shape of the hazard reduction density distribution for forest types B–D suggests structural differences within the compiled high forest stands.

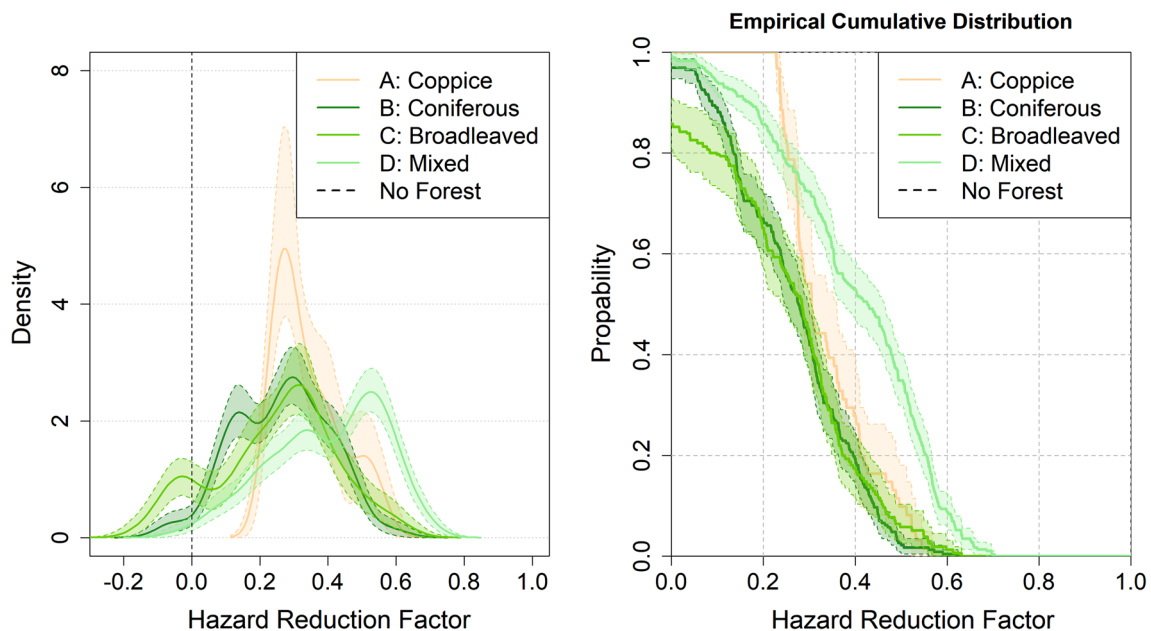
**Table 1** Summary of representative forest parameters for each forest type

Forest types	A Coppice		B Coniferous		C Broadleaved		D Mixed	
	Mean	SD	Mean	SD	Mean	SD	Mean	SD
Stem number (N/ha)	1437	–	616	209	441	189	753	316
Basal area (m <sup>2</sup> /ha)	30.8	–	61.9	11.5	38.4	20.7	37.2	10.0
Top height (m)	11.4	–	33.9	4.9	28.5	4.4	23.2	4.5
Number of rockfall trajectories	61		227		155		287	



**Fig. 3** The left panel shows the density together with the 95% pointwise confidence interval, based on 2000 bootstrapping samples, of the angles of reach and energy slopes for each forest type. The dashed lines indicate the minimum (pink) and maximum (red) reach angles, respectively, and energy slopes for rockfall events on non-forested

slopes, while the grey area in between corresponds to the 99.73% interval. The right panel shows the percentage of overserved angles of reach below the minimum (pink), mean (grey) and maximum (red) angles of rockfalls on non-forested slopes



**Fig. 4** The left panel shows the density of the hazard reduction factors of each forest type. The shaded area is the 95% pointwise confidence interval based on 2000 bootstrapping samples. The right panel shows the reliability of the hazard reduction factor of each forest

type, estimated as 1 minus its empirical cumulative distribution. The shaded area is the 95% pointwise confidence interval based on 2000 bootstrapping samples

The reliability plots, however, reveal clear differences in the protective effects of each forest type—showing the probability that a certain hazard reduction factor is exceeded. Forest stands dominated either by coniferous

(B) or broadleaved (C) tree species show the lowest and almost identical reliability against rockfall. Type A, the coppice forest, has the highest probability of a small

**Table 2** Reliability against rockfall of different forest types, assuming a 20% and 50% hazard reduction

Forest types	Reliability against rockfall	
	$x$ (20%), $\alpha_F = 40.14^\circ$ (%)	$x$ (50%), $\alpha_F = 53.45^\circ$ (%)
A	100	10
B	67	2
C	65	6
D	86	35

The reliability values are based on the empirical cumulative distribution, as shown in Fig. 4; right panel. Also listed are the related angles of reach of the considered hazard reduction factors based on Eq. (3)

risk reduction, whereas the highest hazard reduction is obtained in forest type D, which is the mixed forest stand.

