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Mechanisms, effects and management implications of rockfall in forests

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Abstract

At the scale of forest stands, there is a lack of quantitative, statistically valid data on the protective effect of forests against rockfall. Therefore, the first objective of this study was to quantify the velocities, rebound heights as well as the residual hazard of rockfall on a forested and a non-forested slope. The second objective was to evaluate existing rockfall protection forest management guidelines, as well as the underlying criteria. We carried out and analysed 100 real size rockfall experiments at a non-forested site (Site 1) and 102 identical experiments at a forested site (Site 2) on the same slope. We compared the obtained results with literature data on rockfall protection forests. At the non-forested site, results show that the mean maximum velocity is 15.4 m s^{-1} compared to 11.7 m s^{-1} at the forested site. The maximum rebound height decreases from 8 m (Site 1) to 2 m (Site 2) and the number of rocks that surpass the 223.5 m slope distance decreases from 95 out of 100 (Site 1) to 35 out of 102 (Site 2). A major effect of rockfall on a forested slope is the development of a treeless rockfall path or *couloir*, which had evolved after releasing 78 rocks at Site 2. The effect of such a *couloir* can be mitigated by cutting trees on both sides of the *couloir* and leaving the trunks on the slope, diagonally to the slope direction. This is a known and effective technique to reduce the effect of gaps in protection forests. During our experiments, none of the rocks attained their maximal velocity within the first 40 m. They did, however, attain destructive velocities (11–15 m s^{-1}) within that distance. Based on our observations, we propose a maximum gap size in the slope direction of 1.3 times the mean tree height, with a maximum of 40 m. Further, we present various findings that have direct implications for the management of rockfall protection forests. Finally, the results proved that forests can provide effective protection against rockfall.

Keywords: Mountain forest; Natural hazards; Protection forest; Real size experiments

1. Introduction

To sustain today's livelihoods in the European Alps, protection against natural hazards is indispensable. One of the important natural hazards is rockfall. We define rockfall as a relatively small landslide confined to the removal of individual rocks smaller than 5 m^3 from a cliff face (Selby, 1982; Berger et al., 2002). The unpredictability of rockfall potentially endangers human lives and infrastructure, as shown by the numerous examples of infrastructure destroyed or

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people killed by rockfall (e.g., Porter and Orombelli, 1981; Bunce et al., 1991; Badger and Lowell, 1992). Although rockfall is unpredictable, it mostly occurs in spring, due to alternating freezing and thawing and after heavy rain (Erismann and Abele, 2001; Dorren, 2003; Stoffel et al., in press-a). Rockfall in the European Alps is mostly a low magnitude–high frequency event (Dussauge-Peisser et al., 2002; Hantz et al., 2003; Stoffel et al., in press-b). From the different studies on the frequency of rockfall events it is hard to give an indication how often individual rocks smaller than 5 m^3 fall throughout the European Alps. Based on data obtained in the French Alps, one could expect every year a falling rock between 0.5 and 5 m^3 20 km^{-1} cliff length, which will damage forests, roads or buildings (Dussauge-Peisser et al., 2002). Rocks smaller than 0.5 m^3 fall much more often and can cause problems to local traffic and infrastructure more continuously, but such smaller events were not recorded in the dataset used by Dussauge-Peisser et al. (2002).

To protect against rockfall, one could use technical protective measures or eco-engineering techniques (use of ecological processes, possibly combined with engineering design, to achieve physical and environmental goals, e.g., installing wooden barriers, enlarging rock piles and walls using previous rockfall deposits, but also strategic planting, cutting and positioning trunks on the slope in protection forests). An important question with respect to rockfall protective measures is how much they reduce the residual rockfall hazard, i.e., the percentage of rocks that surpasses the protective measure(s) and the kinetic energy of those rocks. Rockfall protective measures can be grouped into preventive and protective ones. The first method aims to prevent the detachment of a rock by anchoring it to a stable part of the cliff. The second is used to mitigate the hazard, either by deviating its trajectory, e.g., by using galleries, or by reducing the natural travelling distance (Heidenreich, 2004). The latter is done, for example, by constructing catch or barrier fences, rockfall dams, restraining nets and dynamic rockfall nets (Hearn et al., 1992; Spang and Sönser, 1995; Peila et al., 1998; Nicot et al., 2001). The protective effect of forests falls mainly in the second class.

Technical protective measures are expensive and they deteriorate with time. Moreover, they cannot always reduce the residual rockfall hazard completely. The latter surely accounts for protection forests as well. However, in combination with technical protective measures it is possible in many cases (Gerber, 1998). The advantage of having and maintaining a protection forest in an optimal state regarding its protective effect as well as its stability in the long term (see Dorren et al., 2004a), is that more modest or sometimes no technical protective measures at all are required, of course depending on the acceptable risk. In those cases, the maintenance of forests designated an explicit protective function is cost-efficient (Kienholz and Mani, 1994; Motta and Haudemand, 2000; Berger et al., 2002; Dorren et al., 2004a; Perret et al., 2004; Brauner et al., 2005).

Many Alpine countries in Europe are developing guidelines for maintaining rockfall protection forests (e.g., Frehner et al., in press; ONF, in preparation). For that, quantitative and statistically valid data are required. However, at the scale of forest stands, there is a lack of such data, especially for rocks with diameters larger than 0.5 m. Therefore, the objectives of this study were: (i) to quantify the velocities, rebound heights as well as the residual hazard of rockfall on a forested and a non-forested slope using real size rockfall experiments and (ii) to evaluate existing management guidelines for forests that protect against rockfall, as well as the underlying criteria, using our experimental data combined with relevant literature data.

