Integrating forests in the analysis and management of rockfall risks: experiences from research and practice in the Alps

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Citation: Dorren, L.K.A. & Berger, F. 2012. Integrating forests ... . In: Eberhardt et al. (eds). *Landslides and engineered slopes: protecting society through improved understanding*. Taylor and Francis Group, London: pp 117 – 127.

ABSTRACT: The protective effect of forests against rockfall cannot be neglected in risk management. This is, of course, under the condition that a considerable slope length in the transit area is forested and that a tree diameter distribution which can provide sufficient resistance against the falling rocks is present. Recognizing that forests offer protection against rockfall is one matter, quantifying this effect is another. The last 15 years we have been working on different aspects of the interaction between forests and rockfall. Carrying out full-scale rockfall experiments on both forested and non-forested slopes enormously improved our understanding. These experiments, which were carried out from 1997 onwards, allowed for the development of rockfall protection forest management guidelines, as well as an efficient rapid assessment tool. In parallel, we developed a 3D rockfall trajectory model (Rockyfor3D), which, if chosen by the operator, explicitly and realistically takes into account the effect of standing trees on rockfall kinematics and trajectories. At present this model is being used by many practitioners throughout the world, most of them, however, working in Switzerland, Austria and France. The model allows risk-based analyzes of the efficacy of forests against rockfall at any study site. As such these protection forests can be compared with technical protective measures on the basis of cost-benefit analyzes. We present a short review of rockfall forest research and describe results of the full-scale rockfall experiments on non-forested and forested slopes. Further, we briefly explain the rockfall model Rockyfor3D, the rapid rockfall-protection-forest assessment tool, the advantages of airborne laser scanning for forest mapping, examples of cost-benefit studies on rockfall protection forests in the Alps, as well as an example of eco-engineering in rockfall protection forests.

1 INTRODUCTION

On forested slopes below steep cliff faces where rockfall is active, one can observe the protective effect of forests. Typical evidence to be found are blocks deposited behind or between trees (Fig. 1), or impact scars on stems in the transit area. Although the rockfall event of the May 2006 on the Gotthard highway in the Swiss Alps caused two casualties, this event showed that forests can significantly mitigate rockfall hazards, even in the case of a rock slide of more than 10,000 m3. Here, only about 15% of the large blocks reached the highway, all the others were stopped in the forest. Without forest cover, the probability of impacting other vehicles would have been dramatically higher.

Figure 1. Typical scene from an active rockfall slope in the Alps covered by a forest. The photo shows a 1 m3 block stopped by beech trees with diameters ranging from 20 – 40 cm.

In the Alps, the protective effect of forest has been recognized since centuries, as evident from to logging bans that were declared from approximately 1350 onwards. During recent decades the damage potential, and therefore the importance of protection forests, has increased. Remote mountainous areas that were formerly avoided in winter time are now expected to be permanently and safely accessible for tourists. Moreover, settlements have been spreading into areas that were considered unsafe in the past, and infrastructures crossing the Alps (traffic ways, power lines, etc.) have greatly increased (BUWAL, 2001).

As a result, large investments in protective measures have become necessary. For example, in the last decade, the Swiss government has spent between 250 – 300 million CHF per year for protective measures against rockfall, avalanches, landslides and debris flows. Approximately 60% of this amount was spent for measures to maintain or enhance the protective effect of the forests.

Parallel to the investment in the current management practices in protection forests, research has been initiated to improve the knowledge on both the protective effect of forests against natural hazards as well as on the management of protection forests. This has led to a range of tools that better quantify the protective effect of forests and the implementation of new guidelines for the management of protection forests.

In this paper we first give a short background in rockfall forest research. The subsequent sections provide an overview of 15 years of our research and practical experiences in the field of rockfall and protection forests. During this period, we have developed two complementary approaches. The first one is based on field observations and robust data acquisition and the second one is based on modeling. The combination of these two approaches helped us in identifying knowledge gaps and partly eliminating some of them. Section 3 presents the results of the full-scale rockfall experiments we carried out since 2001. Then we present the development of the 3D rockfall simulation model Rockyfor3D (Section 4), which has been developed since 1998. Section 5 presents a rapid assessment tool for predicting the protective effect of a forest against rockfall. Section 6 describes three examples of recent developments and applications: 1) the use of laser scanning for protection forest mapping and characterization, 2) eco-engineering in protection forests and 3) examples of cost-benefit studies on rockfall protection forests in the Alps. In the last section, we present the main conclusions.

