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ROCKFALL, FOREST AND HUMAN INTERACTIONS IN THE EUROPEAN ALPS

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ABSTRACT

How much is a tree or a forest worth? There are many answers, depending on whom you ask. One of the valuable services a forest in the Alps provides is protection against natural hazards such as rockfall. Adequate management of a mountain forest that protects downslope areas against impacts of rockfall requires insight into the dynamics of the environment of the hillslope as a whole. Therefore, a combined approach, using field and modelling techniques, was applied to assess the determining factors for rockfall source areas, rockfall tracks and rockfall runout zones. The first question of this study was why rockfall occurs in the first place in the investigated area. The second question was if the knowledge obtained in the field could be translated into a model that simulates rockfall dynamics on a forested slope realistically and satisfactorily (i.e. with sufficient predictive power). The third question was how hillslope characteristics, forest stands and rockfall are interacting and what the role of humans herein is. This paper will answer these three questions. By doing so, it shows that a combined field and modelling research as applied in this study helps to understand the dynamics of rockfall in a protection forest and helps to gain knowledge for managing these forests.

Key words: Rockfall analysis, Protection forest, Human impacts

INTRODUCTION

How much is a tree or a forest worth? There are many answers, depending on whom you ask. The value of timber or what can be made out of the wood is usually the first value placed on a tree. There are many other valuable forest products and services, such as protection against natural hazards such as rockfall (Berger et al., 2002). Sometimes, adequate forest management aiming at optimal protection against rockfall could provide an alternative for expensive technical constructions that deteriorate with time. In Germany, these cost on average 1 million Euro per Hectare (Klein, 2001). In Switzerland, the total amount spent since 1951 is 1,5 billion Swiss Francs (BUWAL, 1999), but nowadays they reduced the amount of money spent on such

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constructions, since more and more technical constructions are being treated as complementary to the protection forests, if possible given the circumstances.

Yet, protection forests need minimum silvicultural interventions to sustain their protective function, because the protective function of the forests could decrease as a result of the continuous disturbance caused by impacts of falling rocks. But where, which and when these interventions have to be carried out requires insight into the dynamics of the environment of the forest hillslope, or the forest geo-ecosystem, as a whole. The first important factor to be known are the dynamics of the forest. These are strongly affected by rockfall, since the distribution as well as the frequency and magnitude of rockfall events determine the development of a forest covering the accumulation area of an active rockfall source area. The second factor to be known are the rockfall dynamics. The distribution of trees on a forested rockfall slope affects the distribution, frequency and magnitude of rockfall events (Jahn, 1988). In other words, there is an interaction between rockfall and forest cover and dynamics of a forested rockfall slope could only be studied by focusing both at forest characteristics and rockfall dynamics. Therefore, a combined approach, using field and modelling techniques, was applied to assess the determining factors for rockfall source areas, rockfall tracks and rockfall runout zones in protection forests in the Austrian Alps.

The first question of this study was why rockfall occurs in the first place in the investigated area. The second question was if the knowledge obtained in the field could be translated into a model that simulates rockfall dynamics on a forested slope realistically and satisfactorily (i.e. with sufficient predictive power). The third question was how hillslope characteristics, forest stands and rockfall are interacting and what the role of humans herein is. This paper will deal with these three questions. By doing so, it presents gained insight in the functioning of the geo-ecosystem of a mountain forest and the relevance of this knowledge for managing protection forests

THE STUDY AREA

The area investigated in this study was the "Ausserbacher" forest, which is located near the village of Gaschurn in the Montafon region in the western part of Austria, between 46°50´ and 47°8´ latitude and 9°41´and 10°9´ longitude. The altitude of the study area ranges from 930 m above sea level in the valley up to 1500 m above sea level. The forest in the area covers a south-southwest exposed slope, which may be divided in a source area that has slope gradients ranging from 50° to 90° and an accumulation area that has a mean slope gradient of 38° in the upper part and 27° in the lower part. The underlying geology is metamorphic bedrock, consisting of amphibolites, mica schist and white/grayish ortho-gneiss (granite bearing). The resistant amphibolites and gneisses were subject to strong glacial abrasion. Therefore steep cliff faces developed that are dissected by three major denudation niches, which are connected with distinct open tracks in the forest (Fig. 1). These faces are currently active rockfall source areas. The "Ausserbacher" forest is a typical mixed mountain forest, which is found on many vegetated talus/debris cones in the montane zone in the European Alps. The dominating species in the study area are primarily Norway spruce (Picea abies) and to a lesser extent sycamore (Acer pseudoplatanus), beech (Fagus silvatica) and hazel (Corylus avellana). The lower part of the study area is well accessible by two forest roads, which have been constructed for forest management practices.

