Reviewer 1

We thank the reviewer for the very careful revision of our paper and the helpful suggestions. In the following, we respond to the author’s comments (blue) and explain changes and adaption we made in the final manuscript. All comments not specifically addressed in the following list are adapted in the manuscript as suggested.

Title

RC1.1) As the paper essentially deals with the impact frequency of blocks and not the occurrence frequency of rockfalls, it is suggested to replace "occurrence frequency" by "impact frequency". Moreover, forest can’t influence rockfall occurrence because rockfalls initiate usually in the upper part of slopes, before the falling blocks can be influenced by forest.

In this study, we define the occurrence frequency as the product of the onset frequency of a block and its propagation probability to a certain position along the slope. The impact frequency is – according to our definition – the product of the occurrence frequency and the presence probability of the element at risk. We agree that the terminology is slightly confusing and, therefore, we try to make it clearer in the introduction (P2 L13, L26ff). We decided to replace “occurrence frequency” by frequency in the title (see also suggestion of Reviewer 2) in order to avoid confusion.

Specific comments

RC1.2) The input data which are used for the simulation of blocks propagation are derived from Carrea et al. (2015). But Carrea et al. (2005) give the distribution of the volumes of rockfall events and not of the individual blocks. Similarly, the cited references (Dussauge-Peisser et al., 2002; Malamud et al., 2004) don’t deal with the distribution of block volumes. Studies on the distribution of block volumes can be found in the following references: Ruiz-Carulla, R., Corominas, J. & Mavrouli, O. 2015. A methodology to obtain the block size distribution of fragmental rockfall deposits. Landslides, 12: 815–825. Hantz D., Ventroux Q., Rossetti J-P., Berger F. 2016. A new approach of diffuse rockfall hazard. In: Landslides and Engineered Slopes - Aversa et al. (Eds). Associazione Geotecnica Italiana, Rome, Italy, ISBN 978-1-138-02988-0, 1063-1067. This confusion doesn’t call into question the results obtained because (a) the simulation has been made on a virtual slope which is not the La Cornalle slope, (b) the values used for the power-law parameters are plausible also for the distribution of block volumes. But the section 2.2 should be rewritten without mentioning the unsuitable references (Dussauge-Peisser et al., 2002; Malamud et al., 2004; Carrea et al., 2005).

Thank you very much for this valuable input. We changed the reference in chapter 2.2 as suggested and excluded the reference for the beta-exponent.

RC1.3) In the widely used terminology of landslides (Varnes, 1978; Cruden & Varnes, 1996), the word "rock" refers to the material which is implied in the movement and not to the fragments which propagate down the slope. The fragments implied in a rockfall can be called fragments, particles, projectiles (Bourrier, Dorren, Hungr, 2013), but the word "block" is more commonly used (for example, Ruiz-Carulla, Corominas, Mavrouli, 2016, Comparison of block size distribution in rockfalls). Then I suggest to replace "rock" by "block" in some places. Moreover, a rockfall event consists in two phases: The detachment of a volume of rock from a steep slope and its propagation down the slope (for example, Bourrier, Dorren, Hungr, 2013). When mentioning a frequency, it is important to precise if it is a detachment (or release) frequency or an impact frequency on an element at risk. The expression "occurrence frequency" used in the manuscript is not explicit, so I suggest to replace it by "release frequency" or "impact frequency".

We agree on that and replaced rock by block as suggested. We further tried to clarify the definition of terms regarding the frequency (P2 L26ff; P6 L9ff).

RC1.4) Page 3, line 6-9 I don't understand what are "reference situations". Could you explain?

We refer here to (hypothetical) comparative situations such as other forest scenarios or non-forested situations. We replaced this in the text (P3 L9).

RC1.5) Page 4, line 7 Could you please explain why it is necessary to randomly vary the slope angle of each cell?

We randomly varied the slope angle aiming at more realistic slope conditions. We agree, however, that this is slightly contradictory to the "controlled conditions". Since we re-ran the simulations (see below), we decided to remove the random variation of the slope angle.

RC1.6) Page 4, line 9 It should be explained why a vertical fall height of 10 m has been chosen (it is not realistic).

Since a vertical cliff face is not represented in our virtual slope, we chose an initial fall height of 10 m which is representative for real rockfall slopes.

RC1.7) Page 4, line 10 The distances are different from the distances in the Figure 1. For example, the last line must be at a distance of 574-100=474 m from the release area (and not 530 m). This point must be clarified.

This is incorrectly written in the text: The distances are measured on the slope (and not horizontally). In Figure 1, we also report the distances along the slope (in the graph).

RC1.8) Page 5, line 31 The 49 scenarios should be explained: 4 forest types and 4 forest structures give 16 scenarios, but how can one obtain 49 scenarios? The number of slope scenarios doesn't appear clearly in table 1.

Correct is a total of 48 scenarios: 4 forest types, 4 forest structures and 3 terrain scenarios (rough + soiltype 3, rough + soiltype 4, zero roughness + soiltype 3 → zero roughness was not combined with soiltype 4).

RC1.9) Page 7, line 2 Power-laws were fitted for the volume-frequency relation, but the powerlaw parameters (alpha and beta) are not given in the paper. It would be interesting to compare the beta-values obtained with the beta-value adopted for the initial distribution of block volume. Concerning the intensity-frequency relation, could you please indicate if the E95 values have been averaged over the 100 simulations to obtain the distribution shown in Figure 9? In other words, is the distribution obtained from 239 E95 values (478 m / 2 m) or from 23,900 values (dividing the number of each energy class by 100,000 years)? In my opinion, the most significant distribution in terms of hazard assessment would have been obtained by considering all the energies calculated in all cells rather than only the 95th percentiles (which doesn't contain all the information about the extreme values).

We only fitted power-laws to the intensity-frequency distribution at a slope length of 300 m and report the parameters in Table 6. Since the second reviewer questions the statistical representativeness of the intensity calculation (due to small block number of large volumes), we decided to re-run the simulations for the whole release area (50 blocks per cell) and calculated the occurrence frequency in a second step by multiplying the onset frequency with the propagation probability (see P6 L9ff for detailed description). The E90 values in the distribution shown in Figure 9 were obtained based on all energy values of the blocks passed through the respective line.

RC1.10) Page 7, line 15-20 The definitions of bA and cbA should be clarified. From the definition given in the line 17, bA is not an area, but a relative area which reflect the proportion of area which is occupied by trees. It should be called "relative basal area". As bA is dimensionless (m2/ha), it should be multiplied by an area to obtain a total tree area, which influences the impact frequency. I suggest to present the definition as follows: "The latter is defined as the product of the basal area (bA; m2/ha) by the area of the forested slope from the top of the release area to the respective EL, for a width of 100 m." And to define fsL after Equation (7) as the forested slope length. As cbA is an area, it must be expressed in m2, and not in m2ha-1 as written in Equation (7), page 11, line 6-7 and in Table 5. Moreover, in the third member of Equation (7) bA represents the basal area of individual trees and not the (relative) basal area as defined previously. I suggest to remove this third member which is incorrect and unnecessary.

It is true that the definition is slightly confusing. cbA is indeed the product of the relative basal area (corrected in the text, P7 L12ff), which is the sum of the basal areas of individual trees divided by the respective horizontal area (from the bottom of the release area to the respective area), normalized by a slope width of 100 m and multiplied with the forested slope length (measured along the slope).

Reviewer 2

We thank the reviewer for the very careful revision of our paper and the helpful suggestions. In the following, we respond to the author's comments (blue) and explain changes and adaption we made in the final manuscript. All comments not specifically addressed in the following list are adapted in the manuscript as suggested.

Title

RC2.1) The actual title of the paper without the term 'occurrence' (see specific comments on terminological approximations) could be used to describe the work done in the paper. However it could be better to highlight the work done on the development of statistical models (meta models) which can predict the protective efficiency of forests against rockfall hazard. The latter result is the innovation in the paper.

We agree that the term "occurrence" can be deleted in the title. The corresponding terms are introduced and explained later in the text. However, we decided not to name the statistical models in the title, although we agree that the "meta models" are a main innovation of the paper.

General comments

Responses to the general comments can be found in the respective specific comments.

Specific comments 1

RC2.2) The phrase "occurrence frequency" is not adequate. The author can use frequency instead. In addition to this remark, it would be appreciated to use a consistent terminology related with the frequency of blocks passing through an evaluation line: either frequency or return period.

We use the "occurrence frequency" as description of the frequency that a certain point is reached in dependence of the rock release and its propagation. It is thus defined as the product of the "onset frequency" and the "propagation probability". We tried to clarify that in the text (P2 L14; P6 L9ff).

Regarding the presentation of the results, we agree that a mixing between the presentation of frequencies and return periods may be confusing. For this reason, we only present yearly frequencies in the results and the graphs (figure 4).