2 BRIEF HISTORICAL BACKGROUND OF ROCKFALL AND FORESTS

Research on rockfall and forests can be divided in three groups on the basis of a spatial scale: 1) research at the scale of a single tree or a single rebound, 2) at the scale of a single slope, meaning from the release to the deposit area and 3) at a local or regional scale.

One of the first reports known to the authors that quantify the energy dissipation of different tree species using impact tests, both in the laboratory and in the field, is published by Couvreur (1982). A few years later, Jahn (1988) published a study on a slope scale, during which full scale rockfall experiments, with small rock dimensions (diameter up to half a meter). These experiments were carried out on a non-forested and a forested section of a 35.5° slope between an upper and lower forest road in Liechtenstein. In parallel, the protective effect of forests has often been reported in geomorphological studies on hillslope processes, in which rockfall was not the primary focus, as for example in Hétu & Gray (2000).

Additionally, rockfall impact wounds on trees have been used, in combination with positions of impact craters on the ground, to recalculate parabolas of single rockfall rebounds. A good description for doing this has been developed in 1993 by Gerber and is recently published in English (cf. Volkwein et al. 2011). Gsteiger (1993) presented the concept of the “mean tree free distance”, which could be used for a rapid assessment of the protection provided by a forest stand against rockfall. This value refers to the statistical mean distance a rock travels between two tree contacts.

A completely different type of research, both at the scale of a single tree as well as a single slope, is dendrogeomorphology, which effectively uses tree-ring series to reconstruct rockfall activity, depending on the available tree stems (cf. Stoffel 2006). In this type of research, tree-ring series are analyzed visually to identify growth disturbances caused by past rockfall. It is based on tree cores samples that are extracted with increment borers, which are then polished and the tree rings counted.

Advancements in the work on rockfall and forests at the local or regional scale have been very much related to the development of Geographical Information Systems (GIS) and the availability of digital terrain models (DTM) (cf. Berger 1997). In parallel, the development of simulation models have allowed for rockfall hazard zoning for entire regions (e.g., Van Dijke & van Westen 1990; Dorren & Seijmonsbergen 2003).

As in all research fields, models have always played an important role, both for gaining a better understanding of the studied phenomena and for prediction. In the field of rockfall, the first model was conceptualized by Heim (1932). This model, the so-called energy line concept or in German *Fahrböschung*, is still a widely used and robust method for a quick initial rockfall hazard assessment at the scale of a single slope, a locality, or an entire region.

In our approach, we consider the forest equal to all other types of technical protective measures, both from the point of its proper resistance capacity and serviceability. Historically in the Alps, technical protective measures have been put in place on non-forested slopes or on slopes where forests did not or could not provide sufficient protection. As an aside, this practice is reflected by many forest acts, as for example, in Austria, France and Switzerland. On those slopes where the forest effectively served its mitigating role, it became increasingly important to maintain or optimize the protective forest structures. For doing so, adequate knowledge and tools were missing. For example, the energy line approach does not allow for analyzing the optimal position and dimension of protective measures. Also missing specifically for protection forests was knowledge on the evolution of forest stands given anthropogenic and natural disturbances (e.g., management, avalanches, rockfall, wind-throw, etc.). Therefore, the last two decades of research on rockfall on forested slopes intensified, in various fields including, rockfall simulation models that account for the effect of trees (cf. Cattiau et al. 1995, Dorren et al. 2004, Lehir et al. 2006, Rammer et al. 2010), field studies on the protective effect of forests against rockfall (Perret et al. 2004, Amman 2006), resistance of single trees (Jonsson 2007, Kalberer 2007, Lundström 2010), the protective effect of coppice stands (Jancke et al., 2009), the use of laser scanning data for automated characterization of rockfall protection (Monnet et al. 2010a), and spatio-temporal analyses of silent witnesses of rockfall using dendrogeomorphology (e.g., Schneuwly & Stoffel, 2008).

3 FULL-SCALE ROCKFALL EXPERIMENTS

About 15 years ago, there was a lack of quantitative, statistically valid data on the protective effect of forests against rockfall. To quantify the velocities, rebound heights, , the residual hazard of rockfall on a forested and a non-forested slope, and also to evaluate existing rockfall protection forest management guidelines, we carried out full-scale rockfall experiments.