2. Existing literature on rockfall in forests

2.1. Previous rockfall experiments in forests

Quantitative field data on rockfall in forests, obtained by rockfall experiments that are similar to ours, have been presented by Jahn (1988) and by Doche (1997). Jahn (1988) described the results of rockfall experiments that were carried out on a non-forested (NF) and a forested (F) section of a 35.5° slope between an upper and lower forest road in Liechtenstein. Section NF is about 25 m wide and 143.4 m long (distance between the starting point and the lower forest road, measured along the slope). Section F is also about 25 m wide and 161.1 m long.

Table 1
Stopping causes of falling rocks on the experimental sites of Jahn (1988)

	Non-forested site ($n = 34$) (%)	Forested site ($n = 98$) (%)
Big rocks	32	16
Trees	6	61
Tree stumps	15	1
Footpath	21	8
Forest road	15	0[a]
Cause unclear	12	13

[a] None of the rocks reached the forest road.

The forest stand consisted of *Fagus sylvatica* L., *Picea abies* (L.) Karst., *Pinus sylvestris* L. and *Fraxinus excelsior* L., with a mean stand density of 3400 trees ha^{-1} and a mean DBH of 13 cm. The mean rock diameter used on section NF was 0.26 m ($n = 34$, spherical shape) and 0.28 m ($n = 98$, spherical shape) on section F (the minimum and maximum diameter of all the used rocks were 0.13 and 0.45 m, respectively, $n = 132$). The maximum rockfall velocity measured by Jahn (1988) was 15 m s^{-1}. Higher peak velocities have been observed, but could not be measured with the chronometer. Jahn (1988) found further that 31% of all the thrown rocks reached the lower forest road on section NF, whereas 0% on section F. Specific causes for rocks to stop at the two sites are given in Table 1. On average, each rock had 0.61 frontal and 0.39 lateral impacts on section F, where 40% of the frontal impacts resulted in immediate stopping of the rocks and 27% of the rocks impacted no tree at all. Only three rocks impacted two or more trees frontally. The lateral deviation from the central fall path was about 8° (Jahn, 1988). The research of Jahn (1988) showed that a very dense forest stand, with a small mean stem diameter, can protect effectively against rocks with diameters of 0.13–0.45 m.

The report of Doche (1997) presents the set-up and the results of the rockfall experiments carried out by Cemagref Grenoble at a forested site in Vailly (France). This site has a mean slope gradient of 38°, a length of 140 m (measured along the slope) and a width of 55 m. It is covered by *P. abies* (48%), *Abies alba* Mill. (16%), *Acer pseudoplatanus* L. (16%), *F. sylvatica* (15%) and various other broad-leaved species (5%). The stand density was 485 trees ha^{-1}, the mean DBH was 28 cm (S.D. = 15 cm), the measured total basal area was 38.7 m^2. The mean diameter of the used rocks was 0.87 m (minimum = 0.65 m, maximum = 1.15 m, S.D. = 0.15 m, $n = 15$, density = 2500 kg m^{-3}, spherical shape). The mean and maximum rebound heights were 0.88 and 2.7 m, respectively. The measured mean maximum velocity was 15.0 m s^{-1}, the absolute maximum velocity measured was 19.6 m s^{-1}. These data were calculated on the basis of video recordings. Doche (1997) describes that eight rocks were stopped due to tree impacts (53.3%), five surpassed the forested zone (33.3%) and two rocks broke into pieces (13.3%) after impacting rocks that were deposited behind trees. Thus, in total, 66.6% of the rocks were stopped by the forest.

Other field research on rockfall in forests has been done by Couvreur (1982), Zinggeler (1990), Gsteiger (1993), Cattiau et al. (1995), Dorren et al. (2004a), Perret et al. (2004), Stokes et al. (in press), which mainly described retro-analyses of rockfall trajectories on forested slopes. In summary, they found that rockfall velocities on forested slopes with a mean slope gradient between 33° and 40° are in the range of 15–25 m s^{-1}, rebound heights are between 1 and 2 m.

2.2. Existing management criteria and guidelines

The potential effects of forests on the rockfall hazard act both in the rockfall source area and in the transport/accumulation area. In the rockfall source area, however, most effects are negative regarding rockfall protection. Tree roots enlarge existing joints in the bedrock and act as wedges. In addition, the presence of roots in the bedrock accelerates chemical weathering (Jahn, 1988). Finally, movement of the tree stem due to snow or wind forces can cause rockfall via the wedge effect of the roots. The positive effect is that a dense root system can hold rocks together on talus slopes (Jahn, 1988; Gerber, 1998). In practice, unstable trees on top of cliffs and trees with big roots penetrating the bedrock should be removed. In the rockfall transport and accumulation area, the effect of a forest is mostly positive, as standing trees and dead wood lying on the slope surface can act as barriers and decelerate or stop falling rocks.

To effectively stop falling rocks in the transport/accumulation area, Schwitter (1998) mentions the rule of thumb that the mean DBH of trees in a forest stand should be 1/3 of the decisive size of the falling rocks. To give an accompanying stand density is difficult, because it depends completely on the size of the falling rock and its kinetic energy. The paradox is that the bigger the rock, the bigger the chance is that tree impacts occur, but also bigger trees are required to stop the rock. For smaller rocks, smaller trees are effective, but many more trees are required to increase the impact probability. In the minimal tending guidelines for managing rockfall forests developed by Wasser and Frehner (1996), the required stand density is independent of the size of the falling rock (400 trees ha^{-1}). Currently, this has been integrated in new guidelines, which have been developed in co-operation with Swiss forest and natural hazard specialists and our research group, in the framework of the NaIS project (in German: *Nachhaltigkeit im Schutzwald*, meaning sustainability in the protection forest, see Thormann and Schwitter, 2004; Frehner et al., in press). For a forest that has to protect against falling rocks, such as the ones we used during the experiments (mean diameter of 0.95 m), the NaiS guidelines aim at a forest consisting of at least 200 trees ha^{-1} with a mean DBH larger than 36 cm in ideal conditions and at least 150 trees ha^{-1} with the same diameters for the worst conditions.

