Results of Real Size Rockfall Experiments on Forested and Non-Forested Slopes

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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, filmed 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. 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. 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. Finally, the results proved that forests can provide effective protection against rockfall.

Keywords: rockfall, real size experiments, digital films, protection forest

Introduction

One of the important natural hazards in the Alps that should be protected against 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). To protect against rockfall, one could use technical protective measures or eco-engineering techniques. 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; 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., 2004*a*), 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., 2004*a*, Dorren et al., 2005).

Many Alpine countries in Europe are developing guidelines for maintaining rockfall protection forests (e.g, Frehner et al., 2005; ONF, 2006). 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 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.

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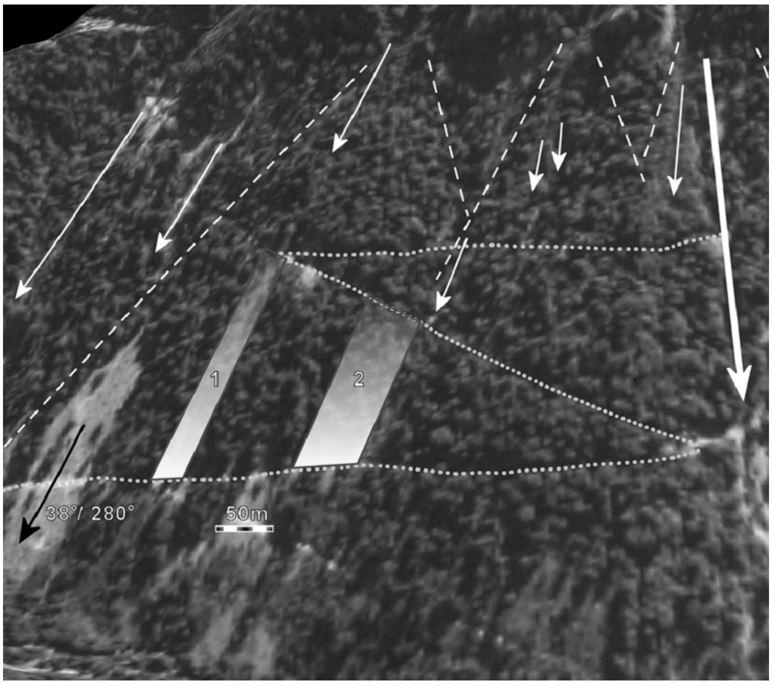

Fig. 1. Overview of the experimental site.

Materials and methods

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 m 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 (*Abies alba* — 50%), Norway spruce (*Picea abies* — 25%), European beech (*Fagus sylvatica* — 17%) and Sycamore (*Acer pseudoplatanus* — 4%). Other occurring species are *Sorbus aucuparia* L., *Betula pendula* Roth, *Ulmus glabra* Huds., *Ilex aquifolium* L., *Fraxinus 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 (cf. Fig. 1). Site 2 is 53 m wide and 223.5 m 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 (std. dev. = 21 cm, max. = 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 (std. dev. = 4.8 m, max. = 36 m). There are no trees in the first 35 meters 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.

At Site 1, the experiments have been carried out in 2001 and at site 2 they have been carried out in 2002 and 2003. We installed five high-speed digital video cameras along the experimental sites at a height of 10 m in trees situated 30 m–40 m away from the central rockfall paths of the two sites. 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. The mean rock volume was 0.49 m^3 (min. = 0.1 m^3; max. = 1.5 m^3; std. dev. = 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). 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

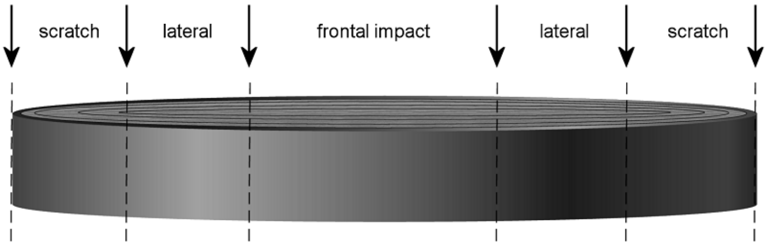

Fig. 2. Definition of the three main impact types according to the horizontal distance between the impact centre and the vertical central tree axis.

released rocks with biodegradable coloured powder to facilitate the identification of the rock trajectories on the digital films, as well as 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.