3.1 *Setup*

The site where we did these experiments was located in the Forêt Communale de Vaujany in France (lat 45°12', long 6°3'), which has an altitude ranging from 1200 m to 1400 m above sea level. It covers a forested, northwest-facing Alpine slope, with a mean gradient of 38º. 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%).

We defined two adjoining sites on a hillslope that is formed by a huge, post-glacial talus cone, consisting primarily of rock 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 denuded of trees. Between the starting point and the lower forest road, it has the morphology of a real channel.

Site 2 is 53 m wide and 223.5 m long and is covered by forest. Both sites uniformly slope approximately 38º. On Site 2, we measured and mapped 271 trees, 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), and the measured total basal area was 29.5 m2 (31.6 m^2 ha^{-1}). 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 useful for our full-scale tree impact analyses before they impact any trees.

The sites are easily accessible by a forest road, which was used by trucks to deliver the rocks for the experiments as well as by the excavator/dozer?? that released the rocks down the slope. A river delimits the base of the site, which excludes any object that could be at risk during the rock-rolling experiments. The site is representative of many active rockfall slopes in the European Alps with regard to its slope surface and forest stand characteristics.

At Site 1, the experiments were carried out in 2001, and at site 2 they were carried out in 2002 and 2003. Five high-speed digital video cameras were installed along the slopes at a height of 10 m in trees situated 30 m – 40 m away from the central rockfall paths. 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 an excavator. 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 for 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. If they occurred, we measured all the impact damage to trees. We painted the released rocks with biodegradable colored 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.

3.2 *Data analysis*

In total, we digitized the trajectories of 100 rocks at Site 1 and 102 rocks at Site 2. 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. We analyzed the digital films of the rockfall trajectories using a free downloadable program called AviStep 2.1.1. This program allows for extracting the position and the velocity of a moving particle for each individual image in a digital film.

We measured the rockfall velocities and the rebound heights, defined as the maximum-reached vertical height between the center 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 recognize. More details on the experiments are published in Dorren et al. 2005.

3.3 *Key Results*

There are significant differences between the non-forested site (Site 1) and the forested site (Site 2), regarding the rockfall velocities and the rebound heights. The mean of all the maximum velocities of the 100 analyzed rocks at Site 1 was 15.4 m s^{-1} (std. dev. = 3.4 m s^{-1}) and the maximum velocity measured in 2001 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). In the years following the experiment, we measured 31.2 m s^{-1}. 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 maximum velocity for the 102 analyzed rocks at Site 2 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 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}.

The residual hazard of the forest stand at Site 2 was 34%, which means that 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 only 11 rocks (11%) stopped before that. At Site 1, 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 involves 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 was strongly determined by tree impacts.

Some of the impacts caused an instantaneous breakage 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 lose their top. In other cases, the tree was 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 shards.

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 where the rocks were released. After releasing 78 rocks, such a path had evolved.

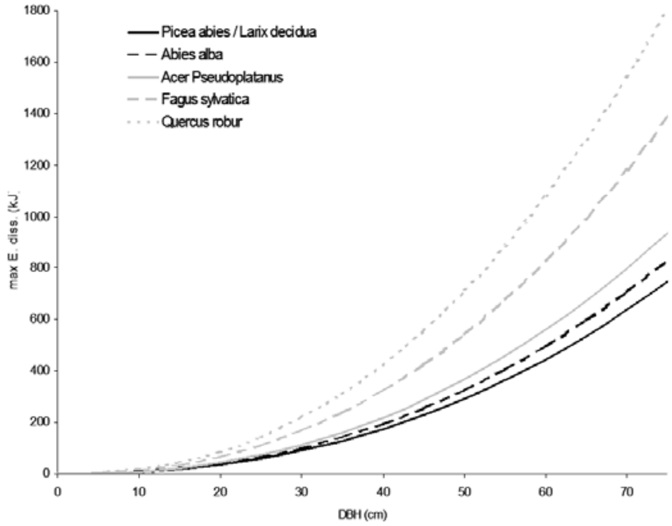

Figure 2. Relationship between the maximum amount of energy that can be dissipated by 6 different tree species (max E. diss. in kJ) and its diameter at breast height (DBH in cm).