These guidelines also mention that distances between trees in the fall direction should not exceed 20 m, because, according to Gsteiger (1993), Wasser and Frehner (1996) and Frehner et al. (in press), rocks reach their maximal speed after falling 40 m down a slope if no tree impacts occur. To estimate the mean distance between two tree impacts in a forest stand, Gsteiger (1993) proposes the concept of the mean tree free distance (MTFD), which is calculated following,

$$\mathrm{MTFD}_{\mathrm{Gsteiger}} = \frac{\mathrm{Area}}{(\mathrm{Nrstems} \times R_{\mathrm{diam}}) + \sum \mathrm{DBH}} \quad (1)$$

where Area is the evaluated area (m^2), Nrstems is the number of stems in the evaluated area, R_{diam} is the mean diameter of the rock (m) that falls in the evaluated area and ΣDBH is the sum of all the stem diameters at breast height (m) in the evaluated area. An alternative calculation is given by Perret et al. (2004):

$$\mathrm{MTFD}_{\mathrm{Perret}} = \frac{\mathrm{Area}}{\mathrm{Nrstems} \times (R_{\mathrm{diam}} + \mathrm{DBH}_m)} \quad (2)$$

where DBH_m is the mean DBH (m) of all the stems in the evaluated area.

A typical practice in rockfall protection forest management is to cut trees and leave the trunks lying on the slope, diagonally to the slope direction (Schwitter, 2001; Dorren et al., 2004a, 2004b; Frehner et al., in press). Such trunks prevent the development of rock accumulations and continue the rock transport in a controlled manner. Experiences in Austria show that bigger *P. abies* trees (>50 cm) can act as effective rockfall barriers for about 10 years (Dorren et al., 2004a).

A similar protective effect as obtained by lying trunks is observed in snag stands (Kupferschmid Albisetti et al., 2003) and on uncleared windthrow areas (Frey and Thee, 2002). Both latter studies report effective protection against rockfall and/or avalanches for 30 years. Cutting all the trees in a protection forest stand and leaving them lying on the slope for protection against natural hazards is, however, not a sustainable management practice. After 30 years, there will be no trees with a sufficiently large diameter to stop falling rocks with a high kinetic energy.

3. Materials and methods

3.1. Rockfall experiments

Our study area is located in the Forêt Communale de Vaujany in France (lat 45°12′, long 6°3′) and has an altitude ranging from 1200 to 1400 m above sea level. It covers a forested, northwest facing Alpine slope, which has a mean gradient of 38°. The main tree species in the study area are Silver fir (*A. alba*, 50%), Norway spruce (*P. abies*, 25%), European beech (*F. sylvatica*, 17%) and Sycamore (*A. pseudoplatanus*, 4%). Other occurring species are *Sorbus aucuparia* L., *Betula pendula* Roth, *Ulmus glabra* Huds., *Ilex aquifolium* L., *F. excelsior* L. and *Corylus avellana* L.

We defined two adjoining sites on a hillslope that is formed by a huge post-glacially developed talus cone (Fig. 1), which mainly consists of rock avalanche, snow avalanche and rockfall deposits. Site 1 is about 25 m wide and 302 m long (distance between the starting point and the lower forest road, measured along the slope). It covers an avalanche *couloir* and is, therefore, denuded of trees. Between the starting point and the lower forest road, it has the morphology of a real channel (Fig. 1). Site 2 is 53 m wide and 223.5 m

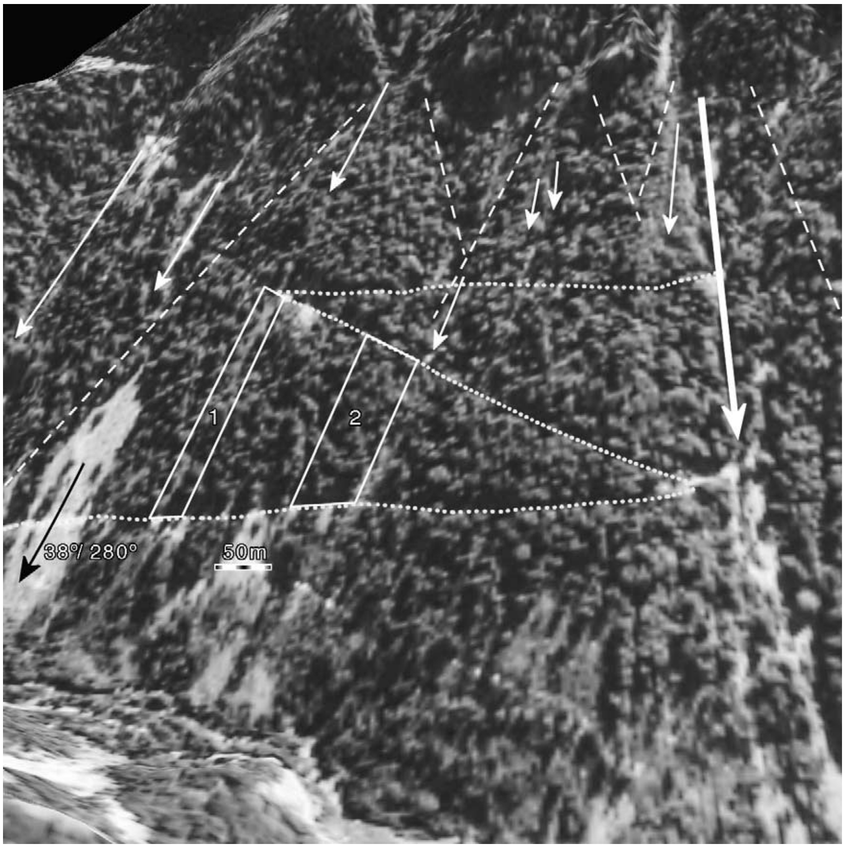

Fig. 1. A digital terrain model of the study area overlain by an orthophoto. This figure shows that the study area consists over several talus cones (dashed white lines) on which preferential rockfall and avalanche tracks exist (white arrows; the size indicates the magnitude of processes acting in the preferential track). The experimental sites are depicted by the numbers 1 and 2 in the white rectangles. The main forest road is indicated by the dotted grey line.