RC2.3) P2, L12: "the propagation probability and thus the occurrence frequency" could be modified in reaching probability.

See comment to RC2.2.

RC2.4) P2, L25, L28 "... the annual exceedance frequency ..." this sentence has to be improved.

We tried to formulate the sentence and the whole paragraph more clearly (P2 L26ff).

RC2.5) P4, L18: What is a 3D vector? RockyFor3D simulate rockfall propagation using a 3D raster map.

This is a slightly unclear formulation. Therefore, we rewrote the sentence (P4 L20).

RC2.6) P4, L20,L24: "The elasticity of the surface material". Elasticity cannot be used to describe the response of the surface during a block impact. If a soil is elastic no energy dissipation occurred during the impact. It would be preferable to use "the response of the surface material" instead. P10, L28 "Soil elasticity" should be replaced. For example : capacity of the soil to dissipate energy.

Thank you for this suggestion which we implemented in the text.

RC2.7) P5, L30: "aisles" could be replaced by corridors.

Corridors would also be a suitable term. However, we decided to keep “aisle”:

Specific comments 2

RC2.8)

References were added where deemed necessary.

Specific comments 3

RC2.9) P4: The first paragraph of the material and methods section is not an introduction. It may be placed in a subsection or restructure according to my last comment.

We placed the first paragraph of section 2 in a separate subsection.

RC2.10) P4: The presentation of RockyFor3D can be improved by adding a description of the input raster maps associated to the tree generation. An highlight on the output used for the creation of the statistical models would be appreciated.

A short description of the tree input data is already present (section 2.2). The output used for the statistical models is described in section 2.5.

RC2.11) P5, L8: The value chosen for the parameter needs to be added.

We added the value for β.

RC2.12) P5, L10-13: Why didn’t you take an interval of block volumes ranging between 0.05 and 5 m3. The justification of the interval: 0.05 and 2 m3, could be improved. In Stockes 2006, forests are presented as having a protection function for block volume until 5 m3 (Berger et al. 2002; Stoffel et al. 2005).

We decided to simulate only block volumes between 0.05 and 2 m^3 because certain references mention a volume of 2 m^3 as limiting volume for the protective function of forests (reference changed in the article in order to avoid confusion; P5 L11ff). Blocks with volumes between 0.05 and 2 m^3 are most risk relevant as they exhibit high occurrence frequencies.

RC2.13) P5, L31: According the element given in the paper, 68 simulation scenarios are

identified (2 soiltype * 2 rugosity * 4 forests * 4 horizontal structure + 2 soiltype * 2 rugosity * 1 noForest). The author reach only 49 scenarios.
Did you define 49 scenarios or 68? It would be appreciated, in both cases, to present them clearly in your paper.

Correct is a total of 48 scenarios: 4 forest types, 4 forest structures and 3 terrain scenarios (rough + soiltype 3, rough + soiltype 4, zero roughness + soiltype 3 > zero roughness was not combined with soiltype 4). We tried to better explain them in the text (section 2.4) and Table 1.

RC2.14) P5, 32: Can you give us details about the number of blocks considered for each interval, in particular the interval [1.9-2] m3. Could you create a table to indicate the number of blocks for each interval? This point is particularly important to evaluate the robustness of your statistical analysis.

Due to your justified questioning of the statistical robustness of the simulation results for larger volumes, we decided to run new simulations with a higher and more robust number of blocks. We simulated the whole release area (7500 cells) with 50 simulations per block for all block volumes. Based on these simulations, we calculated the propagation probabilities of the blocks (described in section 2.2.) and multiplied them with the onset frequency in order to obtain the occurrence frequencies. We further evaluated the 90-percentile of the maximum energies of all blocks passing an evaluation line (not as the mean of the 90-percentile of all cells).

RC2.15) P6 L15-20: It would be preferable to choose either the passing frequency of the block through a line or the return period for all the analysis.

See response “Specific comments 1, 1.”

RC2.16) P6, L29: A precise description of the method used to calculate the indicator E95red is required to evaluate the robustness of the method. Calculating E95 using the average of E95 values along an evaluation line (these values being averaged over a hundred simulations) cannot be used as a relevant statistical indicator. In addition using the percentile 0.95 of a distribution is only valid for a high number of blocks passing through a line.
How many blocks are used to calculate E95 for the different evaluation lines (especially for large block volumes)?

See response “Specific comments 3, 7.”

RC2.17) P7, L5-13: In this section a complete description of the two main statistical analyses is required. The statistical model are the main results of this work. Thus, a description of the hypothesis associated to each one is requested.
In addition, for the regression tree models, (P7, L10-11) either you have to explain all the method to select the splitting variable and the impurity reduction or you have to remove those two sentences from the article.

RC2.18) P7, L23: The presentation of the GLM method is to short, additional information on the method is requested.

We agree that the statistical models are the main results of the study and a special focus should be placed on them. However, since the two applied multivariate models are well-established and well-described in literature, we describe them briefly, providing relevant literature references for more detail.

Specific comments 4

RC2.19) Results of the Wilcoxon rank sum test (methodology section P7 L5) have to be added to the results section.

P-values of the Wilcoxon rank sum test are reported in brackets for the respective variables. In order to keep the result section short and concise, we do not report exact p-values and parameters of the Wilcoxon rank sum tests.

RC2.20) Results of the Spearman correlations coefficient (methodology section P7 L5) have to be added to the results section.

The Spearman correlation coefficients were calculated in order to exclude strongly correlated explanatory variables in the multivariate statistical models. This was not clearly described in the article and thus adapted. In order to keep the result section focused, we do not report them in detail.

RC2.21) P8, L16: In the legend of Fig 4 and 5, the volumes of the blocks ranging between 0.01 to 2 m3 are indicated. A different range is presented in the material and methods section (block volumes ranging between 0.05 to 2 m3).

Thank you for this indication. Volumes ranging from 0.05 to 2.0 m^3 were simulated.

RC2.22) P8, L19-L25: The results presented in Fig 6 and Fig 7 should be improved. The data on which each curve are fitted could be placed in the background of each figure. In addition, the smoothing techniques used to create the curves (Fig 6 and Fig 7) should be detailed in the material and methods section.

We decided to plot only the fitted curves in order to highlight and summarize the main tendency of the data in a striking way. However, we understand your point and, thus, we added the 10%- and 90% confidence intervals.

RC2.23) P8, L31: A simplification of the results presented in table 3 could be done to improve its understanding. In addition, each term used in the table has to be defined in the material and methods section. For example: (Intercept), Vol, GLMFreq, GLMInt... In table 4 RTFreq and RTE95 are not defined in the material and methods section.

You are right that certain abbreviations are not introduced in the material and methods and the table caption, respectively. We corrected this. The presented parameters of the GLM (e.g. Z-value), however, correspond to the standard representation of the results of a GLM and thus, we omit to explain them in more detail.

RC2.24) P8, L21: Where are the results illustrating the influence of the forest structure? The only results presented are simulation scenarios with random or no forest (Fig4 and Fig5).

We decided to show results of two different forest types and no forest in fig. 4 and 5 as we do not want to overload the figure. The influence of the forest structure is reported in the text and can be seen in fig. 9 (intensity-frequency curves) as well as the statistical models.

RC2.25) P9, L1: Why, for the level 8 of the RTFreq model (Fig 8), a volume < 1.1 m3 has a smaller Nrpred value than a volume > 1.1 m3, and why, for the level 11 of the RTFreq model (Fig 8), a volume < 1.2 m3 has a higher Nrpred value than a volume < 1.2 m3? Could you explain the difference?

There was a mistake in the initial graph at level 8: There is a smaller Nrp_{red} value for volume > 1.1 m^3 than for volumes < 1.1 m^3. The graph was adapted according to the new regression tree model based on simulations for all source cells.

RC2.26) P9, L30: Which data were used to build the Fig 9?

We corrected the description of the figure according to “Specific comments 3, 5.”

Specific comments 5

RC2.27) P10, L22-32: This paragraph is currently a description of your results. A comparison between your results and other one from the literature would improve significantly the discussion. Here is a list of recent papers working on similar subjects:

We thank for the interesting literature suggestions and integrated part of them in our discussion. However, we did not substantially change the mentioned paragraph as we do not only describe the results but also highlight and summarize their significance. A discussion and comparison with other literature follow in the next paragraph(s).

Other comments

RC2.28) P3, L17-20: This two sentences should be located in the material and methods section. In the introduction, it would be appreciated to have a short paragraph describing the different rockfall models that can be found in the literature and highlight the few one that take into account the protection effect of the forest.

We made reference to Volkwein et al. 2011 who summarize and describe in detail a wide variety of existing rockfall models (P4 L19).

RC2.29) P4, L5: A justification for the choice of a concave profile with slope angle varying between 20 to 40° needs to be added.