ROCKFALL CAUSES IN THE STUDY AREA

To deal with the question why rockfall occurs in the study area we started with a reconnaissance of the area, including detailed geomorphological mapping at 1:2000 scale using the mapping system described by Seijmonsbergen (1992). We furthermore measured the slope gradient and the exposition of the slope face as well as the dip and strike of the bedding planes and the most prominent joint sets at 33 different locations in the rockfall source areas. These measurements were plotted in an equal area projection to carry out a Markland test (see Markland, 1972) in order to identify potential sliding surfaces resulting from discontinuities in the bedrock in relation to the orientation of the local topography (Fig. 2). We calculated a friction angle value of 37 degrees using the uni-axial compressive strength (see Carson and Kirkby, 1972), which was obtained from a uni-axial compression test applied on three amphibolite samples and on one gneiss sample, in combination with the *Hoek-Brown* criterion (Hoek and Brown, 1997).

Figure 2 shows that the two major joint planes (J1 and J2) create potential wedge failures as the point of intersection of the J1 and J2 circles lies between the friction angle circle and the great circle of the slope face. Especially in combination with the bedding plane that dips in opposing direction, thereby creating the 'roof' of potential falling rocks, wedge shaped blocks are easily produced (Fig. 2). In the field we observed that the orientation of both joint sets (J1 and J2) and the orientation of the bedding planes resulted in rocks breaking out at the bottom parts of the steep cliff face. This leads to undercutting of the slope face and subsequent migration of rockfall activity upslope. Fortunately, the joint spacing is generally small and therefore mainly small rocks are produced (rock diameter mainly between 0.25 m and 0.5 m).

Another factor, which also contributes to rockfall activity in the study area, is the presence of large tensional fissures in the area above the steep cliff face (Fig. 3). These fissures indicate large-scale rock creep. Parallel tensional rebound of the valley slope after glaciation during Late Glacial and Early Holocene conditions was probably the main cause of this. The effect, however, is increased by the presence of mica schist layers underneath the amphibolite and gneiss bedrock layers. The mica schist layers act as weak zones, which cause additional bulging forward and toppling of the creeping bedrock towards the valley. As a consequence, the steep cliff face maintains its steepness despite active mass wasting and therefore facilitates slope failures and resulting mass wasting.

Local inhabitants informed us that rockfall generally occurs in spring and after heavy rain, which was also observed during fieldwork. Unfortunately, the inhabitants were not able to tell which source areas particularly produce falling rocks. The transport channels visible in Figure 1 suggest that the main rockfall activity occurs within the denudation niches upslope of the transport channels. We observed, however, that the production of potential falling rocks in the study area was not merely concentrated within the niches, but all the steep cliff faces throughout the area acted as rockfall source area. After we completed the geomorphological map it was interesting to observe that the largest tensional fissures are aligned with the longitudinal direction of the denudation niches. This suggests that the weaker zones that are responsible for the development of the denudation niches have been predetermined by tensional fissuring.