long and is covered by forest. In total, we measured and mapped 271 trees at Site 2, which gives a mean stand density of 290 trees ha^{-1} (planimetric). The mean DBH of all the measured trees at Site 2 was 31 cm (S.D. = 21 cm, maximum = 89 cm), the measured total basal area was 29.5 m^2 (31.6 m^2 ha^{-1}) and the mean tree height was 26 m (S.D. = 4.8 m, maximum = 36 m). There are no trees in the first 35 m of the fall line downslope of the starting point, which is necessary for the rocks to reach a velocity that is interesting for our experiments before they impact any trees. Both sites have a mean slope gradient of 38° and are easily accessible by a forest road, which was used by trucks to deliver the rocks for the experiments as well as by the caterpillar that released the rocks down the slope. The set-up of the experiments is visualized in Fig. 2. A river delimits the foot of the site, which excludes any object that could be at risk due to the experiments, and the site is representative for many active rockfall slopes in the European Alps regarding the slope surface and forest stand characteristics. It took almost three years to find and get access to a site that met all our conditions and where we were allowed to carry out the experiments.

At Site 1, the experiments have been carried out in 2001 and at site 2 they have been carried out in 2002 and 2003. Before the experiments, we installed clear warning panels to close off the complete area around the sites. We also installed five high-speed digital video cameras along the experimental sites at a height of 10 m in trees situated 30–40 m away from the

Fig. 2. (A) rocks are painted to leave marks after tree impacts or rebounds on the slope surface; (B) a caterpillar throws the rocks down the slope; (C) video cameras are installed along the slope to record the rockfall trajectories; (D) a rock accelerating in the first meters; (E) after each individual rockfall experiment, we capture its trajectory to obtain a three dimensional trajectory; (F) a sequence of movie images (each 1/4 s) taken at Site 2.

central rockfall paths of the two sites (Fig. 2C). We used the same protocol throughout all the experiments. Rocks with a mean diameter of 0.95 m were released individually, one after the other, by a caterpillar (Fig. 2B and D). The mean rock volume was 0.49 m^3 (minimum = 0.1 m^3; maximum = 1.5 m^3; S.D. = 0.3 m^3, $n = 202$) and the rock volume distribution was similar at both sites. After each rock, we surveyed its trajectory from the release to the stopping point using an Impulse LR 200 laser distance meter manufactured by Laser Technology Inc. (Centennial, Colorado, USA) (Fig. 2E). If they occurred, we measured all the damages on trees due to impacts (height and horizontal position of the impact and the size and depth of the wounds). The horizontal position of the impact on the tree stem was measured by the horizontal distance between the impact centre and the vertical central tree axis as seen from the impact direction. We painted the released rocks with biodegradable coloured powder (Fig. 2A) to facilitate the identification of the rock trajectories on the digital films and the impacts of the rocks against trees and on the ground. We neutralised impacts on the slope surface as well as on trees by leaving coloured marks in the impact craters or on the impact wounds to prevent mapping the impact twice. After finishing the trajectory survey we clambered up the slope to release the next rock. On average we managed to carry out eight rockfall experiments per day.

3.2. Data analysis

In total, we analysed the trajectories of 100 rocks at Site 1 and 102 rocks at Site 2. In total, we measured 286 rockfall impacts on tree stems. According to the position of the impact centre on the tree stem, we defined three main impact types: frontal, lateral and scratch (Fig. 3). For each impact type we determined the deviation of the fall direction after the impact with respect to the fall direction before the impact. The trajectory survey allowed us to calculate the energy line angle, which is the angle of the straight line between the starting point and the maximum stopping point (Heim, 1932; Gerber, 1998; Meißl, 1998).

We analysed the digital films of the rockfall trajectories using a free downloadable program called AviStep 2.1.1, which is developed by M. Delabaere (Saint Denis de la Réunion, France). This program allows extracting the position and the velocity of a

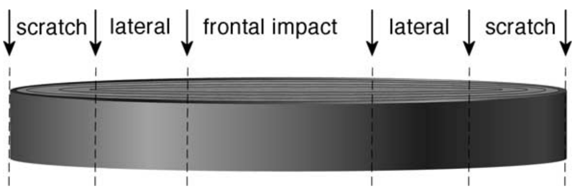

Fig. 3. Definition of the three main impact types according to the horizontal distance between the impact centre and the vertical central tree axis.

moving particle for each individual image in a digital film. The principle is as follows. Initially, each film has to be referenced in x and y direction, which means that in the first image of each film, we defined the distance in meters between two known points in the terrain, which were also clearly recognisable on the first film image. In our case, we used known distances between clearly marked trees. Then, we analysed the trajectory of each falling rock in 2D using a sequence of movie images (Fig. 2F).

We measured the rockfall velocities and the rebound heights, i.e., the maximum reached vertical height between the centre of the rock and the slope surface after each rebound on the ground. Since we used high-speed digital cameras we captured the velocities (both in x and y direction, as well as the resultant translational velocity) of each falling rock every 1/25th second. Therefore, we could accurately determine the translational velocity of a falling rock before and after tree impacts or rebounds on the slope surface. Determining the angular velocity was more difficult, as we had to determine the number of sequential images for the rock to rotate once, which was not always easy to recognise.