We chose a concave profile as this corresponds to typical and probably most frequent slope geometries of rockfall slopes. In order to test the influence of the slope profile on the results, we validated the statistical models with results of simulations on linear slopes with slope angles of 32°, 35°, 38° and 40°.

RC2.30) P4, L6: Why do you add random slope angle variation to your profile? Adding this angle variation comes in conflict with the "controlled conditions" you are looking for P4, L4.

RC2.31) P4, L10: Why do you add a road into your slope profile? Adding a road does not appear to be necessary for the analysis done in the paper. Its influence is never presented in the result section nor in the discussion and conclusion section.

We randomly varied the slope angle of each cell aiming at more realistic conditions. We agree, however, that this is slightly contradictory to the “controlled conditions”. For this reason, we decided to run the new simulations without slope angle variation and we also omitted the road in the new slope as it is indeed not necessary for the presented analysis.

RC2.32) P7, L16: Why do you choose to calculate cbA using a slope width of 100 m? Did you test other widths and analyse their influence on this indicator?

The slope width of 100 m is used to normalize the cumulative basal area for a given runout distance. As such, it does not make any difference whether we use 1, 10 or 100 m.

RC2.33) P8: Can you give a ranking of the influence of the different parameters for the 4 statistical models?

The p-values of the parameters and the position in the regression tree can be regarded as ranking. This, however, has to be interpreted carefully, since the multivariate models reflect interactions of the parameters and a ranking does not necessarily make sense.

Quantifying the effect of forests on frequency and intensity of rockfalls

Christine Moos[1], Luuk Dorren[1], Markus Stoffel[2,3,4]

[1]Berne University of Applied Sciences, School of Agricultural, Forest and Food Science HAFL, Länggasse 85, CH-3052 Zollikofen, Switzerland

[2] Climatic Change and Climate Impacts, Institute for Environmental Science, University of Geneva, 66 Bvd Carl Vogt, CH-1205 Geneva, Switzerland

[3] Department of Earth Sciences, University of Geneva, rue des Maraîchers 13, CH-1205 Geneva, Switzerland

[4] Dendrolab.ch, Institute of Geological Sciences, University of Bern, Baltzerstrasse 1+3, CH-3012, Bern, Switzerland

Correspondence to: Christine Moos (christine.moos@bfh.ch)

Abstract. Forests serve as a natural means of protection against small rockfalls. Due to their barrier effect, they reduce the intensity and the propagation probability of falling rocks and thus the occurrence frequency of a rockfall event for a given element at risk. However, despite established knowledge on the protective effect of forests, they are mostly neglected in quantitative rockfall risk analysis. Their inclusion in quantitative rockfall risk assessment would, however, be necessary to express their efficiency in monetary terms and to allow comparison of forests with other protection measures. The goal of this study is to quantify the effect of forests on the occurrence frequency and intensity of rockfalls. We therefore defined an onset frequency of blocks based on a power-law magnitude-frequency distribution and determined their propagation probabilities on a virtual slope based on rockfall simulations. Simulations were run for different forest and non-forest scenarios under varying forest stand and terrain conditions. We analyzed rockfall frequencies and intensities at five different horizontal distances from the release area. Based on two multivariate statistical prediction models, we investigated which of the terrain and forest characteristics are predominantly driving the role of forest in reducing rockfall occurrence frequency and intensity and whether they are able to predict the effect of forest on rockfall risk. The rockfall occurrence frequency below forested slopes is reduced between approximately 10 and 90 % as compared to non-forested slope conditions; whereas rockfall intensity is reduced by 10 to 50 %. This reduction increases with increasing slope length and decreases with decreasing tree density, tree diameter and increasing rock volume as well as in case of clustered or gappy forest structures. The statistical prediction models reveal that the cumulative basal area of trees, block volume and horizontal forest structure represent key variables for the prediction of the protective effect of forests. In order to validate these results, models have to be tested on real slopes with a wide variation of terrain and forest conditions.

1. Introduction

Rockfall is a widespread and frequent natural hazard occurring below steep rocky cliffs. The occurrence of rockfall often threatens infrastructures, transportation corridors, and human life. We here define it as a fragment of rock (a block) detaching from a release area and proceeding downslope by bouncing, falling, or rolling (Whittow, 1984). Different protective measures are typically implemented in order to reduce risks in rockfall prone areas. These include structural protection measures, land-use planning, early-warning systems or biological measures, nowadays referred to as nature-based or ecosystem-based solutions (Agliardi and Crosta, 2003; Corominas et al., 2005; Sättele et al., 2016; Renaud et al., 2013). With regards to rockfall, a well-known biological measure is the protection forest. Such forests can serve as a natural means of protection against rockfall due to their barrier effect. Forests influence rockfall risk by (i) reducing the intensity of falling rocks after collisions with tree stems and by (ii) reducing the propagation probability and thus the occurrence frequency of an event at a given element at risk (Wasser and Perren, 2014; Dupire et al., 2016). The occurrence frequency is here defined as the product of the onset frequency and the propagation probability of a block at a certain position.

In order to appropriately account for the positive effects of protective measures on rockfall risk and associated uncertainties, their design should be based on a quantitative risk analysis (Corominas et al., 2005; Straub and Schubert, 2008; Peila and Guardini, 2008). In doing so, the protective effect of the measure can be expressed in monetary terms, thereby allowing to evaluate its efficiency in a cost-benefit analysis (Agliardi et al., 2009). In the case of protection forests, quantitative, risk-based approaches have been only rarely applied in the past. Despite the advanced knowledge on the protective effect of forests and its maintenance (Dorren et al., 2007; Bigot et al., 2009; Radtke et al., 2014; Fuhr et al., 2015), open questions remain on how protection forests can be quantitatively integrated into rockfall risk analyses (Masuya et al., 2009; Trappmann et al., 2014). Currently, the effect of forests is mostly neglected or only qualitatively assessed in hazard and risk analyses.

The quantification of the influence of forests on rockfall occurrence frequency is particularly demanding, especially if one aims at evaluating the effect of forests at the level of the element at risk. The onset frequency of a rockfall event is usually described by the annual exceedance frequency of its magnitude (expressed as the rockfall volume) or intensity (expressed as the kinetic energy of the blocks), assuming that rockfall occurrence follows a Poisson distribution (Corominas et al., 2013). Depending on the data availability and site characteristics, the onset frequency can be estimated by different approaches including the analysis of historical datasets (Hantz et al., 2003; Hungr et al., 1999; Guzzetti et al., 2003), magnitude-frequency relationships based on power laws (e.g. Agliardi et al., 2009; Lari et al., 2014; Dussauge-Peisser et al., 2002), empirical models describing rockfall frequency as a function of topographic or geological parameters (e.g. Budetta, 2004;

Lan et al., 2010), or expert opinion (e.g. Romana et al., 2003). Furthermore, several techniques exist based on which the depositional ages of rocks can be reconstructed in absolute terms (e.g. Lang et al., 1999; McCarroll et al., 2001). Dendrogeomorphology (Stoffel and Corona, 2014) represents one such approach and has proven to be a reliable method to estimate past rockfall frequencies through coupling the number of rockfall impacts with tree age (Moya et al., 2010; Corona et al., 2013; Trappmann et al., 2014; Perret et al., 2006). However, in most cases, reliable data is scarce and estimation of robust frequencies remains difficult (Hantz et al., 2003; Lari et al., 2014; Straub, 2005). Based on the estimation of the onset frequency, practitioners usually assume scenarios of pre-defined return periods and corresponding block volumes (e.g. Borter et al., 1999). Such scenarios are typically derived for the current (e.g. forested) situation, but are also applied to hypothetic non-forested situations (Jahn, 1988). At the same time, however, the barrier effect of forests is expected to decrease the occurrence frequency of rockfall at the location of the element at risk. Consequently, scenarios derived with the practitioner’s approach may not necessarily be valid for the non-forested situation and might thus result in biased risk estimations.

Forests do not only reduce the occurrence frequency of rockfall events, but also reduce their intensity by stopping blocks completely and/or by absorbing (part of) their energy (Lundström et al., 2009). In this sense, the intensity of an event refers to the kinetic energy which is released by the block at impact with the element at risk (Jaboyedoff et al., 2005; Abbruzzese et al., 2009; Lari et al., 2014).

The effect of forest on the occurrence frequency and the intensity is also expected to depend on the structure of a forest stand. Furthermore, the capacity of a tree to absorb energy will vary between species and will depend on its diameter at breast height (DBH) (Dorren et al., 2006). At the stand level, high stem densities are considered to stop falling blocks more effectively because of an enhanced impact probability (Dorren and Berger, 2005; Wehrli et al., 2006). The three-dimensional, probabilistic-deterministic rockfall simulation model RockyFor3D (Dorren, 2015) accounts for these forest effects. It integrates trees spatially explicitly and calculates the energy loss due to impacts against single trees as a function of tree species, DBH, impact height and the horizontal position of the hit (Dorren et al., 2006).