REALISTIC SIMULATION OF ROCKFALL THROUGH A FOREST

To simulate rocks that collide with tree stems we developed a model that combines a process-based model to calculate the physical motions of a falling rock and a GIS-based model to account for different spatially distributed characteristics of the hillslope and the forest. The latter are the main input data of the model. The forest data were gathered by carrying out a detailed forest inventory using the probability proportional to size sampling within a grid with cells of 30 m × 50 m. The inventory provided standard forest parameters such as the number of trees per hectare, the diameter at breast height (DBH), the basal area and the height of the trees, but also the number of scars on tree stems caused by heavy impacts of falling rocks and the height of these damages on the tree stems. We combined these data with a map containing the spatial distribution of trees, which were obtained automatically from digital aerial photographs (see Uuttera et al., 1998). The Digital Elevation Model (DEM) with a resolution of 2.5 m × 2.5 m was obtained by interpolating contour lines. These were created on the basis of slope transects measured in the field, the detailed geomorphological field map and existing contour lines with an interval of 20 m. Other methods such as tachymeter measurements or digital photogrammetric height measurements were not possible. The data needed to calculate the energy loss during bounces on the ground, i.e. estimates of the elasticity and the number of various barriers or surface roughness, were derived from a detailed slope surface cover map (1:2000).

The developed model simulates a falling rock by calculating the kinetic energy balance during sequences of motion though the air and collisions on the slope surface or against trees. Start locations for the rockfall simulations were derived from field mapped rockfall source areas. From each start location one single falling rock was simulated. Standard algorithms for a uniform accelerated parabolic movement through the air calculated the motions through the air. Algorithms modified from Pfeiffer and Bowen (1989) calculated the energy balance before and after collisions with the slope surface and tree stems. The modifications were such that the factor compensating for the effect of the rockfall velocity on the elasticity of the collision was left out, because the empirical constants required to calculate it were not available for the study site. The algorithms for bouncing and motion through the air were combined with a procedure that calculated the fall direction using a modified multiple-flow algorithm (Wolock and McGabe, 1995). To randomise the fall direction from a raster cell for each simulation run, this method calculated a fall direction raster repeatedly each time by sampling the fall direction randomly from a probability distribution for each cell. The latter was determined by the steepness of the mean slope gradients between the central cell and all its downslope neighbouring cells. Technical details about the model and used algorithms are described by Dorren et al. (2003).

Validation data were extracted from geomorphological map. This map included the locations of recent rock accumulation areas throughout the test site. This could be determined first by the absence of mosses and vegetation covering the accumulated material and second by the relative age of the deposits as inferred from the slope morphology. Within the 18 validation squares (Fig. 4) we evaluated whether a cell that was predicted as being an end location of a falling rock was also mapped as a recent accumulation area. This provides a Boolean dataset with a modelled and a mapped value (rockfall accumulation: value=1, if not: value=0) for every cell within all validation squares. On the basis of this dataset we calculated an R-squared of 0.74. A black coloured cell shown in Figure 4 indicates that, at least during one simulation, a rock stopped within that cell. Thus it is also possible that a larger number of rocks stopped in that cell. This map only visualises the accumulation patterns, whereas the frequency map (not presented here) showed that most rocks stopped in the upper part of the accumulation area, where the dense black cloud is visible in Figure 4.

To analyse the change of the rockfall hazard if the protection forest continues to deteriorate, the simulation model, which seemed to predict current accumulation patterns satisfactorily, was used to test scenarios with a random tree distribution with 50% fewer trees (Fig. 4, case C) and with no trees covering the site at all (Fig. 4, case D). The results of these simulations show that the amount of rocks reaching the valley is still zero in case C. A distinct difference is that more rocks reach the upper forest road. In case D, however, many rocks reached the lower boundary of the test site. There, the velocities of the rocks were still approximately 20 m/s. As the simulation model predicts current accumulation patterns satisfactorily, we believe that it also confirms that the present rockfall activity within the denudation niches is comparable to the other steep cliff faces on the non-dissected mountain face between the large denudation niches. We also found indicators for this during the field work (freshness of joints, colour and roughness of the cliff face). The large denudation niches currently produce rocks that fall down and fill up local depressions between the larger talus cones in the upper part of the study area. Rocks originating from the large denudation niches fall down the slope into the forest and stop in local accumulation areas where the surface roughness is high because of previously deposited large rocks. Another observed feature is that rocks accumulate behind standing trees or felled trees that lie diagonally or perpendicular to the slope direction. Small rocks are deposited in the upper part of the accumulation area or even in the transport channel of the niches. Occasionally, rocks originating from the niches fall all the way down the existing transport channels underneath the denudation niches. Rocks that do fall through the transport channel gain a high velocity because the surface roughness in the channel is low and trees or shrubs are absent. The latter is due to the fact that falling rocks destroy seedlings. In addition, snow creep and snow avalanches starting in the denudation niches also contribute to restriction of growth or even removal of seedlings.