In addition, we calculated the mean tree free distance (MTFD) for Site 2. Since it is rather a certain surface of the tree than the tree diameter that intercepts a falling rock, we propose to calculate the MTFD using the basal area, following,

$$\mathrm{MTFD_{ba}} = \frac{\mathrm{Area}}{\mathrm{Nrstems}(R_{\mathrm{diam}} + \sqrt{(4G_{\mathrm{tot}})/(\pi \mathrm{Nrstems})})} \quad (3)$$

where Area is the evaluated area (m^2), Nrstems is the number of stems in the evaluated area, R_{diam} is the mean diameter of the rock (m) that falls in the evaluated area G_{tot} is the total basal area in the evaluated area. In fact, here we calculate the $\mathrm{MTFD_{Perret}}$ using a mean DBH derived from the total basal area. The latter can easily and quickly be measured in the field using a relascope (Bitterlich, 1984). We calculated the $\mathrm{MTFD_{ba}}$ in many different forests where we analysed the rockfall hazard and it seems to give a more realistic value for the MTFD compared to the first two approaches. This is because the mean measured DBH tends to underestimate the total interception surface of a forest. To show the differences, we calculated $\mathrm{MTFD_{Gsteiger}}$, $\mathrm{MTFD_{Perret}}$ and $\mathrm{MTFD_{ab}}$.

4. Results

4.1. Differences in velocities and rebound heights

There is large difference between the non-forested site (Site 1) and the forested site (Site 2) regarding the rockfall velocities and the rebound heights (Table 2). The mean velocity over the whole section at Site 1 was 10.9 m s^{-1}, but this varied enormously between the upper part and the lower part. The mean of all the maximum velocities of the 100 analysed rocks was 15.4 m s^{-1} (S.D. = 3.4 m s^{-1}) and the maximum velocity measured was 30.6 m s^{-1} (attained at a distance of 184 m from the starting point, measured over the slope; the maximum translational energy was 954 kJ). On average, the rocks attained a maximum

Table 2
Summary of the observed rockfall characteristics at our experimental sites

	Site 1 non-forested (n = 100)	Site 2 forested (n = 102)
Average translation velocity (m s^{-1})	11	8
Average maximum translation velocity (m s^{-1})	15.4	11.7
Maximum translation velocity (m s^{-1})	30.6	24.2
Number of rocks stopped after 223.5 m	5	65
Number of rocks stopped on the lower forest road	15	13
Number of rocks surpassing the forested zone	n.a.	35
Mean number of tree impacts per falling rock	n.a.	2.8
Mean rebound height (m)	1.5	1
Maximum rebound height (m)	8	2 (5[a])
Number of rocks to develop a *couloir*	n.a.	72

[a] A rebound with a height of 5 m was observed after the rock hit an old tree stump that was not cut high enough, which therefore acted as a trampoline.

velocity of 11.2 m s^{-1} within the first 40 m and 15.4 m s^{-1} after 80 m. In total, 71 rocks (71%) attained a velocity higher than of 10 m s^{-1} within the first 40 m. The maximum velocity measured within the first 40 m at Site 1 was 14.8 m s^{-1}.

The mean velocity at Site 2 was 8.2 m s^{-1}, the mean maximum velocity for the 102 analysed rocks was 11.7 m s^{-1} (S.D. = 2.2 m s^{-1}) and the maximum velocity measured was 24.2 m s^{-1} (the distance from the starting point was 115 m; the maximum translational energy was 1092 kJ). On average, the maximum velocity within the first 40 m at Site 2 was 8.4 m s^{-1}. In total, 21 rocks (21%) attained a velocity higher than of 10 m s^{-1} within the first 40 m. The maximum velocity measured within the first 40 m at Site 2 was 11.6 m s^{-1}.

4.2. Rockfall trajectories, tree impacts and runout zone

Regarding the residual hazard of the forest stand at Site 2, 35 rocks (34%) surpassed the forested zone (slope length of 223.5 m), of which 13 rocks (13%) subsequently stopped on the forest road. At Site 1, we observed that 15 rocks (15%) stopped on the forest road and 11 rocks (11%) stopped before that. At Site 1, only 5 rocks (5%) stopped within the first 223.5 m, which is the length of the forested zone at Site 2. The maximal distance between the release and the stopping point (measured along the slope) was 501.3 m for Site 1, which is in the valley bottom. For Site 2, this was 324.9 m, which was below the lower forest road. Here, the forest stand characteristics were identical to the ones in the upper section. The accompanying energy line angles are 31.9° for Site 1 and 38° for Site 2.

Another observed effect of the forest cover on the rockfall trajectories is the width of the runout zone. We measured that, due to impact against trees, the falling rocks are laterally deviated from the central fall line parallel to the mean slope direction with a mean angle of 10°. At Site 1, this mean angle was less than 5°. This deviation mainly occurred as soon as the rocks passed the lower forest road at Site 1. There, their movement was no longer controlled by the channel morphology. The deviation at Site 2 is strongly determined by the different types of tree impacts: frontal, lateral and scratch. Table 3 presents the occurrence frequencies of the three main impact types, as well as the percentage of effective impacts, i.e., the tree impacts that resulted in immediate stopping of the falling rock.

Table 3
The occurrence frequency of different types of impacts (%) and their efficacy in stopping rocks, based on 286 analysed tree impacts (from Dorren and Berger, in press)

Type of impact	Occurrence (n = 286)
Frontal	63.8% (14% of these were effective[a])
Lateral	20.0% (20% of these were effective)
Scratch	16.2% (0% of these were effective)

[a] Effective means that the rock stopped immediately after the impact.