The recordings of nine impacts causing instantaneous breakage of *Abies alba Mill.* trees were analyzed in detail. An exponential relationship between stem diameter at breast height (DBH) and the maximum amount of energy a tree can dissipate was highly correlated for all of our experimental data. We applied this relationship to other tree species based on published fracture energies (Fig. 2). The relationships obtained for *Cedrus spp*., *Fagus sylvatica L.* and *Picea abies (L.) Karst.* were significantly correlated with data from other dynamic impact tests in the field and with maximum bending moments obtained from tree-pulling experiments. Details on energy dissipation of trees during rockfall impacts are described in Dorren & Berger (2005).

4 THE DEVELOPMENT OF ROCKYFOR3D

Another important activity during the last 15 years has been the development of Rockyfor3D, which has been done in parallel to the full-scale experiments. Rockyfor3D is a simulation model that calculates trajectories of single, individually falling rocks, in three dimensions (3D). The model combines physically-based, deterministic algorithms with stochastic approaches, which makes Rockyfor3D a so-called ‘probabilistic process-based rockfall trajectory model’. Rockyfor3D can be used for regional, local and slope-scale rockfall simulations.

Rockyfor3D has originally been developed by the first author since 1998, initially on the basis of earlier work on rockfall simulation models (e.g., Habib 1977; Azimi et al. 1982; Bozzolo & Pamini 1986; Spang 1988; Pfeiffer & Bowen 1989; Van Dijke & Van Westen 1990; Descoeudres 1997; for a detailed overview see Guzetti et al. 2002 or Volkwein et al. 2011). Later it has been developed further on the basis of personal field observations, experiments with the team of Frédéric Berger, and simulation tests with many self-developed or other published model algorithms. Especially the full-scale rockfall experiments described above, as well as the numerous hazard analyses that have been completed with the help of the program, led to major improvements.

The evolution of Rockyfor3D is recorded under different names (Rocky3, RockyFor) in a series of scientific articles (Dorren & Seijmonsbergen 2003; Dorren et al. 2004; Dorren et al. 2006a; Stoffel et al. 2006, Bourrier et al. 2009). In 1998, programming started in Matlab, but recently the model has been coded in C, which has led to an enormous reduction of computation time (30 to 100 times faster).

The specialties of Rockyfor3D are:

- The rock-size-dependent treatment of the rebound calculation, which also includes the penetration depth in different soil types.
- A transparent and more objective estimation in the field of the parameters required for calculating the tangential coefficient of restitution.
- The combined physical-stochastic solution for calculating the fall direction of the blocks, which allows calculating a 3D movement vector of the falling block.
- The possibility of explicitly integrating the barrier effect of individual tree stems, with specific tree positions and stem diameters in each calculated trajectory.

The required input data consists of a set of ASCII rasters (ESRI format), which define the topography and the slope surface characteristics, as well as a set of parameters that define the release conditions. The output raster maps provided by Rockyfor3D are:

- the mean of the maximum kinetic energy values (translational + rotational; in kJ) of all the simulated blocks in a given cell.
- the 95% confidence level (CL) of all maximum kinetic energy values (in kJ) recorded in each cell.
- the mean of the maximum passing height (in m; measured in normal direction to the slope

surface) of all blocks that passed through the cell.
- the 95% CL of all maximum passing height values (in m; measured in normal direction to the slope surface) recorded in each cell.
- the number of blocks passed through each cell (# of passages).
- the number of source cells “feeding” a given cell. In other words, this map shows for each cell, from how many different source cells the blocks arrived in that given cell.
- The reach probability (# of passages*100) / (# of simulations per source cell * # of source cells; in %). This map shows whether it is probable (higher values in the map) or improbable (lowest values > 0 in the map) that a rock arrives in a given cell.
- the number of blocks stopped in each cell.
- the maximum block volume (in m^3) stopped in each cell.
- a raster map with the minimum recalculated energy line (EL) angles per cell (in °). The energy line angle (cf. Heim 1932; Jaboyedoff & Labiouse 2003) is the slope angle of a virtual direct line between the stopping location and the source location of a fallen block. This raster map can be useful to compare EL angles calculated from Rockyfor3D simulations with commonly used EL angle values (27° – 33° in the case of non-forested slopes and higher values for forested slopes).
- the minimum time needed to reach a raster cell from the defined source areas[s].
- the absolute maximum simulated velocity per raster cell (m/s). This data should be used with caution as there is no further information on the statistical distribution of the block velocities; the output was added on request.