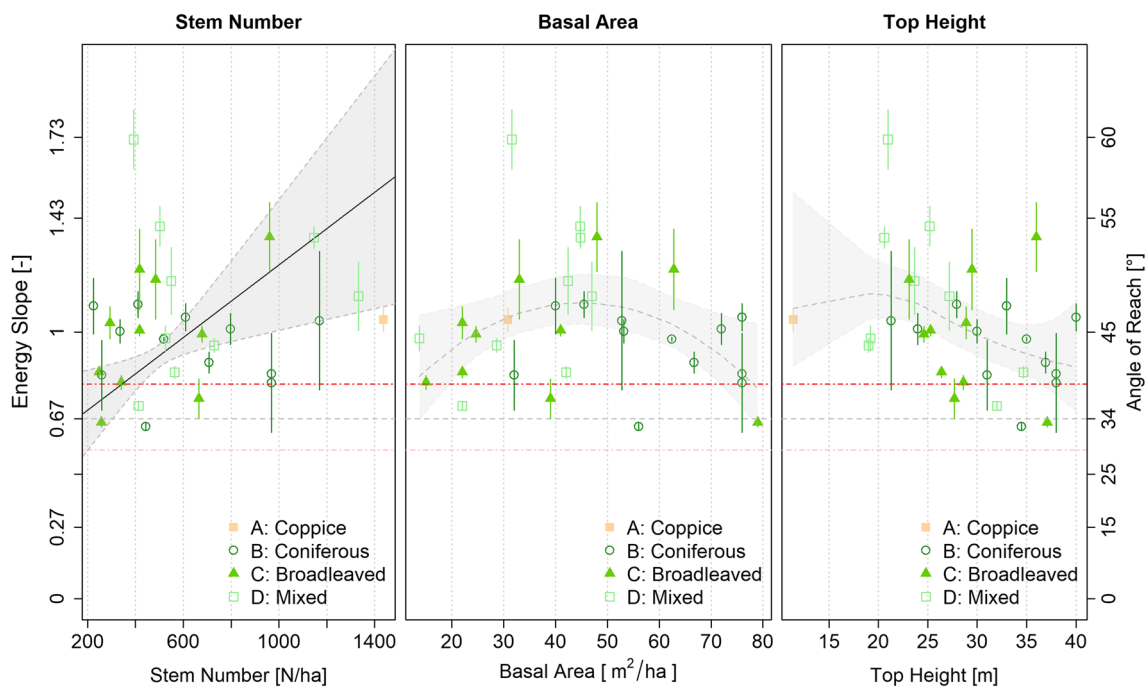
Table 2 compares the probability (reliability) for a 20% and 50% hazard reduction assumption, based on the empirical cumulative distribution, per forest type (Fig. 4 right). The reliability for a rather low hazard reduction is very high for the coppice forest stands (type A) and lowest for the forest types B and C, either dominated by coniferous or broadleaved tree species. On the contrary, the reliability of a 50%

hazard reduction is highest for the mixed high forest stand (type D).

Figure 5 shows the mean and the 95% confidence interval of the back-calculated energy slopes, estimated as  $\pm 1.96 * s * n^{-0.5}$  with  $s$  the standard deviation and  $n$  the number of observations, as a function of stem number, basal area and top height.

By means of weighted linear regression, using the reciprocal of the squared standard deviation as weights, only the effect of the stem number with a  $p$  value of 0.001 showed a significant correlation. The results indicate a positive relation between stem number and energy slopes. The higher the number of stems per hectare, the steeper the energy slope. Hence, the reduction of rockfall runout improves with an increase in stem density. The slope of the regression implies a 7% increase in the hazard reduction factor per 100 trees per hectare rise in stem number.