The goal of this study is to quantify the effect of forests on the occurrence frequency and intensity of rockfall by using multiple series of rockfall simulations. In this paper, we define a rockfall onset frequency based on a power-law magnitude-frequency distribution. Simulations were run for different forest and non-forest scenarios under varying forest stand and terrain conditions. They provide input data for the determination of rockfall occurrence frequencies and intensities at five different distances from the release area. These data are analysed with multivariate statistical prediction models in order to yield information how specific forest and terrain characteristics control rockfall occurrence frequency and intensity along a slope. Based on these approaches, we then investigate (i) how rockfall occurrence frequency and intensity differ at a given location with an element at risk on forested and non-forested slopes; (ii) what terrain and forest characteristics are predominantly driving the role of forest in reducing rockfall occurrence frequency and intensity, and (iii) whether multivariate statistical models fitted with these terrain and forest characteristics can indeed predict the effect of forest on rockfall occurrence and hence rockfall risk.

2. Material and methods

2.1. Virtual slope

As this study aimed at an assessment of rockfall in forests under controlled conditions, it was preferred to run simulations on a virtual slope. We designed a slope raster with a resolution of 2 m, a horizontal width of 478 m and a horizontal length of 574 m. The virtual slope is cylindrical, has a concave shape in vertical cross-section, and slope angles which are increasing linearly from 20 to 40° from the slope bottom to the release area of rockfalls, therefore resulting in a height difference of 328 m. The rockfall release area is rectangular and has a horizontal length of 100 m and a width of 300 m (Fig. 1). Within this area, blocks are randomly released from a height of 10 m above the slope surface. We added five virtual evaluation lines located at distances of 0, 140, 300, 410, and 480 m from the downslope side of the release area to the bottom of the slope (measured on the slope). These lines allow a systematic assessment of changes in rockfall occurrence frequency and intensity with increasing distance from the release area of rockfalls (Fig. 1). The lines were defined based on equal height differences between them.

2.2. Rockfall simulation model

To simulate rockfall trajectories, a wide variety of models exists (see Volkwein et al. 2011). For this study, we used the model RockyFor3D, which is a probabilistic process-based rockfall trajectory model simulating trajectories of falling blocks in three dimensions (Dorren, 2015). RockyFor3D was developed on the basis of real-size rockfall experiments in the field and uses raster maps describing topography (Digital Elevation Model, DEM), rockfall source cells, the response of the surface material, slope surface roughness, the number of trees per cell, DBH of trees in each cell and tree species per cell as input data (Dorren et al., 2004; Dorren et al., 2006). For each rockfall source cell, the trajectories of a given number of blocks are simulated by considering flying and bouncing. Rolling is simulated with short distance bouncing, similar to the approach of Pfeiffer and Bowen (1989). The trajectory of blocks is primarily determined by topography. The response of the impacted material is considered based on the normal coefficient of restitution (Rn) which is predefined by seven different soil types or undergrounds. Surface roughness is represented by a mean obstacle height (MOH) representative for 70, 20 and 10 %, respectively, of each cell (for more details see Dorren, 2015). RockyFor3D explicitly calculates the deviation and energy loss after impacts with trees dependent on tree diameter, impact position, and the kinetic energy of the block before the impact. Provided that the exact positions of trees within the slope are not known, trees are randomly positioned within each pixel according to the number of trees (i.e. forest stand density) assigned to each pixel. The main output of RockyFor3D consists of raster cells containing the maximum kinetic energy, the 90 % confidence interval of all maximum kinetic energy values, the maximum bounce height, the number of blocks passed through each cell, the number of deposited blocks, the maximum simulated velocity, the maximum tree impact height and the number of tree impacts per cell (Dorren et al., 2006; Dorren, 2015). We simulated 50 blocks per source cell to obtain robust results and did not consider rock fragmentation.

2.3. Onset probability

We assume a power-law distribution for the magnitude-frequency relationship of rocks released from the release area, since power laws have proven to fit the release volume distribution of rockfalls (e.g. Ruiz-Carulla et al. 2015; Hantz et al. 2016). They have the general form:

$$F(V_i) = \alpha V_i^{-ß} \qquad (1)$$

where $F(V_i)$ is the annual exceedance frequency of volume i (V_i).

We used an exponent ß of 0.7 which is in the typical range of exponents of power-laws fitted for block volume distributions (e.g. Ruiz-Carella 2016, 2015; Hantz 2016). For the scope of our study, we considered blocks with volumes between 0.05 m^3 and 2.0 m^3. These volumes can be potentially hazardous but are still within a range for which forests are assumed to have an effect on rockfall propagation and energy (Dorren et al., 2007). The constant α of the cumulative power-law distribution was defined as 12 in our study corresponding to a rockfall retreat rate of approximately 0.2 mm/yr for the considered volume range (0.05 m^3 and 2.0 m^3). This is in the typical range of rockfall retreat rates in alpine regions (Sass and Wollny, 2001; Hoffmann and Schrott, 2002; Moore et al., 2009).

2.4. Forest and terrain scenarios

The soil scenarios (Table 1) considered scree or medium compact soil with small rock fragments (soil type 3) and talus slope or compact soil with large rock fragments (soil type 4), as these are expected to be most frequent, often continuous and with a large spatial distribution. The release area was in all cases defined as soil type 5 (bedrock with thin weathered material or soil cover). As shown in Table 1, soil roughness was set to 0 m (100 %) in the scenario “zero roughness” and to 0.15 m (10 % of the surface), 0.05 m (20 %) and 0.01 m (70 %) in the scenario “rough”, respectively. Definition of the four forest types (Table 2) was based on natural rockfall protection forests as defined from the Swiss National Forest Inventory (Messmer, 2014). The forest types differ with respect to the diameter at breast height (DBH; ranging from 21-40 cm), dominant tree species (deciduous, conifers) and the number of tree stems (with DBH > 12 cm) per hectare (Nha; 200-500 trees ha^{-1}). The forest stands of each forest type were designed for four different horizontal forest structures (Fig. 2) as follows: random tree distribution, clustered tree distribution, random distribution with gaps of 20 x 20 m and random distribution with 3 aisles of 20 m in width.

The combination of the different forest types (4) and structures (4) and terrain scenarios (3) yielded 48 different simulation scenarios.

2.5. Statistical analysis

Simulation results were analysed statistically as follows:

- (i) zonal statistics of rockfall occurrence frequencies and energies at the level of the evaluation lines
- (ii) statistical comparison of rockfall occurrence frequency and intensity between different scenarios and by fitting power-law based intensity-frequency curves
- (iii) design of multivariate statistical models relating the frequency and the intensity reduction of forests to terrain and forest characteristics
- (iv) assessment of the performance of the statistical models and sensitivity to changes in slope angle

For each volume class j and simulation scenario, we calculated the *propagation probability* ($P_{prob,EL,j}$; Eq. 2) of blocks per evaluation line EL by dividing the number of blocks passing a EL (i.e. number of passages) by the total number of simulated blocks Nrp_{tot} (numbers of source cells x number of simulations per block).

$$P_{prob,EL,j} = \frac{Nrp_{EL,j}}{Nrp_{tot}} \qquad (2)$$

Multiplying the propagation probability by the yearly *onset frequency* ($F_{onset,i}$) of the respective block volume derived from the magnitude frequency relationship results in the yearly *occurrence frequency* ($F_{occ,EL,j}$; Eq. 3) per EL and block volume j.

$$F_{occ,EL,j} = P_{prob,EL,j} \times F_{occ,j} \qquad (3)$$

We calculated an indicator for the reduction in the number of passages by the forest stand (Nrp_{red}) in order to evaluate changes in the frequency between forested and non-forested conditions. The indicator Nrp_{red} is defined as the difference between the number of passages without (Nrp_{nF}) and with forest (Nrp_F), divided by the number of passages without forest (Eq. 5):

$$Nrp_{red} = \frac{Nrp_{nF} - Nrp_F}{Nrp_{nF}} \qquad (4)$$

We then used the 90th percentile of the maximum energy (E90 in kJ) as an indicator for rockfall intensity. For each EL, we calculated the E90 of all blocks passing through the line. Similarly to occurrence frequency, we calculated the intensity reduction offered by forests ($E90_{red}$). This indicator is defined as the difference between E90 without ($E90_{nF}$) and with forest ($E90_F$) divided by $E90_{nF}$ (Eq. 5):

$$E90_{red} = \frac{E90_{nF} - E90_F}{E90_{nF}} \qquad (5)$$

We further determined intensity-frequency distributions of E90 (intensity) and F_{occ} (occurrence frequency) under different forest and non-forest scenarios and at a slope length of 300 m, to which power-law distributions (Eq. 1) were fitted based on least squares (Draper and Smith, 1998).