In case of a “with-forest” simulation, the following two rasters are additionally created:
- the maximum tree impact height per raster cell (in m).
- the number of tree impacts per raster cell.

All the output raster maps are in ESRI ASCII Grid (raster) format and can be directly opened and visualized in most GIS software. In some cases an import in the GIS program will be necessary. Rockyfor3D is freely available for all members of the association ecorisQ (www.ecorisq.org). By doing so, the model is being used by experts all over the world and their feedback leads to continuous improvement of the model. An important future activity is the integration of the Goldsmith equations (cf. Bourrier & Hungr, 2011) in the current rebound algorithm. Details on the program can be found in Dorren (2012), freely downloadable from the website of the association.

5 RAPID ASSESSMENT TOOL

5.1 *Introduction of Rockfor.net*

At the request by some who are responsible for the protection provided by forests, we developed a more rapid assessment tool referred to as Rockfor.net. (www.rockfornet.net). This tool does not require a large terrain mapping effort, in contrast to Rockyfor3D, quantifies the protective capacity of a forest, and considers the size and energy of the falling rock. There were three reasons to undertake this effort. Firstly, these individuals are responsible for deciding which forests require silvicultural interventions to prevent an increase of the risk posed by rockfall. Due to the natural evolution of forest stands, the protective capacity against rockfall of a forest changes over time (Ott 1978, Brang 2001). “Curative” silvicultural interventions should maintain the forests in an optimal state regarding their protective capacity. Secondly, quantifying the protective potential of a forest stand allows for mapping forest zones where a protective function should be assigned. Thirdly, such a tool provides for more detailed site investigations of local rockfall hazards, and better targets future investments in rockfall protection using a combination of civil engineering and forest management techniques.

Rockfor.net calculates the protective capacity of a forest stand using a small dataset formalized in a user-friendly tool. The input data gives a global representation of reality and needs to be recorded at the scale of a single slope or an entire forest stand.

5.2 *Basic Principle of Rockfor.net*

The underlying principle of Rockfor.net is that the existing forest is considered as a sequence of open rockfall nets that consist of a row of trees, hereafter referred to as curtains. Rockfor.net begins by calculating the total energy developed by a falling rock, as calculated with the energy line principle. Then it calculates the energy dissipative capacity of each curtain and the number of curtains required for dissipating the total energy of the rock. Subsequently, the required number of curtains is converted in a required basal area using the mean DBH. Finally, Rockfor.net calculates the basal area that is theoretically encountered by the rock when it falls through the given forest. The protective role of the forest against rockfall can subsequently be quantified by comparing the required basal area with the theoretically encountered basal area. All these steps, as well as the calibration of the parameters needed for the calculations performed in these steps, are explained in detail in Berger & Dorren (2007).

5.3 *Validation and use of Rockfor.net*

To evaluate the performance of Rockfor.net we validated the developed tool with either: 1) past rockfall events, 2) rockfall forest inventories during which the terminal positions of previously fallen rocks in forests were mapped, or 3) data from rockfall experiments other than those carried out at our test site in Vaujany. In Berger & Dorren (2007), we summarize 7 validation cases including the input parameters used for Rockfor.net, as well as the real and calculated probable rockfall hazard at the foot of the forested slope. The tool has been online and in use worldwide since 2005, but its use has mainly been in the European Alps. Currently, Rockfor.net is being used for a revision of the Swiss rockfall protection forest guidelines NaiS (Frehner et al. 2005).

6 RECENT DEVELOPMENTS AND APPLICATIONS

6.1 *LiDAR-based forest mapping*

Reliable data on the structural characteristics of mountain forest stands with high spatial resolution is not only required for integrated natural hazard and protection forest assessment, but also for decision-making for protection forest management. Such data can be provided by airborne laser scanning (ALS).

The applications of ALS for forestry have been identified since the late 1990s, and numerous studies have shown its accuracy for the retrieval of tree and stand characteristics (an overview of the applications of small-footprint laser scanning in boreal forests can be found in Hyyppä et al., 2008).