No significant correlation, however, exists between basal area or top height and energy slope. Based on a locally weighted scatterplot smoothing (Fig. 5), the basal area shows a parabolic trend with the highest reduction of rockfall runout around 40–50 m<sup>2</sup>/ha. Influence of top height is opposite to stem density, as higher values show lower energy slope, respectively, and longer rockfall runout.



**Fig. 5** Influence of forest parameters: stem number, basal area and top height, on the mean energy slope and hazard reduction factor of each release area. The error bars were estimated as 1.96 times the standard error, and symbols and colours refer to the forest types A to D. The solid line within the stem number plot is a weighted linear regression, using the reciprocal of the standard error as weights. The

dashed lines for the basal area as well as top height show the locally weighted scatterplot smoothing (Loess). The shaded area in all three plots is the 95% confidence interval of the estimated regression and loess, respectively. Also given is the 99.73% interval of angle of reaches, respectively, and energy slopes for rockfall events on non-forested slopes, indicated as horizontal dot dashed lines

## Discussion

The classification of the different forest types in this study follows a transregional approach. This means that a classification of the locally considered forest is relatively easy to implement, independent of the natural conditions.

### Hazard reduction of coppice forest stands

The results for the coppice forest type (A) must be considered in the context that the compiled rockfall trajectories all started from the same release area and thus the characteristic forest parameters of the passed forest-related land-cover units do not show great variation. Nevertheless, the key protective role of coppices on active rockfall slopes, as proposed by several studies (Ciabocco et al. 2009; Jancke et al. 2009; Favillier et al. 2015; Buckley et al. 2018), suggests an even higher reliability potential of coppice forest stands than indicated by our results. This can be crucial for coppice silviculture which has a very long tradition in alpine countries like Italy, French and partly in Switzerland (e.g. Unrau et al. 2018). In Austria (Gschwantner et al. 2019) and Slovenia (SFS 2019), however, only 2–3% of the total forest area is covered by coppice stands, and in the southern mountain parts of Germany, coppice forests play a rather subordinate role. However, in addition to their natural distribution, coppice forests are also used as rockfall protection for railway infrastructure facilities—especially in areas where high forests endanger the electric power lines. Similar structures and thus potentially comparable protective effects on rockfall can be found near the ecotone in the subalpine region of dwarf shrub stands, covered by populations of mountain pines (*Pinus mugo*) or green alder (*Alnus viridis*). Their reliability against rockfall has not been considered in this study, as such stocks are rarely managed and are located in areas where rockfalls do not normally endanger settlements or infrastructural facilities.

### Hazard reduction of high forest stands

Of all three high forest stands (B, C and D), the mixed forest stand type D shows the highest probabilities with increasing hazard reduction factors. Our result indicates that a higher energy dissipation potential can be assumed when analysing rockfall events through this type of forests. This confirms also findings of previous studies that mixed stocks represent the highest hazard reduction (c.f. Dupire et al. 2016). Tree species mixture seems to contribute to a higher vertical structure (e.g. Barbeito et al. 2017; Ishii and Asano 2010) and thus be also beneficial for rockfall protection. Contrarily, forest type B shows generally a weaker protective

performance compared to the other forest types. From the results of our study, it can be deduced that a 50% hazard reduction due to the protective effect of a forest differs even by a factor of three between forest type C (high forest stands dominated by broadleaved tree species) and forest type B (high forest stands dominated by coniferous forests), the latter showing the weakest hazard reduction performance.

The results for types B and C seem at first surprising, since the broadleaved dominated forest type has the lower stem number than the coniferous dominated forest type. In the forest with the lower stem number, a lower hazard reduction would be expected (c.f. Fig. 5) and Dorren et al. (2005) noted that the number of impacts is more important than the energy dissipated. We assume that even small-scale forest structures have a protective effect that should not be underestimated. In our study, we did not consider the friction effect provided by deadwood and lower vegetation. Indeed, these parameters can be related to forest cover and could partially explain the results obtained. For instance, in the Italian Alps, the highest average amount of deadwood and shrubs biomass has been found in broadleaved forests (Gasparini et al. 2013). Moreover, the broadleaved tree species compiled in this study, oak and in particular beech, have a higher crown ratio and thus also a lower height to the crown base than Norway spruce, larch or pine (e.g. Hasenauer and Monserud 1996). This is in line with the findings of Dupire et al. (2016), who stated that the more shade-tolerant tree species had a better protection potential.