To detect possible effects of forest and terrain characteristics on the forest effect, we first assessed whether Nrp_{red} and $E90_{red}$ significantly differ between different forest and terrain scenarios based on the Wilcoxon rank-sum test, with a significance threshold of $p \leq 0.05$. Subsequently, we applied regression tree (RT) models (Breiman et al., 1984) and generalized linear models (GLM) (McCullagh and Nelder, 1989) relating Nrp_{red} and $E95_{red}$ to possible explanatory variables.

RTs are a non-parametric regression approach which recursively partitions the data based on explanatory variables. At each node, the data is split into two groups using a single predictor (Breiman et al., 1984). The splitting variable is selected aiming at impurity reduction. This means that daughter nodes have to be as homogeneous (“pure”) as possible. RTs consider parameter interactions and account for non-linearities (Vorpahl et al., 2012). RT models were fitted using the *rpart* function of the party package in the statistical software R (Ripley et al., 2015).

We used rock volume, soil type (categorical), soil roughness (categorical), the horizontal forest structure (categorical) and the cumulative basal area (cbA; Eq. 7) of the forest as potential explanatory variables. The latter is defined as the product of the relative basal area (rbA; m^2/ha) for a slope width of 100 m and the forested slope length (fsL; m) from the top of the release area to the respective EL. The basal area (bA) is defined as the area per hectare which is occupied by the cross-section of tree stems (Bitterlich, 1948).

$$cbA\,[m^2ha^{-1}] = \frac{rbA}{100\ m} \times fsL = \frac{\sum_{EL} bA / \sum_{EL} area}{100\ m} \times fsL \qquad (6)$$

We calculated the Spearman correlation coefficients to check that the explanatory variables are not substantially correlated. The final GLM was determined using a stepwise backward variable selection with the aim to minimize the Akaike Information Criterion (AIC). The quality of the models was examined with goodness-of-fit tests and customary residual diagnostic plots (Stahel, 2013) indicating that the cumulative basal Area (cbA) should be transformed to the natural logarithm.

The GLM and RT were fitted with the simulation data of the concave slope. They were subsequently calibrated with a training data set representing 75% of the data. We further applied three times repeated 10-fold cross validation and calculated the average performance across the hold-out predictions with the aim to avoid over-fitting (Kohavi, 1995). The predictive performance was assessed based on the Root Mean Squared Error normalized with the range of the simulated data (nRMSE).

Furthermore, we tested the statistical prediction models for Nrp_{red} with field data of a study site in the French Alps at which real-size rockfall experiments were conducted on forested and non-forested sites (Dorren et al., 2006). We evaluated Nrp_{red} at a distance of 223 and 324 m from the release point (as measured along the slope).

To assess whether the forest effect on rockfall occurrence frequency and intensity depends on the slope angle, we conducted additional simulations for four linearly shaped slopes with varying slope angles (32°, 35°, 38°, 40°) for forest type 1 with random tree distribution, soil type 3 and rough conditions. On these slopes, we tested the multivariate statistical prediction models designed for the concave slope (GLM, RT) and calculated their performance. On the linearly-shaped slopes, evaluation lines were defined with the same distances along the slopes.

3. Results

3.1. Effect of forest on rockfall occurrence frequency

Forest stands considerably reduce rockfall occurrence frequency, with differences in the frequency between the forested and non-forested slope scenarios increasing strongly with increasing slope length. In the case of forest type 1 (*Fagus sylvatica* forest with 460 stems ha^{-1}) with randomly distributed trees, the frequency at a distance of 480 m from the release area has been shown to decrease to zero whereas on the non-forested slope, F_{occ} remains at values ranging from 0.1 to 1 yrs^{-1}, depending on block volume (Fig. 4). We also show that with decreasing cbA, the effect of the forest is decreasing ($p < 0.05$; Fig. 6), and the reduction of rockfall is becoming less effective. In a pole-stand *F. sylvatica* forest (forest type 4), by contrast, F_{occ} decreases to values between 0.001 and 0.01 yrs^{-1} at a slope length of 450 m. In the conifer forest composed of *Pinus sylvestris* and *Larix decidua* (forest type 2), F_{occ} is slightly higher as compared to deciduous forests. Furthermore, we also illustrate that differences between forested and non-forested slopes will chiefly depend on forest structure. In this sense, Nrp_{red} is significantly smaller for a clustered tree distribution, gaps or aisles than for a random tree distribution ($p < 0.05$).

The reducing effect of the forest is decreasing with increasing block volume (Fig. 7; $p < 0.05$). This is especially pronounced for forests with small tree diameters (e.g., forest type 4). Also, Nrp_{red} is significantly reduced in case of zero roughness ($p < 0.05$). A significant difference in Nrp_{red} also exist between soil types 3 and 4 (see Table 1).

According to the final generalized linear model (GLM_{freq}), Nrp_{red} is significantly influenced by the cumulative basal area (cbA), block volume, horizontal forest structure, soil type, soil roughness, and the percentage of conifers present in the forest stand (Table 3). GLM_{freq} has a R^2 of 0.80 and a normalized Root Mean Squared Error (nRMSE) of 0.16 with cross-validation for the training data set and the test data set. We also realize that the nRMSE changes only slightly if GLM_{freq} is applied to linear slopes (Table 4).

The variables reported above were also decisive in the regression tree model (RT_{freq}). The dataset was first partitioned based on a threshold of ~75 m^2 ha^{-1} for cbA. In the case where cbA is larger than this value, Nrp_{red} is between 0.3 and 1. At the same time, however, Nrp_{red} clearly decreases in the case that block volumes become > ~1 m^3. On the other hand, and if cbA is smaller than 75 m^2 ha^{-1}, the mean Nrp_{red} drops to 0 (cbA < 22 m^2 ha^{-1}) and 0.4 (cbA > 22 m^2 ha^{-1} and a block volume < 0.5 m^3). The normalized Root Mean Squared Error (nRMSE) of RT_{freq} is 0.16 with cross-validation for the training dataset and 0.17 for the test dataset. As can be seen from Table 4, the nRMSE is in the same range of values for the linear slopes.

In the case of the field site in Vaujany (Table 5), for which real data exist from experiments, the GLM_{Freq} and the RT_{Freq} models predict Nrp_{red} values of 0.55 and 0.61, respectively, at a distance of 223 m (0.64 measured value) and 0.66 and 0.73, respectively, at a distance of 324 m (1.0 measured value).

3.2. Effect of forest on rockfall intensity

On the concave slope, the blocks reach energies of up to 2700 kJ under non-forested and 2000 kJ under forested conditions at a slope length of 300 m. Similarly to the rockfall occurrence frequency, energy is distinctly reduced on the forested slopes compared to the non-forested slope (Fig. 5). Again, the reducing effect is decreased with decreasing cbA, increasing rock volume and for the clustered and gappy forest structures (Fig. 6-7). Furthermore, $E90_{red}$ is significantly smaller on slopes with soil type 4 compared to slopes with soil type 3 ($p < 0.05$), but is not significantly reduced on slopes with zero roughness.

In the final GLM (GLM_{Int}), the horizontal forest structure, percentage of conifer trees, cbA, soil roughness, soil type and block volume have a significant effect on $E90_{red}$. GLM_{Int} has a R^2 of 0.69 and a nRMSE of 0.6 with cross-validation for the training data set and 0.9 for the test data set. If GLM_{Int} is applied to linear slopes, we observe that the nRMSE values increase slightly (Table 4).

In the regression tree model (RT_{Int}), cbA and horizontal forest structure were selected as splitting variables. Figure 7 illustrates that in the case of high cbA (>85 m^2ha^{-1}), $E90_{red}$ is distinctively smaller with a clustered or gappy forest structure. The nRMSE of RT_{Int} is 0.10 with cross-validation for the training data set and 0.09 for the test data set. Similar to GLM_{Int}, we observe that the nRMSE of RT_{Int} values hardly changes on linear slopes (Table 4).

3.3. Intensity-frequency curves

Analysis of intensity-frequency distributions of rockfalls depends strongly on the forest cover. In the case of non-forested slopes, the intensity-frequency curve is substantially shifted upward compared to forested slopes at a distance of 300 m downslope from the start area, thereby indicating a higher frequency (intensity) for a given intensity (frequency) (Figure 10). In other words, the ß and the α coefficients (Eq. 1) of the power law fitted to the intensity-frequency distributions are considerably lower when forest cover is present as compared to non-forested conditions (Table 6). Furthermore, the occurrence frequencies of small intensities are distinctly reduced on forested slopes ("rollover effect").

4. Discussion and conclusion

In this study we investigated the role of forests – in terms of stand density and species composition – on rockfall occurrence at increasing distances from the release area of rockfalls by using a hypothetical slope typical of mountain environments.