Our ALS-forest mapping research focuses on two main approaches: 1) image-processing methods using a raster image of the vegetation height as input to delineate single trees, and 2) statistical methods using the raw point cloud to establish relationships between laser metrics and stand attributes. Most studies mainly focused on coniferous stands with gentle topographic conditions (e.g., Maltamo et al., 2005, Hyyppä et al., 2008); however, many authors have shown its efficiency in hardwood forests in Canada, and mixed forests in an alpine environment (Popescu et al. 2002, Zimble et al. 2002, Lim et al. 2003, Dorren et al. 2006b, Heurich & Thoma 2008, Monnet et al. 2011,).

Available studies generally show that methods based on the identification of local maxima in ALS data accurately identify the height and position of dominant individual trees, also in steep terrain. To achieve acceptable accuracies of the outcomes, such tree-top-detection algorithms require precise, study-area-dependent calibration. Clusters of multiple trees growing close to each other are detected as single tree crowns, and understory vegetation is frequently undetected. Therefore, the number of trees detected by ALS is systematically underestimated. On average our studies show that only 65 – 80% of the dominant trees are detected by ALS in steep mountainous terrain (cf. Dorren et al 2006b, Monnet et al. 2010b).

The accuracy of ALS-based predictions of different forest structural characteristics can generally be summarized as follows (cf. Monnet et al. 2010a, 2011): results are satisfactory for mean diameter and dominant height, with coefficients of variation of the root-mean-square error of ~10 - 15% in the cross validation with terrain inventory data. Accuracy then decreases for basal area (~15 - 20%) and stem density (~25 - 30%). The DTM of steep mountainous terrain provided by LiDAR, and the positions and heights of individual trees automatically derived from the ALS, have an enormous added value for natural hazard simulation models in comparison with traditional (lower resolution) DTMs derived from stereo aerial photographs and tree positions derived from orthophotos.

Figure 3. Eco-engineering for rockfall mitigation in a protection forest using obliquely felled trees.

6.2 *Eco-engineering and rockfall protection*

In Austria, but also increasingly in Switzerland and France, the effects of the presence of couloirs or larger openings in protection forests are mitigated by cutting trees and 1) leaving the tree stumps that remain after cutting as high as possible (> 1.3 m) and 2) positioning the felled stems 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 trunks on top of each other, are clearly more effective barriers), tree instability, the effect on tree regeneration, the size of the gaps after cutting, as well as the shadow effect. That is, in protection forests, trees tend to grow behind each other, i.e., the older tree protects younger trees downslope (see Dorren et al 2005).

Another important aspect is the direction in which the felled trunk is positioned on the slope. A choice can be made to direct 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). Alternatively, if the couloir has become a real channel, in which forest regeneration is inhibited, all the rocks could be directed into this channel by using accurately positioned felled trunks that orient rocks towards this channel. 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.

To test the efficacy and the durability of such diagonally felled trees we started research projects in which 1) experiences from practitioners as well as resistance measurements on the durability of felled stems were collected and 2) full-scale rockfall experiments on felled stems were carried out.

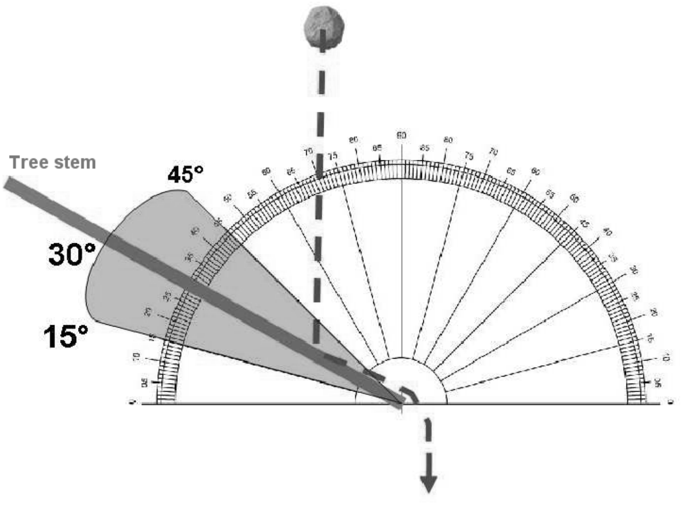

Figure 4. Representation of the range of optimal angles (gray zone) for stems positioned oblique to the steepest slope direction or the main fall direction of the rocks (dashed line).