The trajectory surveys enabled us to construct ‘deviation’ matrices for each impact type that show the deviation in the fall direction after a tree impact (Fig. 4). In fact, the analysis of all the deviations in all the fall directions, taking into account all the tree impacts as well as all the rebounds on the ground, resulted in a deviation matrix that is equivalent to the one of the scratch impact (Fig. 4). The deviation matrix of the frontal impact shows that a large percentage (44%) of the rocks continued its fall direction straight on. This includes all the rocks that: (i) stopped behind a tree; (ii) broke or uprooted a tree and continued in the same direction; and (iii) the ones that impacted a tree and subsequently bounced a bit to the side or turned around the tree and continued more or less in the same direction.

On average, each rock had 2.8 impacts against trees (286 impacts/102 rocks), the maximum number of impacts per rock was 8 and 11 rocks (11%) impacted no tree at all (Fig. 5). The mean and maximum impact height was 0.72 and 2 m, respectively. The mean rebound height at Site 1 was 1.45 m, the maximum rebound height was 8 m. At Site 2, the mean rebound

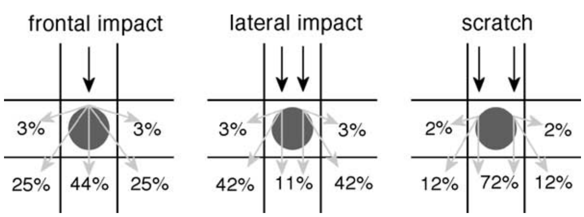

Fig. 4. Deviation matrices for the three main impact types showing the percentage of rocks that deviated from the impact direction (indicated by the downward arrow) towards the general direction indicated by the matrix cell (indicated by the grey arrow) after impacting a tree (represented as the circle).

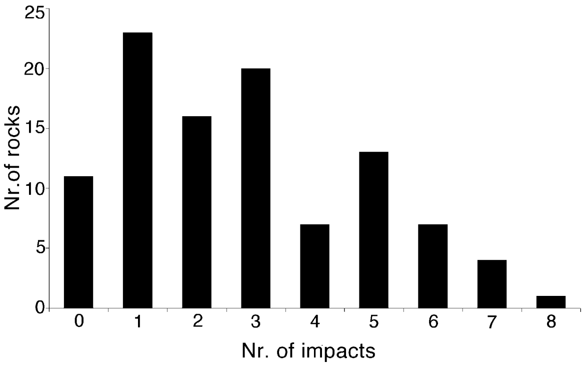

Fig. 5. Histogram of the number of tree impacts per falling rock.

height was 1.01 m, the maximum rebound height was 2 m. The $MTFD_{Gsteiger}$ for Site 2 is 34.9 m, $MTFD_{Perret}$ is 34.7 m and $MTFD_{ba}$ = 33.0 m.

Some of the impacts caused an instantaneous fracture and cutting of the tree stem. During an impact, the kinetic energy of the rock causes a displacement of the whole tree including the root system. At that moment the kinetic impact energy is transferred to the root–soil system and to the tree stem. If the tree is anchored well enough in the soil and if the stem does not break or fracture, the tree makes a hula-hoop effect and transfers the energy to the tree crown. Thereby most coniferous trees loose their top. In other cases the tree will be uprooted or broken. In fact we observed the following three main types of damage: uprooting, stem breakage and breaking of the treetop (Fig. 6). Other occurred damages were: rockfall wounds on the stem due to impacts, partial fracture of the stem and explosion of tree stems into wood sparks.

An important consequence of the cutting and uprooting of tree stems by rock impacts is the development of a rockfall path or *couloir*. This path follows the mean slope direction from the point were the rocks were released (Fig. 7). After releasing 78 rocks, such a path had evolved. After that, only four of the remaining 24 rocks followed the *couloir*, the rest was laterally deviated.

5. Discussion and conclusions

The results of this study enable us to compare the velocities, rebound heights as well as the residual hazard of rockfall on a forested and a non-forested slope. It showed that the residual rockfall hazard on a 38° slope, expressed in terms of the number of rocks that surpass a certain zone, decreases with 63% in case a forest cover is present. Not only the number of rocks

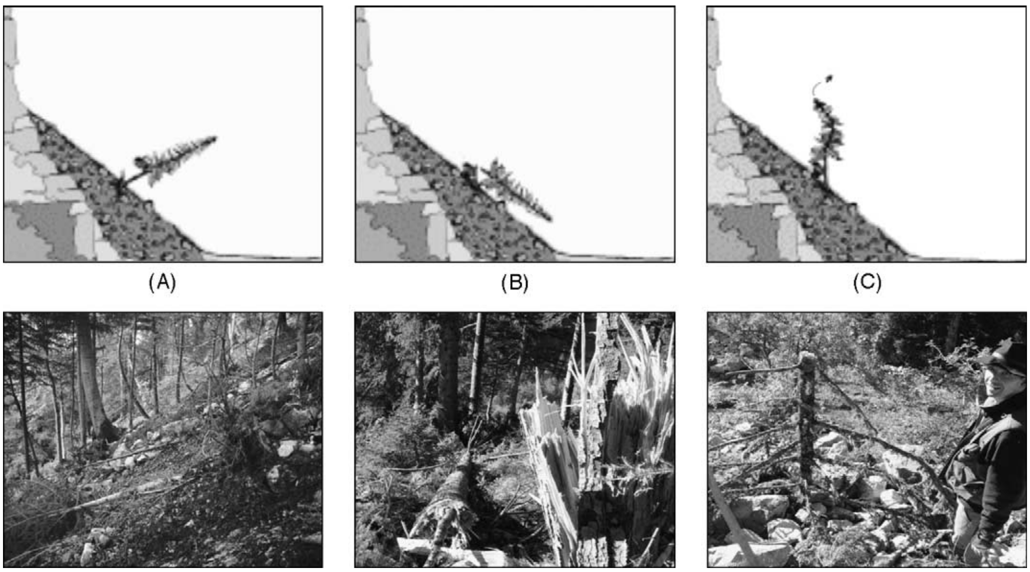

Fig. 6. Main types of tree damage observed on a forested active rockfall slope (sketch and photo of: (A) uprooting; (B) stem breakage; and (C) hula-hoop effect causing tree top break off).