Data analysis

In total, we analysed the trajectories of 100 rocks at Site 1 and 102 rocks at Site 2. In total, we measured 235 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. 2). 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 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. 2-F).

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.

Results

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 1). 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} (std. dev. = 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 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} (std. dev. = 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

Table 1. Summary of the observed rockfall characteristics at our experimental sites.

Site		**1** **Nod- foreste** (*n*=100)	**Site 2** **fodes** (*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
Number of rocks to develop a *couloir*	n.a.		72

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}.

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.

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. 3). 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 (cf. Fig. 3). 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 (235 impacts / 102 rocks), the maximum number of impacts per rock was 8 and 11 rocks (11%) impacted no tree at all. The mean and maximum impact height was respectively 0.72 m and 2 m. The mean rebound height at Site 1 was 1.45 m, the maximum rebound height was 8 m. At Site 2, the mean rebound height was 1.01 m, the maximum rebound height was 2 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. 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

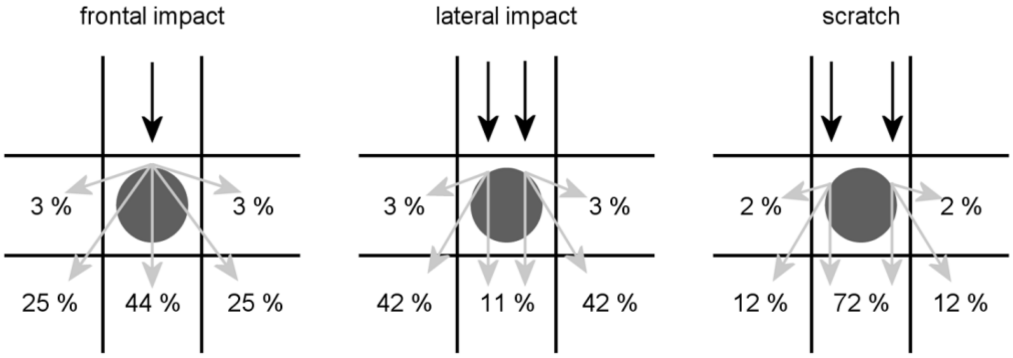

Fig. 3. Deviation matrices for the three main impact types showing the percentage of rocks that deviated from the impact direction (indicated by the downward arrow) towards the general direction indicated by the matrix cell (indicated by the grey arrow) after impacting a tree (represented as the circle).

were released. 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.

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 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), Gsteiger (1993), Doche (1997), Dorren et al. (2004b) and Dorren et al. (2005) that rockfall velocities on a forested slope with a mean gradient between 33 and 40 degrees 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 degrees.

The data by our experiments, 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 m 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 Mean Tree Free Distance principle described in Dorren et al. (2005), which should not be larger than 40 m. The required mean diameter can be calculated by using the equations published by Dorren and Berger (2006). The rule of thumb, mentioned by Schwitter (1998), that the mean DBH of 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 general characteristics for 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.

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. 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. If trees with an effective diameter (> 35 cm) have developed downslope of an older tree upslope, the latter could be felled.

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.

References

Berger, F., Quetel, C., Dorren, L.K.A. (2002) Forest: a natural protection mean against rockfalls, but with which efficiency? *International Congress Interpraevent 2002 in the Pacific Rim*, Matsumoto, Japan. Conf. Proc. Vol. 2, 815–826.

Doche, O. (1997) *Etude expérimentale de chutes de blocs en forêt.* Cemagref / Institut des Sciences et Techniques de Grenoble (ISTG), Cemagref doc. 97/0898, 130 p.

Dorren, L.K.A. and Berger, F. (2006) Stem breakage of trees and energy dissipation at rockfall impacts. *Tree Phys.* 26, 63–71.