INTERACTIONS BETWEEN ROCKFALL, PROTECTION FORESTS AND HUMANS

The protection forest that covers the study area is almost continuously under attack by rockfall, but especially during the spring and after heavy rain. An increased tree density, both in the transport channel and in the source area, could reduce the impact of rockfall, snow creep and snow avalanches. Unfortunately, trees, shrubs and seedlings are absent at present in the transport channels shown in Fig. 1 and mentioned in the paragraphs above. In short, the degradation of the protection forest in the area underneath the denudation niches is currently a self-reinforcing process, which needs to be reversed. This situation is not only an effect of rockfall but also of human actions in the forest, other natural hazards and forest ecological processes. To explain the current situation some historical background is required.

Until 1960, up to 300 sheep grazed in the Ausserbacher forest during the months May, June and October. As sheep have a selective feeding behaviour, natural regeneration of deciduous trees and shrubs in particular, was suppressed. This had a long-term effect on the species composition of the forest. Indicative is that the present coverage of beech (*Fagus sylvatica*), is not more than 10%, although the potential natural forest community up to an altitude of 1050 m corresponds to a beech-dominated one. After 1960, two feeding stations for deer and roe deer were installed on the foot slope of the Ausserbacher forest, which then served as a winter habitat for ungulates for over two decades. The increased ungulate population resulted in an enormous browsing pressure, which was identified as the main cause for the lack of natural regeneration, which is a known problem in the Alps (Motta, 1996). In addition to the direct and indirect human interference there has been a permanent impact of natural disturbances such as rockfall, snow avalanches and wind, of which rockfall has always been the most dominant disturbing agent in the Ausserbacher forest.

In 1988 the protective function of the forest reached a critical level because firstly most of the trees had been damaged by rockfall while substantial regeneration was lacking and secondly, the forest was prone to wind throw. The latter had already caused gaps in the lower parts of the forest. These had been widened by a subsequent bark-beetle invasion (see Fig. 5, situation 1988). Therefore, the local forest authority initiated a rehabilitation project to improve the forest structure. The ideal structure of a protection forest, mainly composed of the tree density, the diameter distribution as well as the gap size and the vertical layering, depends on the type of natural hazard the forest should protect against. Currently, foresters and researchers believe that management should aim at a large number of trees per hectare, rather than having tick tree stems. Generally is agreed that gaps in the forest should not exceed a length of 20 m in the direction of the slope.

To assess the true status of the forest, a inventory was carried out in 1988, during which the developmental phases of the forest were mapped using the method described by Leibundgut (1959). About 84% of all the trees in the Ausserbacher forest were damaged by rockfall. About 45% of the total forest area was in a so-called ageing phase (Fig. 5), which was amongst others indicated by a low tree density of 290 trees per hectare. At first sight these stands appeared stable against wind throw because of the varying horizontal and vertical structure. But the high percentage of trees with heart rot reduced this apparent resistance. Crucial for the prospective stand development was the lack of regeneration. Twenty-two percent of the forest was identified as being in an optimal phase in terms of stand development and had an average number of 560 trees per hectare. These forest stands were spruce-dominated and mainly structured in homogeneous single-layers. It was to be expected that this homogeneous structure would not change in the future. Only 19% of the area could be classified as a so-called selection forest with has a preferred multi-layered structure and a mosaic of ageing, breakdown and regeneration phases.