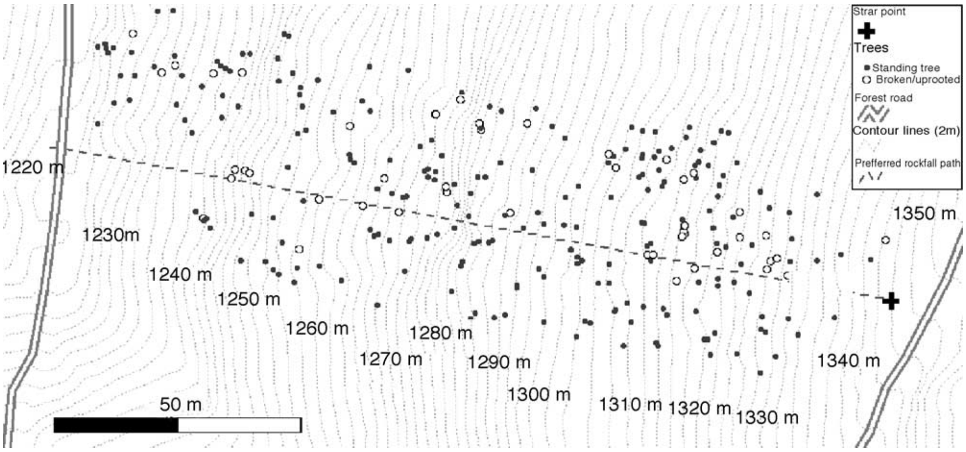

Fig. 7. Map showing all the trees at Site 2, including the ones that have been cut or uprooted by falling rocks, and the resulting rockfall *couloir*.

that stops on the slope increases on forested slopes, also the bounce height and the velocity decrease significantly. When comparing the forested with the non-forested slope, the velocities are on average reduced with 26% and the mean rebound height is reduced with 33%. These results confirm the findings of of Jahn (1988), Zinggeler (1990), Gsteiger (1993), Doche (1997), Dorren et al. (2004b) and Perret et al. (2004) that rockfall velocities on a forested slope with a mean gradient between 33 and 40° are between 15 and 25 m s^{-1} and that bounce heights are generally between 1 and 2 m. Furthermore, both our results and those of Jahn (1988) show that a forest road stops between 13 and 15% of the rocks falling on a slope with gradient between 35.5 and 38°.

The MTFD calculated with the three approaches presented in Eqs. (1)–(3) does not vary much at Site 2. We proposed the $MTFD_{ba}$ because in general it gives more realistic values and it is a good indicator for the impact probability. In combination with the mean DBH and the tree species, which are indicative for the energy dissipative capacity during rockfall impacts (Fig. 8), the efficacy of a protection forest stand can be estimated.

The obtained experimental data, combined with relevant literature data and a review of existing rockfall protection forest management guidelines, allow us to evaluate and propose management criteria. During the experiments we observed that the number of impacts against trees is more important than the efficacy of the impact expressed in the amount of dissipated energy. An enormous rock (e.g., 1.5 m^3) could be stopped by a small tree, e.g., with a DBH of 10 cm, if the rock impacted a large tree just before. Therefore, we believe that for effective protection, a large number of trees is more important than having thick trees only. Also Jahn (1988) showed that small trees could stop rocks with diameters between 0.13 and 0.45 m, if the stand is dense enough. For larger rocks, a larger mean stem diameter is required, which is clearly shown by the work of Doche (1997). An estimate of the required stand density can be calculated with the $MTFD_{ba}$, which should not be larger than 40 m, the required mean diameter can be calculated by using Fig. 8, which is based on work of Dorren and Berger (in press). The rule of thumb, mentioned by Schwitter (1998), that the mean DBH of

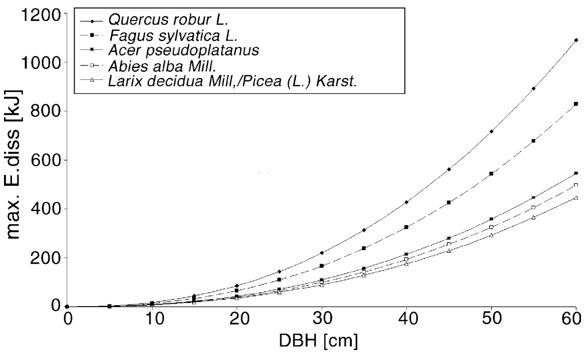

Fig. 8. Relationship between the diameter at breast height (DBH) and the maximum amount of energy that can be dissipated during a rockfall impact for six tree species (after Dorren and Berger, in press).

trees in a forest stand should be 1/3 of the decisive size of the falling rocks is valid for Site 2, but to give further characteristics of an optimal rockfall protection forests is not possible. What is very much needed is a tool that takes into account the mean diameter of the falling rock, the mean kinetic energy of the rock, the maximum length of the stopping zone and the tree species, because these parameters determine the required mean diameter and accompanying stand density.