The first results indicate that beech stems maintain sufficient resistance for a period of 5 and 7 years, while coniferous trees may last 10 to 15 years. The duration of functionality depends primarily on the number of rockfall impacts, the impact energy and the degree of destruction after a rockfall impact, but also on decay, which depends on the slope exposition, the rainfall regime and the how the base of the stem is embedded in soil material. The research has further shown that the felled trees have a significant effect on the energy loss (in average 30% during an impact on a felled stem) and on the fall direction of the rock. If all the stems are oriented in the same direction, laboratory experiments showed that the rock effectively changes its direction. The results also indicate that the most optimal orientation of the stems would be between 45° and 70° less than the steepest slope direction (slope aspect) (see Fig. 3).

6.3 *Economic evaluation of protection forests*

The protective effect of a protection forests can also be assessed in economically, as is currently being done in the Swiss project Protect-BIO, in which the effect of the forest on gravitational hazard processes is evaluated in three steps. It starts with (1) a general assessment, followed by (2) an assessment of the protection forest characteristics, and finally (3) a quantitative assessment of the protective effect. The hazards accounted for are snow avalanches, rockfall, shallow landsliding and local flooding/debris flows. The ultimate goal of the quantitative assessment is to be able to carry out cost-benefit analyses of protection forests in a similar manner as is being done for technical protective measures, such as, for example, rockfall nets, rockfall and avalanche dams and sediment retention basins.

In step 1, a simple decision tree is applied to reveal if the forest has a protective effect, a worsening effect or no effect at all on the natural hazard. This step allows in an affordable way to assess if the subsequent steps for assessment are needed or not. Step 2 evaluates characteristics of the protection forest with regards to the hazard that allows for assessing the reliability of the protection forest. The relevant criteria, i.e. structural safety, usability and durability, are assessed by using different scenarios. Step 3 finally quantifies the influence of the measures on the hazardous process under consideration of the relevant criteria mentioned above. This is done per scenario and results in values of magnitudes and frequencies, which can be plotted on intensity maps. The latter then serve as a basis for establishing a quantitative risk analysis, which includes the value of infrastructure and human lives protected, and hazard maps.

Based on the risk analysis, the potential yearly damage (e.g., infrastructure and housing destroyed, casualties, delay cost to traffic) due to natural hazards can be expressed in monetary terms. As an input variable, a hazard scenario (its magnitude and frequency) can be used to analyze with and without the