Based on a large number of simulation runs using different scenarios, we show that rockfall occurrence frequency below forested slopes is reduced between approximately 10 and 90 percent as compared to non-forested slope conditions. Rockfall intensity is also reduced – although to a slightly smaller extent – by 10 and 60 percent. These findings are in agreement with the study of Lopez-Saez et al. (2016) who found a distinct increase in rockfall return periods (e.g., from 143 yrs under non-forested conditions in 1850 to >2000 yrs under recently grown forest in 2013 and for a block volume of 1.2 m^3). In this particular case in the Chartreuse massif (France), the disappearance of viticultural landscapes has led to intense (natural) afforestation and can thus be seen as a natural example for the validation of our theoretical results. Similar to our study, Lopez-Saez et al. (2016) also observe that the kinetic energy of rocks clearly decreases at the bottom of the slope and with increasing forested surface, which is again in concert with the findings of our study. Stoffel et al. (2005) investigated spatial and temporal variations of rockfall activity in a protection forest in the Swiss Alps based on dendrogeomorphic data. They reconstructed a decrease in rockfall rates after the recolonization of part of the slope where most of the forest was destroyed after a high magnitude event in 1720. Masuya et al. (2009), on the other hand, did not find a decrease in the number of blocks reaching the damage potential at a distance of 350 m from the rockfall source based on three-dimensional simulations taking vegetation probabilistically into account, but an increase in the spread of the rockfalls and lower rock energies. It has to be mentioned that the considered vegetation cover featured relatively small trees and low tree density.

The multivariate statistical models used in this study allowed quantification of the reduction of rockfall occurrence frequency and intensity and its prediction under varying forest and slope conditions. Both models (GLM and RT model) revealed that the effect a forest stand has on rockfall will depend clearly on the cumulative basal area (cbA) of trees, the horizontal forest structure, and on the block volume. We realize that the occurrence frequency and intensity are significantly increased with decreasing cbA and increasing block volume as well as in clustered or gappy forests, and are now able to quantify these effects. Moreover, the results also demonstrate how the reducing effect of forests is enhanced with increasing soil roughness and soil elasticity. The influence of the two slope parameters was, however, only significant in the GLM, but not in the RT model.

According to the RT models, the forest effect of rockfall frequency appears to depend mainly on cbA and rock volume, whereas cbA and forest structure appear as the most decisive factors for the reduction in rockfall intensity. Block volume, by contrast, only has a small influence on the reducing effect of forest on rockfall intensity (Fig. 8). The maximum reduction of the rockfall energy by forests is reached for volumes between approximately 0.6 and 1.0 m^3. This appears to be the optimal combination between a sufficiently high tree impact probability and impact energy. For larger blocks, however, impact probability increases further, but the block energy cannot be dissipated during a single tree impact.

The cbA appears to be a good measure of the protection efficacy of forests, as it combines the basal area (which is determined by tree density and tree diameter) with the forested slope length – two parameters which have been promoted as key variables for forest management in previous work (Perret et al., 2004; Berger and Dorren, 2007; Rammer et al., 2015; Fuhr et al., 2016). In a recent study, Dupire et al. (2016) show that the protective effect of forests regarding rockfall frequency and energy can be evaluated only on their basal area, their mean diameter at breast height and the length of the

forested slope. Based on our results, we recommend a minimum cbA of about 80 m^2 ha^{-1} for block volumes larger than 1 m^3 and a minimum cbA of about 30-40 m^2 ha^{-1} for volumes smaller than 1 m^3. Compared to the minimum threshold of 20 m^2 ha^{-1} for the basal area of a rockfall protection forest as suggested by Dorren et al. (2015), this corresponds to a forested slope length of 450 m (block volume >1 m^3) and 200 m (block volume <1 m^3), respectively.
According to the RT models, the horizontal forest structure is particularly important when it comes to the reduction of rockfall intensity. We demonstrate that the kinetic energies of blocks are significantly higher in the case of forest stands with a clustered tree structure or in forests with gaps or aisles compared to random tree distribution. The horizontal forest structure, by contrast, is only of secondary importance for the reduction of rockfall frequency and the number of trees which are impacted by the block in motion will be decisive. Radtke et al. (2014) found significantly longer run-distances in forests with clustered tree distribution compared to random distribution based on rockfall simulations.

The performance of the implemented statistical prediction models is satisfactory. They yielded relatively low normalized Root Mean Squared Error (nRMSE), also when applying cross-validation. This indicates that the generalization capacity of the models is relatively high and over-fitting unlikely. The application of the models to four different linear slopes with varying slope angles (32°, 35°, 38°, 40°) did not substantially change the nRMSE (Table 4) suggesting that the models are relatively robust with respect to slope angles.

Various factors influence the robustness of the developed models with respect to the applicability to real slopes. The simulated block volume was limited to 2.0 m^3 and therefore they do not necessarily apply to larger volumes. In the GLM, the Nrp_{red} is linearly extrapolated for larger block volumes, whereas in the RT model a threshold of 2.0 m^3 is fixed and the reductive effect of the forest for larger volumes might be overestimated. Furthermore, since we used the rockfall model Rockyfor3D as an important basis for this study, we assume that this model simulates the rockfall process and impacts against trees sufficiently realistic. It has to be considered, however, that the model takes into account two “species” only, being coniferous and broadleaved, for calculating the energy dissipative capacity of trees. In reality, the range of this capacity is much larger and shows huge variations due to, for example, tree vitality, tree anchoring and other site conditions determining tree growth. Additionally, Rockyfor3D uses a simplified stochastic approach to account for different block shapes. When considering a single block event with a rock shape that does not correspond to standard shapes such as rectangular or spherical, differences between model and reality can be expected.

We could show that the intensity-frequency distributions of rockfall events can be significantly altered below forests compared to non-forested situations. On forested slopes, we observed a typical “rollover effect” for small intensities (e.g. Malamud et al. 2004). This supports the importance of a coupled consideration of intensity and frequency in order to fully account for the forest effect as it was already reported for other natural hazard processes (Alila et al., 2009). Otherwise, risk analyses are expected to be biased and the risk below forests may be overestimated resulting in over-dimensioned structural protection measures associated with high costs.

Overall, this study substantiates the importance of forests in reducing rockfall risk. The statistical prediction models based on the simulation results for different forest and terrain scenarios allow to quantify this effect and to predict it for other slopes, given the constrains mentioned above. In order to validate these results, the models have to be tested on real slopes. Dendrogeomorphic data on tree impacts (Trappmann and Stoffel, 2013, 2015; Morel et al., 2015) might help evaluation of changes in frequency reduction along the slope depending on the forest structure (Corominas and Moya, 2010). However, serious validation of the difference between forested and non-forested slopes remains difficult since data is missing.

The shown influence of the forest type and structure on rockfall occurrence frequency and intensity underlines the importance of forest management aiming at maintenance of its protection function. Disturbances, such as fire, wind, or insects, can temporarily eliminate or at least substantially reduce the protective effect of forests (Maringer et al., 2016; Cordonnier et al., 2008). Also the rockfall process itself, and such as extreme rockfall events, can destroy considerable parts of the forest and, thus, encompass higher rockfall frequency and intensity in the following years (Stoffel et al., 2005).

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Figures

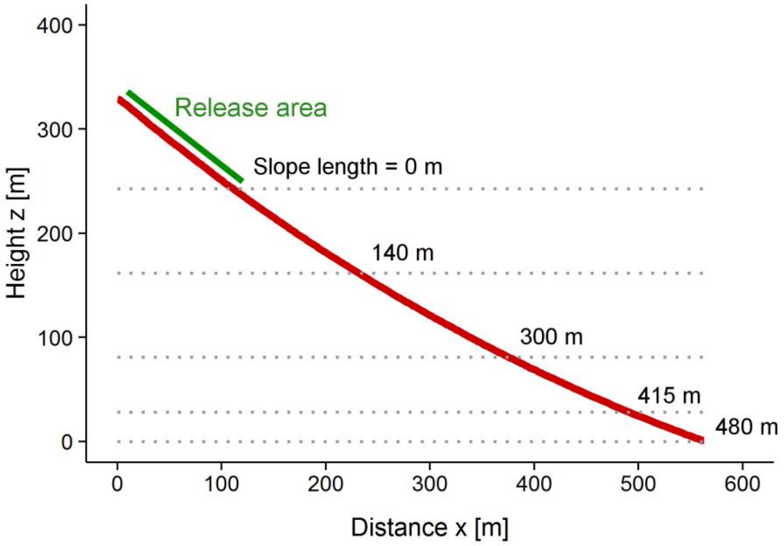


Fig. 1: Profile of the virtually constructed digital elevation model (in red) used for the rockfall simulations. Dotted lines with slope lengths measured on the slope indicate the levels at which rockfall occurrence frequency and intensity were evaluated. The rockfall release area is marked in green. The initial fall height of rocks was set to 10 meters above ground.