During our experiments, none of the rocks attained their maximal velocity within the first 40 m, neither at Site 2, nor at Site 1. For that, a minimal distance of 80 m was required. However, rocks did attain destructive velocities after 40 m. Therefore, 40 m should be the maximum gap length in the slope direction in protection forests. Shorter ones are preferable, but not always realistic. We propose to use the length of an effective $MTFD_{ba}$. At site 2 this was 33 m, which was 1.3 times the mean tree height (MTH). In parallel to the maximum size of regeneration gaps in avalanche protection forests (gap length along the slope = 1.5 × MTH; gap width = 0.65 × MTH, Berger, 1997), the gap length and width in protection forests could be, respectively 1.3 × MTH and 0.5 × MTH (calculated using the lateral deviation of 10°), where the absolute maximum length and width are, respectively 40 m and 15 m, measured along the slope.

Regarding our study site, the protection provided against falling rocks with a mean diameter of 0.95 m would be sufficient if the earlier described rockfall *couloir* would not be present. The effect of the presence of such a *couloir* can be mitigated by cutting trees on both sides of the *couloir* and leaving the trunks on the slope, diagonally to the slope direction (Fig. 9). Important criteria for selecting the trees to be cut are: the position and the growth tendency with respect to the *couloir*, the DBH (thicker stems, or if possible multiple parallel trunks, are clearly more effective barriers), tree instability, the potential effect on promoting regeneration, gaps that will evolve after cutting as well as the hiding effect. That is, in protection forests, trees tend to grow behind each other, i.e., the older tree protects younger trees downslope (c.f. Gsteiger, 1993). This effect can also be seen on the map of our study site (Fig. 9). If trees with an effective diameter (>35 cm) have developed downslope of an older tree upslope, the latter could be felled.

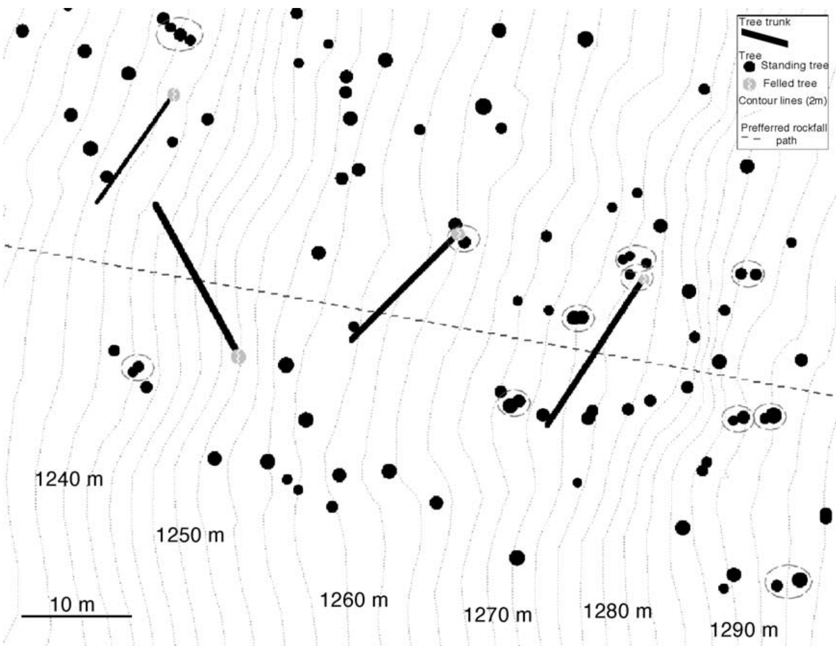

Fig. 9. Map showing a part of Site 2, including the management measures that we propose in the rockfall *couloir*. The diameter of the points represents the relative DBH of the trees and the dashed circles indicate examples of the hiding effect (see text for explanation).

Another important aspect is the direction in which the felled trunk is positioned on the slope. A choice can be made to deviate all the rocks away from a channel, preferably into areas with a high stand density or a high surface roughness (e.g., depressions where many larger rocks have been deposited). On the other hand, if the *couloir* has become a real channel, in which regeneration is impossible, all the rocks could be deviated into this channel by using accurately positioned felled trunks. A condition for the latter case would be that there is sufficient protection at the end of the *couloir*, e.g., a rockfall net or a rockfall dam.

Finally, we observed that a rotten, low cut stump acted as a trampoline for one falling rock. This resulted in a rebound height of 5 m. Consequently, trees that are to be felled in a rockfall protection forest should be cut very high (>1.3 m, if possible higher). In many places in the European Alps, rockfall nets are installed along traffic ways. Trees bordering the roads are often felled before installing these nets. Especially there it is important that those trees are cut either high enough or very low, if not, rocks can jump over the installed rockfall nets.

In some cases the selling of the felled wood could cover a large part of the forest management interventions described above, but in most cases the responsible forest management department is very much dependent on subsidies. It is for those situations that the question has to be asked whether civil engineering, protection forest management (an eco-engineering technique), or the combination of the two is most appropriate. Mountain forests in the European Alps and the protection they provide have a long and distinguished history, especially regarding protection against rockfall, snow avalanches, floods and debris flows, but active management is currently a necessity to sustain or optimise this service (Kräuchi et al., 2000; Brang, 2001; Dorren et al., 2004b). The fact that not only large stem diameters are required, allows the application of selective thinning or other minimal tending techniques that promote regeneration and ensure the forest to stay in an optimal condition regarding its protective function (Motta and Haudemand, 2000; Dorren et al., 2004b).

Unfortunately, society has nowadays often more confidence in technical protective constructions, but it turns out that they cannot always sustain the time periods that were originally planned, which results in unforeseen costs. Healthy forests at the other hand can provide long term protection, especially in combination with more modest and cheaper technical constructions that reduce the residual risk at the bottom of forested slopes. If all the services forests provide should be taken into account in the calculation of the costs of protective measures, the cost-effectiveness of protection forest management would look very different.

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