Dorren, L.K.A., Berger, F., Imeson, A.C., Maier, B., Rey, F. (2004*a*) Integrity, stability and management of protection forests in the European Alps. *For. Ecol. Manag.* 195, 165–176.

Dorren, L.K.A., Maier, B., Putters, U.S., Seijmonsbergen, A.C. (2004*b*). Combining field and modelling techniques to assess rockfall dynamics on a protection forest hillslope in the European Alps. *Geomorphology* 57, 151–167.

Dorren, L.K.A., Berger, F., Le Hir, C., Mermin, E., Tardif, P. (2005) Mechanisms, effects and management implications of rockfall in forests. *For. Ecol. Manage.* 215 (1–3), 183–195.

Frehner, M., Wasser, B., Schwitter, R. (2005) Nachhaltigkeit und Erfolgskontrolle im Schutzwald. Wegleitung für Pflegemassnahmen in Wäldern mit Schutzfunktion. *Bundesamt für Umwelt, Wald und Landschaft*, Bern.

Gerber, W. (1998) *Waldwirkung und Steinschlag.* In: R. Schwitter (Editor), Dokumentation der 14. Arbeitstagung der Schweizerischen Gebirgswaldpflegegruppe mit der FAN 1998, Grafenort / Engelberg, 1–15.

Gsteiger, P. (1993) Steinschlagschutzwald. Ein Beitrag zur Abgrenzung, Beurteilung und Bewirtschaftung. *Schweiz. Zeit. Forstw.* 144, 115–132.

Hearn, G., Barret, R.K., McMullen, M.L. (1992) CDOT Flexpost rockfall fence development, testing, and analysis. In Rockfall Prediction and Control and Landslide Case Histories. pp 23–29. *Transportation research record* 1343, National Academy of Sciences, Washington, D.C.

Heidenreich, B. (2004) *Small- and half-scale experimental studies of rockfall impacts on sandy slopes.* PhD Thesis, EPFL, Lausanne, 231 pp.

Heim, A. (1932) Bergsturz und Menschenleben. *Beiblatt zur Vierteljahrschrift der Naturforschenden Gesellschaft in Zürich*, 77, 218.

Jahn, J. (1988) Entwaldung und Steinschlag, *International Congress Interpraevent*, Graz. Conf. Proc. Vol. 1, pp. 185–198.

Kienholz. H., Mani, P. (1994) Assessment of geomorphic hazards and priorities for forest management on the Rigi north face, Switzerland. *Mt. Res. Dev.* 14, 321–328.

Meißl, G. (1998). *Modellierung der Reichweite von Felsstürzen. Fallbeispeile zur GIS-gestützten Gefahrenbeurteilung aus dem Beierischen und Tiroler Alpenraum.* Ph.D. Thesis, Universität Innsbruck, Innsbruck, 249 pp.

Motta, R., Haudemand, J.C. (2000) Protective forests and silvicultural stability — An example of planning in the Aosta Valley. *Mt. Res. Dev.* 20, 180–187.

Nicot, F., Cambou, B., Mazzoleni, G. (2001) Design of Rockfall Restraining Nets from a Discrete Element Modelling. *Int. J. Rock Mech. Min. Science* 32(2), 99–118.

ONF, 2006. *Guide des sylvicultures de montagne.* ONF / CRPF / Cemagref, France.

Schwitter, R. (1998) Zusammenfassung und Schlussfolgerungen, In: R. Schwitter (Editor), *Dokumentation der 14. Arbeitstagung der Schweizerischen Gebirgswaldpflegegruppe mit der FAN 1998*, Grafenort / Engelberg, 1–5.

Selby, M.J. (1982) Controls on the stability and inclinations of hillslopes formed on hard rock. *Earth. Surf. Proc.* 7, 449–467.

Spang, R.M., Sönser, T. (1995) Optimized rockfall protection by "ROCKFALL". In: T Fuji (Ed.), *Proceedings of the 8th International Conference on Rock Mechanics*, 25–30 September 1995, Tokyo, Japan, 1233–1242.