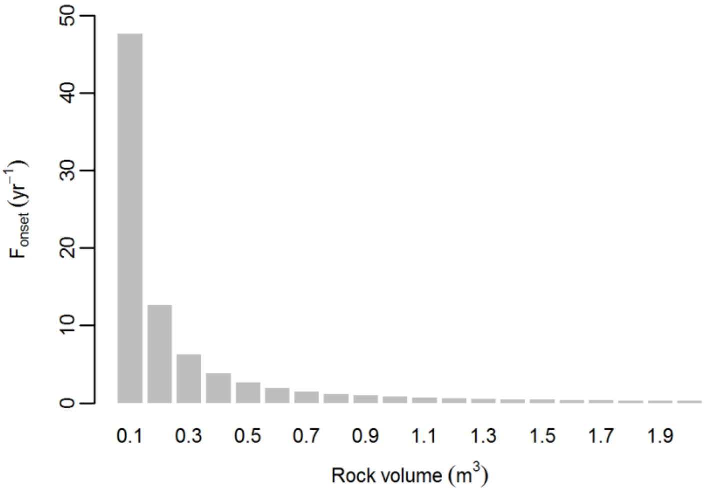


Fig. 2: Expected onset frequency (blocks released per year) on the virtual slope. Calculations are based on a power-law volume-frequency relationship, where ß is the power-law exponent of the cumulative volume frequency distribution and calculated at 0.7 , and where α was set to 12.

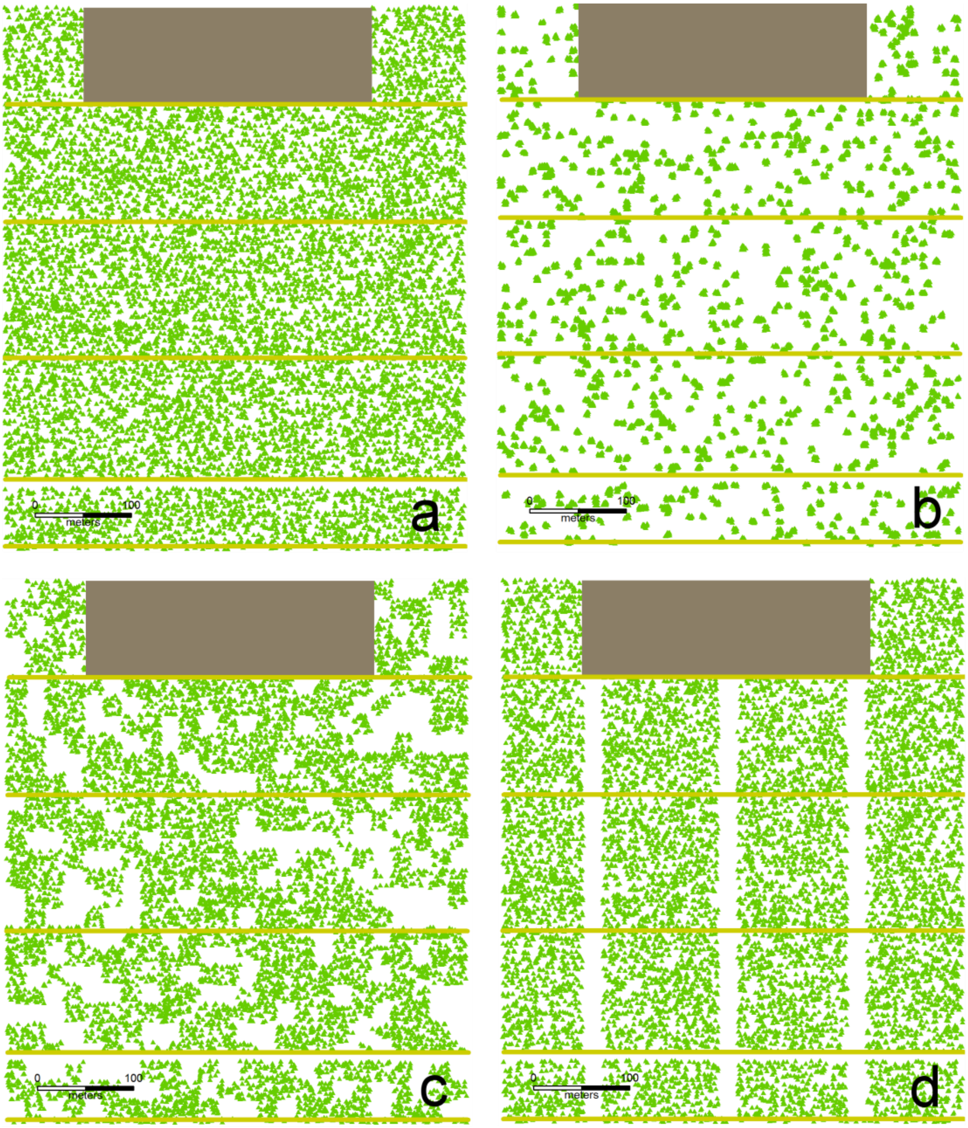


Fig. 3: Design of forest structures and release area of rockfalls for simulation runs. For each forest type, we considered four different scenarios regarding the horizontal forest structure. Forest type 1 is illustrated in (a) with a *random* tree distribution and (b) with random distribution of trees in *clusters* of 10 trees; (c) with a distribution of trees with *random gaps* (minimum 20 x 20 m); and in (d) with 3 *aisles* of 20 m in width starting below the release area of rockfall.

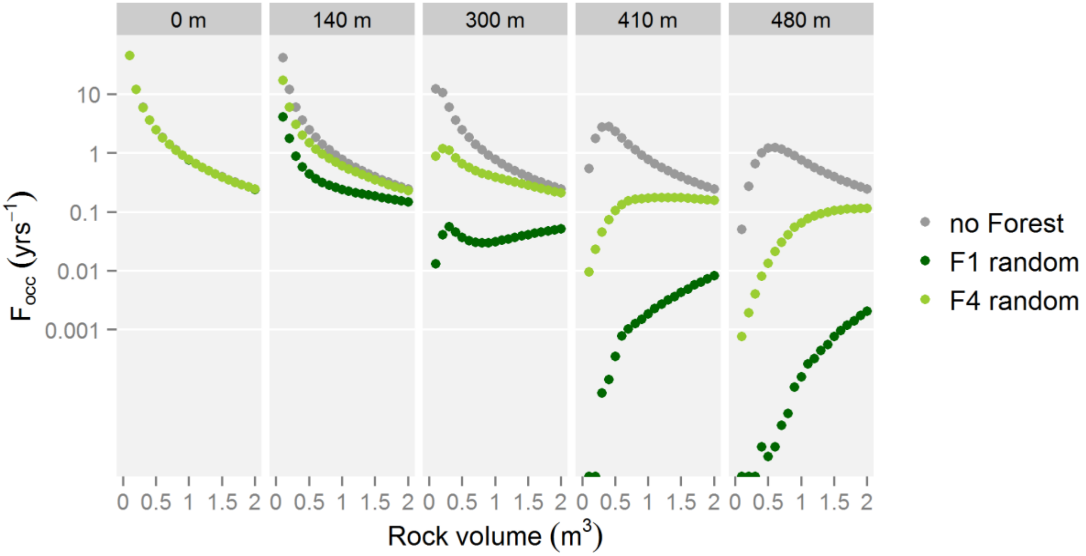


Figure 4: Occurrence frequencies of rockfalls (onset frequency x propagation probability) at different evaluation zones located at 0-500 m downslope of the release area and for block volumes ranging from 0.01 to 2.0 m^3 under forested (forest type 1 (F1): dark green; forest type 4 (F4): light green) and non-forested conditions (grey) with a random tree distribution, soil type 3 and rough slope conditions. Note that the Y-axis is log-transformed.