The unstocked channels exist due to snow gliding, intensive rockfall and the browsing pressure. In 1988, these areas accounted for 14% of the total potential forest land. It would be impossible to achieve regeneration without a reduction of the browsing pressure of ungulates and the construction of avalanche barriers in these areas. On the basis this of the previously described information, the local forest authority regarded firstly the reduction of ungulate population, secondly the improvement of the accessibility via forest roads and thirdly the construction of avalanche barriers and rockfall nets in the major gully as urgent. These measures were a prerequisite for 1) small-scale felling with on-site deposition of trees diagonal to the mean slope gradient, 2) narrow irregular stripe felling by means of cable cranes all arranged diagonal to the slope direction, 3) reafforestation of unstocked forest land and 4) coppicing hazel shrubs to stimulate its growth. All these measures aimed at achieving the optimal condition with respect to protection against rockfall that is feasible and sustainable. Most optimal would be a high tree density and tree stems as thick as possible. These two factors are, however, related to two different developmental stages of a forest, being regeneration/transition and optimal phases. Moreover, it is impossible to maintain a forest in a certain ‘desired’ condition over a long period of time because a forest is a dynamic system and therefore subject to change (Brang, 2001). Thus by taking these measures the local forest authority aimed for a mosaic of stand patches at different developmental stages. In order to achieve such a mosaic, the homogeneous optimal and optimal/ageing stands in particular had to be split up into smaller patches. By means of the irregular stripe felling these patches were created and regeneration phases were initiated. Once

Figure captions

Fig.1: Photograph from 2001 showing the study area. The arrow pointing to the map of Austria indicates the location of the study area. The white outline demarcates the test site used for simulation modelling within this study. The numbers indicate the three denudation niches and the associated transport channels.

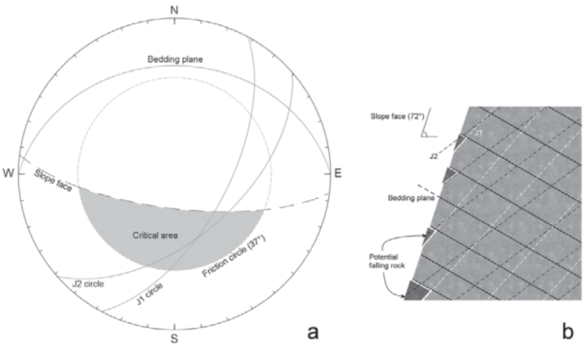

Fig.2: a) The lower hemisphere projection of an equal area net showing the great circles of the slope face, the bedding planes and the two most prominent joint sets (J1 and J2). b) Two-dimensional visualisation of the effect of the intersection of the bedding planes and the joint sets in the rockfall source areas in the study area.

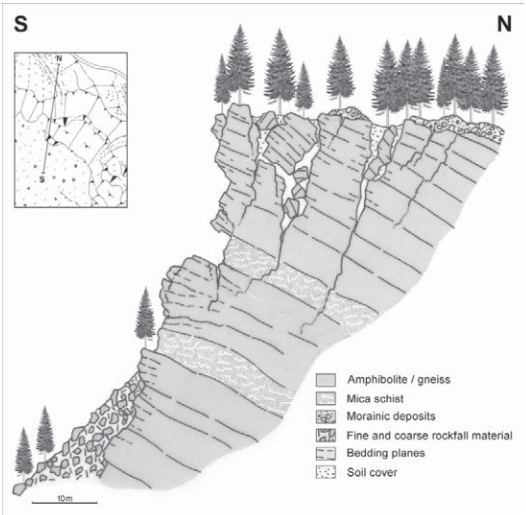

Fig.3: Cross section showing internal rock deformation due to active large-scale tensional fissuring in the area above the steep cliff faces. The inset shows a part of the geomorphological map of the source area and the location of the cross section.