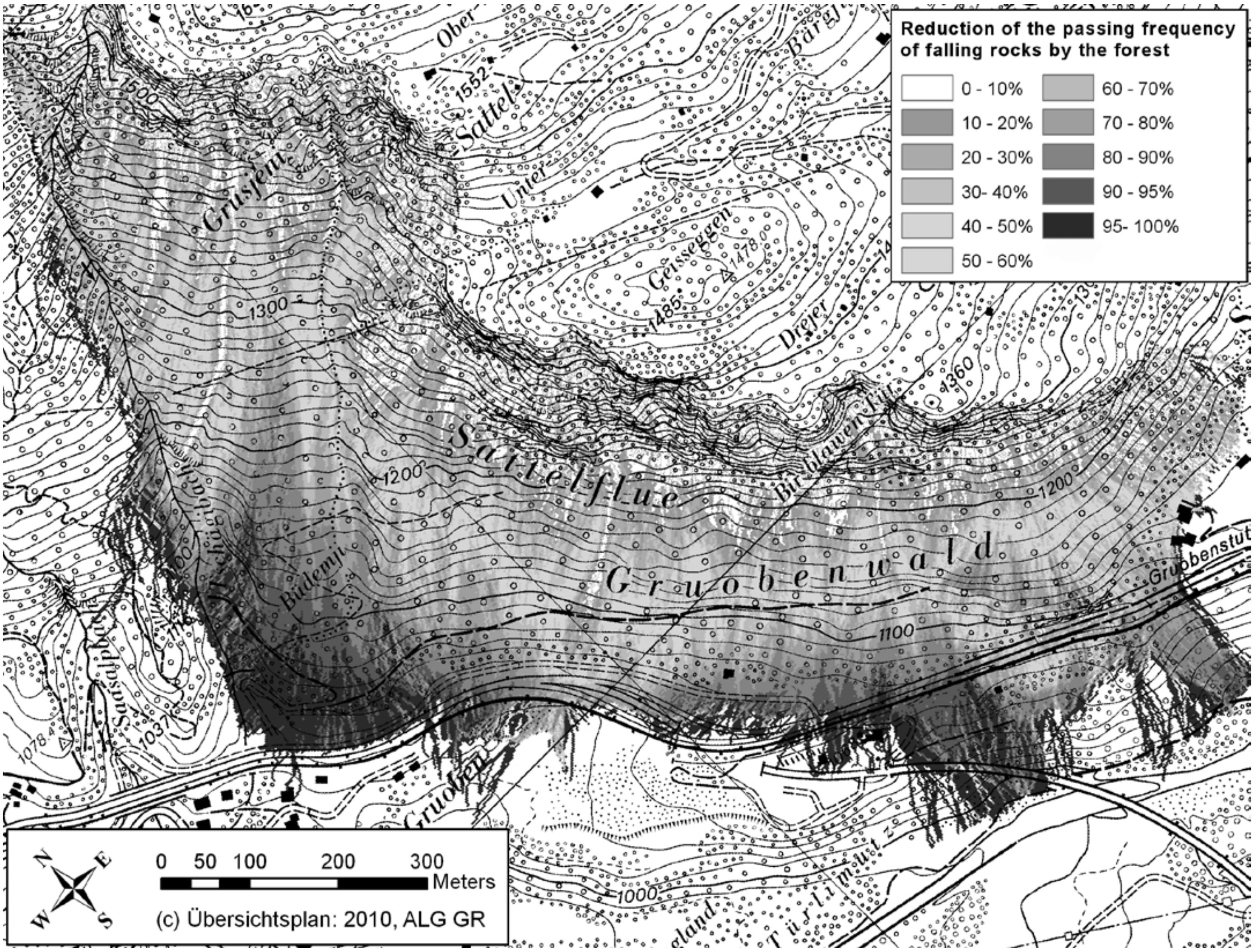

Figure 5: The protective effect of the forest expressed as the reduction of the number of passing rocks (image: tur GmbH, Switzerland). To create this map, the current forested situation was compared with non-forested conditions.

mitigation effect of a given forest. The difference in valued potential yearly damage between the two scenarios provides the risk reduction due to the forest, expressed in monetary terms. Figure 5 shows the protective effect of a mountain forest in the Swiss Alps against rockfall. In the given case, the rockfall risk was evaluated, for those driving on the roads downslope from the forest-covered, active rockfall slope, using Rockfyfor3D simulations with and without the mitigation effect of the existing forest. It shows that the forest reduces the risk for the road users at this given site by 91 %. In monetary terms, this risk reduction corresponds to approx. 1000 $ per ha/year. The same approach applied at 6 other sites, in the framework of the French/Italian/Swiss Interreg project IFP, resulted in risk reductions varying from approx. 50 – 1000 $ per ha/year. In addition, another approach was used to quantitatively evaluate the protective role of forest against rockfall, which was based on the calculation of the replacement cost. This means that it has been evaluated how much it costs if a forest needs to be replaced by a technical structure that provides the same degree of protection. This approach provided sums of 18,000 – 53,000 $/ha.

7 CONCLUSIONS

Our complementary approaches, the field observations, robust data acquisition and modeling have proven to be an excellent basis for research on the interaction between rockfall and protection forests, as well as for the development of tools that are relevant for practitioners working in the field of natural hazard and risk management. Carrying out full-scale rockfall experiments on both forested and non-forested slopes enormously improved our understanding. Not only the data obtained, but also the field observations were crucial for the progress in our work. With the help of the data and tools, we have been able to show that forests have the capacity to provide a degree of protection that is comparable to many other technical measures. They offer therefore possibilities for using mixed ecological and technical solutions for rockfall hazard management. It all depends on the size and energy of the falling rocks, the length of the forested slope between release area and the elements at risk, and the structure of the forest. The effect of a protection forest is mainly achieved through the reduction of the rebound heights and consequently the kinetic energy of the falling rocks, but also the reduction in the number of rocks that reach a given zone at risk. These effects can be very well quantified with the latest generation 3D simulation models that use ALS data both for mapping the forest and the terrain. Based on those analyses, the efficacy of the forest might be improved over the years by using the latest knowledge on protection forest management which includes the mentioned eco-engineering techniques.

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