Our results show that coniferous stands are generally mature, overstocked and typically represented by mono-layered Norway spruce stands, potentially already not providing an optimal protection (Dorren et al. 2004a).

Regarding the expected increase in the global average surface temperature of 3–5 °C by 2100 (IPCC 2014) with an associated increase in forest disturbances in Europe (Seidl et al. 2014), such populations can lose their residual hazard reduction effect on rockfall in a short time over large areas through windthrow, snowfall or insects' outbreaks (Vacchiano et al. 2016)—the latter more and more also observed at higher altitudes (Stadelmann et al. 2013; Raffa et al. 2013).

A combination of stem density and average size is, however, confirmed as fundamental for the hazard reduction. The fact that the intermediate basal area values showed the highest performance is strictly correlated to the combination of maximum number possible with a certain mean DBH. Increasing the mean size, density will decrease according to the self-thinning rule (Yoda et al. 1963), and the probability of impacts with trees will decrease accordingly. With respect to silvicultural guidelines for the alpine space (Frehner et al. 2005; Ancelin et al. 2006; Berretti et al. 2006; Perzl 2008), our results are in line with the recommended minimum stem



densities of about 200–600 trees per hectares (Fig. 5, left panel). Silvicultural objectives applicable in management provide, for instance, representative averages of structural parameters like the stem density for forest types within hazard process zones. Nonetheless, until now, all guidelines neglect the influence of the silvicultural system and of trees species composition. Possibly, national forest inventories could take into account the proposed rockfall relevant forest parameters for future surveys in protection forests.

### Reliability of forests against rockfall

Our approach to estimate the reliability against rockfall of different forest types offers the possibility to predict the protective effect of forests against rockfall. Compared to local-scaled studies, the proposed concept can be applied on standardized, available forest data which follow a transnational forest-type classification. Thus, our model supports or extends rockfall risk analysis for endangered areas on a European level—necessary for a regionally scaled evaluation of forest ecosystem services. This can help to find strategies how to maintain or improve the water or soil balance and habitat development in combination with technical and natural-based measures against rockfall. Developed for such a scaling level, the reliability models further can support general cost–benefit considerations of nature-based solutions and results could be used to indicate a minimum standard of the protective effect of forests against rockfall in the alpine region. More specifically, it can be used for first-order analyses to identify areas where management strategies need to be prioritized, or to obtain a quick overview of forest effects in areas at risk of rockfall. It might also serve as a basis for risk communication advocating management implementations that ensure sustainable protection.

Nevertheless, the proposed reliability models are based on the empirical cumulative distribution of a limited data set which does not cover the entire alpine region and lacks information especially regarding coppice forests. However, the existing data can be extended, if the presented sampling design will be considered for future documentations on rockfall events in forests. With a more comprehensive set of data, the empirical reliability models can then be adjusted by means of known probability distributions (c.f. Gamma, Weibull, Lognormal, ...) providing independent prediction models. However, since there is only a weak link between such a statistical modelling approach and the underlying physics, it is required to take a closer look at the hazard reduction potential and the underlying physics. Using this insight also helps to improve the reliability as well as reliability predictions (Triebl 2012).

### Conclusion

To assess the protective effect of forests for large areas, available data are often not sufficient, and the costs of forest surveys increase with the spatial resolution of the data—required by the modelling approach. Existing data on forest use and forest cover allow, however, the differentiation of main forest types—an information that can be provided or supplemented by the most cost-effective means of remote sensing. For this reason, our attempt to quantify the potential hazard reduction of rockfall focused on four pre-defined forest types and allows to estimate the effectiveness of forests as protection measure against rockfall. The results of this study indicate that the risk reduction of rockfall improves with increasing stem density and that mixed high forest stands have the highest protection potential. Besides hazard reduction, mixed stands also showed to be more resilient to both disturbances and climate changes, since the species and structure heterogeneity should guarantee better adaptations to changes (e.g. coexistence of different traits). Dealing with protection forests in the Alps, an increase in broadleaves share in mountain forests is expected (Berger et al. 2013), potentially increasing the protective effect of the stands (Lingua et al. 2020). However, further data collection, based on standardized methods for documenting hazard and forest structures along trajectories of natural hazards (e.g. Perzl et al. 2018; Scheidl et al. 2018), would substantially expand the state of knowledge about the protection potential of different forest types.

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