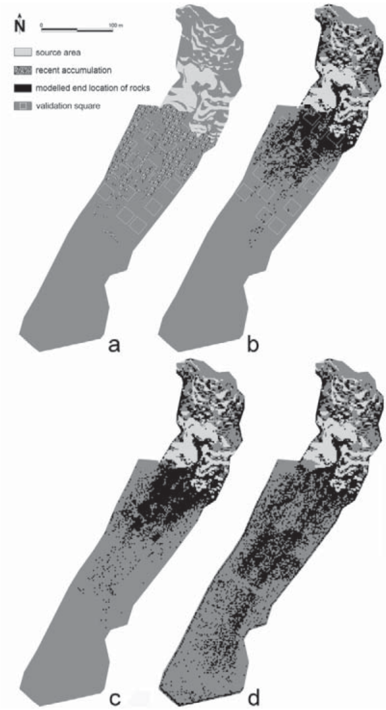

Fig.4: Validation data and results of the simulations: a. Map showing the active or recent accumulation areas, as derived from the geomorphological map and field observations; b. Map showing the simulated end locations using the current situation in the field; c. idem., only with 50% less tree density; d. same simulation, only without forest cover. All the graphs are the result of 100 simulation runs with a rock radius of 0.25m.

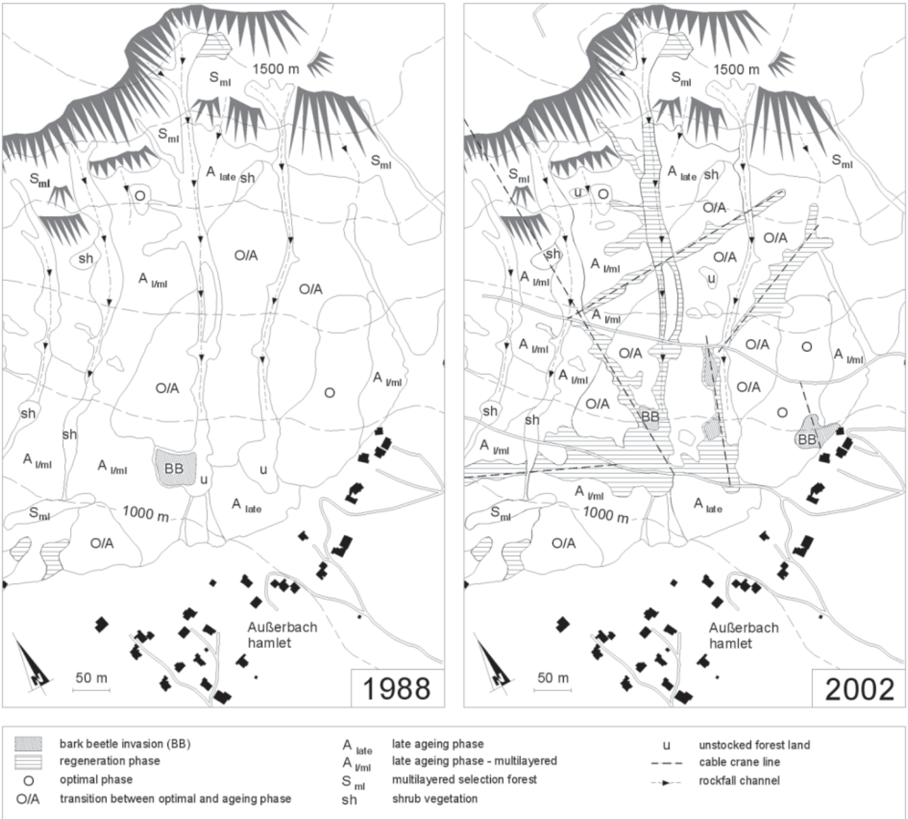

Fig.5: Distribution of developmental phases, disturbances and silvicultural measures in the Außerbacher forest in 1988 and in 2002.

regeneration in a previously felled stripe has reached a secure stage, the mosaic-creation process will be continued by additional stripe felling using cable crane lines. This process has to be carried out during a whole developmental cycle of a stand, which takes about 200 years, in order to obtain phase-shifted mosaic structures (see Otto, 1994).

In sparsely stocked ageing stands, cable crane logging is inappropriate as excessively large gaps could come into existence. In such stands only relatively few trees were felled in carefully selected positions in order to initiate regeneration. The cut stems were left on site and deposited diagonal to the slope direction in order to decelerate and to redirect rockfall. Stems that are deposited perpendicular to the slope direction result in large rock accumulations behind them and possibly in rock avalanches once the stems have decayed. The local forest authority observed that in the course of felling activities the vulnerability to bark beetle infestation increased due to bark damages, sunburn on the stem, which reduces the sap flow, and the attraction of bark beetles by left slush timber. During warm and dry summers this indeed resulted in two subsequent bark beetle invasions (see Fig. 5), but fortunately it was observed that bark beetle impact contributed to the mosaic creation process. When comparing the situation of 1988 and 2002 it can be seen that 15% of the optimal phase changed into a regeneration phase. Furthermore, 32% of the unstocked forest land and areas covered with shrubs also showed regeneration. In summary, the protective function of the Ausserbacher forest seems to improve slowly but steadily at present.

CONCLUSIONS

Finally, we believe that a combined field research and modelling approach as applied in this study is a prerequisite for better understanding the dynamics of rockfall on a forested slope. It also helps to gain knowledge for managing protection forests. For a true understanding of the feedbacks between rockfall and forest growth, for example to predict the long-term effects of forest management interventions, we recommend the development of a dynamic rockfall - forest growth model.

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LITERATURE

Berger, F., Quetel, C. and 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. Congress publication, volume 2; pp. 815-826.

BUWAL (1999): "Leben mit dem Lawinenrisiko. Die Lehren aus dem Lawinenwinter 1999". *BUWAL*, Bern; 27 pp.

Carson, M.A., Kirkby, M.J. (1972): "Hillslope form and process." *Cambridge University Press*, Cambridge; 475 pp.

Dorren, L.K.A., Maier, B, Putters, U.S. and Seijmonsbergen, A.C. (2003): “Combining field and modelling techniques to assess rockfall dynamics on a protection forest hillslope in the European Alps.” In press in *Geomorphology*.

Hoek, E., Brown, E.T. (1997): ”Practical estimates of rock mass strength.” *International Journal of Rock Mechanics and Mining Science* 34 (8); 1165-1186.

Jahn, J., (1988): ”Entwaldung und Steinschlag”. *Interpraevent*, Graz. Tagungspubl. Bd.1; pp. 185-198.

Klein, H. (2001): “Die Bedeutung des Waldes für den Natur- und Umweltschutz in Deutschland. 10 Argumente für den Wald“. *[Online] URL: http://home.t-online.de/home/WaldKlein/.*

Leibundgut, H. (1959): “Über Zweck und Methodik der Struktur- und Zuwachsanalyse von Urwäldern.“ *Schweizerische Zeitschrift für Forstwesen* 110; 111-124.

Markland, J.T. (1972): ”A useful technique for estimating the stability of rock slopes when the rigid wedge sliding type of failure is expected.” *Imperial College Rock Mechanics Research Report* No. 19.

Motta, R. (1996): ”Impact of wild ungulates on forest regeneration and tree composition of mountain forests in the Western Italian Alps.” *Forest Ecology and Management* 88, 93-98.

Otto, H.J. (1994): “Waldökologie.” *Verlag Eugen Ulmer*, Stuttgart; 391 pp.

Pfeiffer, T.J., Bowen, T.D. (1989): “Computer simulation of rockfalls.” *Bulletin of the Association of Engineering Geologists* XXVI (1); 135-146.

Seijmonsbergen, A.C. (1992): “Geomorphological evolution of an alpine area and its application to geotechnical and natural hazard appraisal in the NW. Rätikon and S. Walgau (Vorarlberg, Austria), including map series at 1:10,000 scale.” *PhD Thesis, Univ. of Amsterdam*, Amsterdam; 109 pp.

Uuttera, J., Haara, A., Tokola, T., Maltamo, M. (1998): ”Determination of the spatial distribution of trees from digital aerial photographs.” *Forest Ecology and Management* 110; 275-282.

Wasser, B. and Frehner, M. (1996): “Minimale Pflegesmassnahmen für Wälder mit Schutzfunktion.“ Wegleitung. *BUWAL*, Bern.

Wolock, D.M., McCabe-Jr., G.J. (1995): “Comparison of single and multiple flow direction algorithms for computing topographic parameters in TOPMODEL.” *Water Resources Research* 31 (5); 1315-1324.