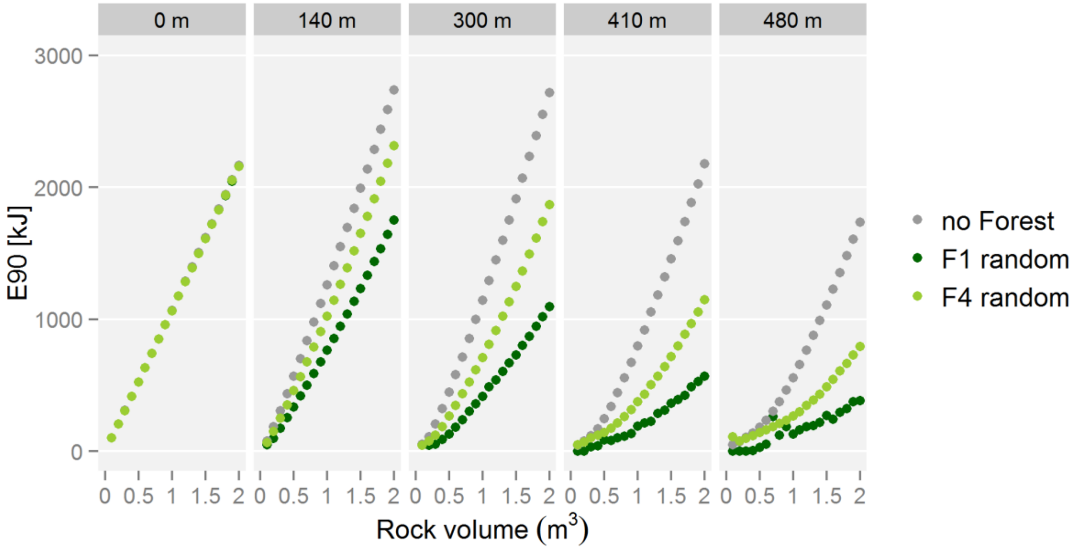


Figure 5: Illustration of the 90th percentile of maximum kinetic energies (E90) of blocks at different evaluation zones located at 0-530 m downslope of the release area based on 50 simulations per block. As before, results include a range of rock volumes from 0.01 to 2.0 m^3 under forested (forest type 1 (F1): dark green; forest type 4 (F4): light green) and non-forested conditions (grey) and with a random tree distribution, soil type 3, and rough slope conditions.

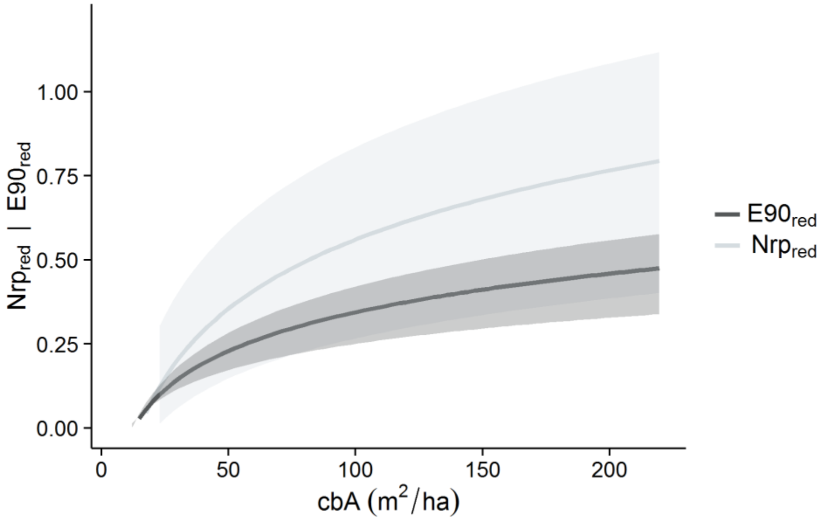


Fig. 6: Nrp$_{red}$ (light grey) and E90$_{red}$ (dark grey) based on the simulation of all forest and terrain scenarios on the concave slope and depending on cbA using a logarithmic smoothing function and the respective 10% - and 90%-quantiles (shaded).

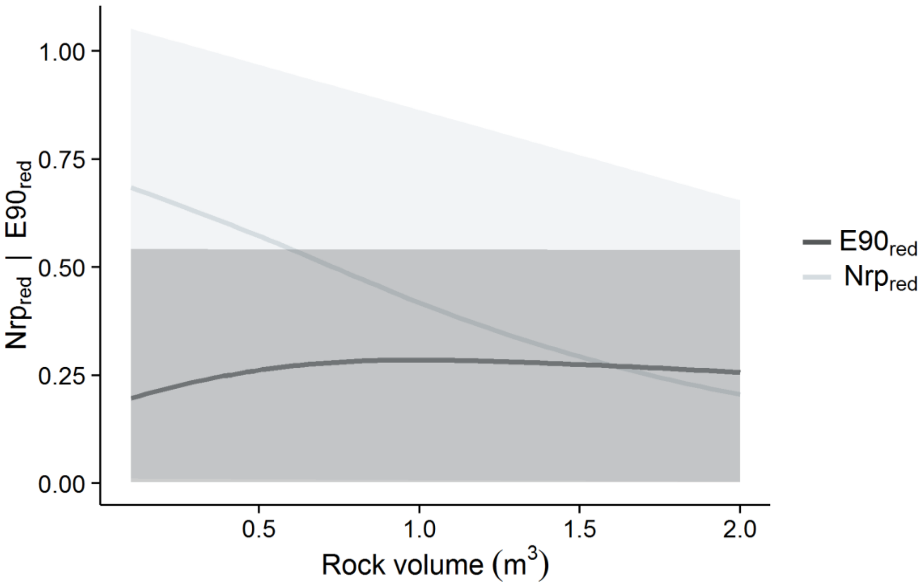
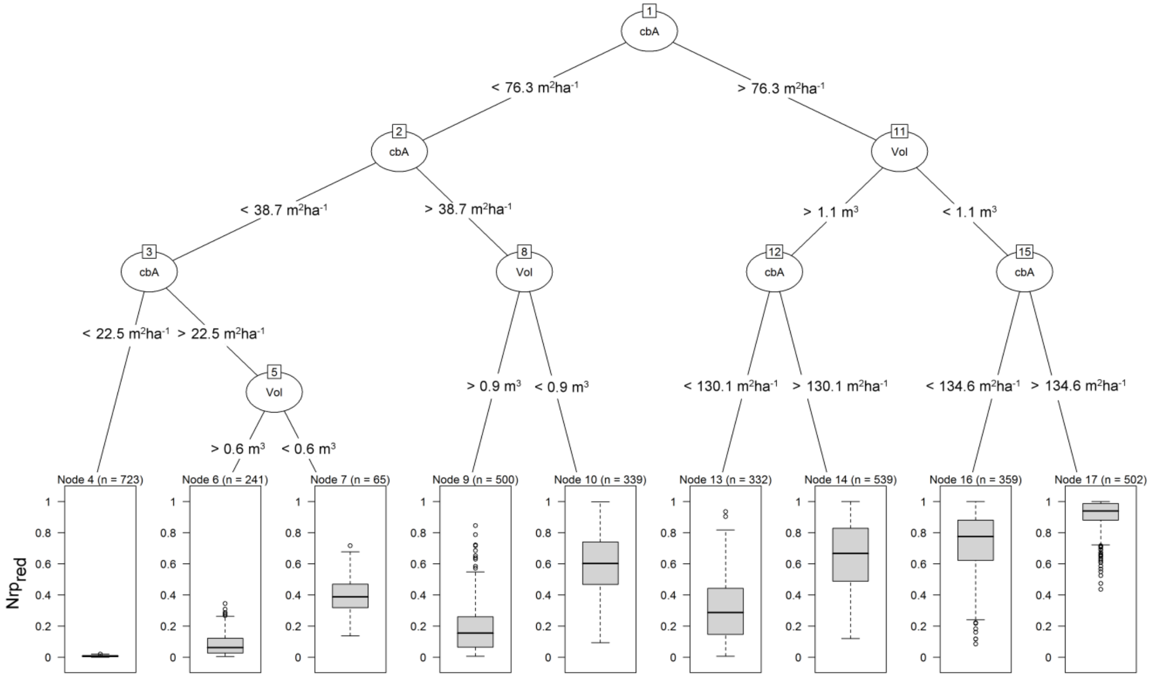


Fig. 7: Nrp$_{red}$ (light grey) and E90$_{red}$ (dark grey) based on the simulation of all forest and terrain scenarios on a concave slope and depending on rock volume using a “loess” smoothing function and the respective 10% - and 90%-quantiles (shaded).


1
cbA
< 76.3 m^{2}ha^{-1}
> 76.3 m^{2}ha^{-1}
2
cbA
11
Vol
< 38.7 m^{2}ha^{-1}
> 38.7 m^{2}ha^{-1}
> 1.1 m^3
< 1.1 m^3
3
cbA
8
Vol
12
cbA
15
cbA
< 22.5 m^{2}ha^{-1}
> 22.5 m^{2}ha^{-1}
5
Vol
> 0.9 m^3
< 0.9 m^3
< 130.1 m^{2}ha^{-1}
> 130.1 m^{2}ha^{-1}
< 134.6 m^{2}ha^{-1}
> 134.6 m^{2}ha^{-1}
> 0.6 m^3
< 0.6 m^3
Node 4 (n = 723)
Node 6 (n = 241)
Node 7 (n = 65)
Node 9 (n = 500)
Node 10 (n = 339)
Node 13 (n = 332)
Node 14 (n = 539)
Node 16 (n = 359)
Node 17 (n = 502)
Nrp$_{red}$
1
0.8
0.6
0.4
0.2
0

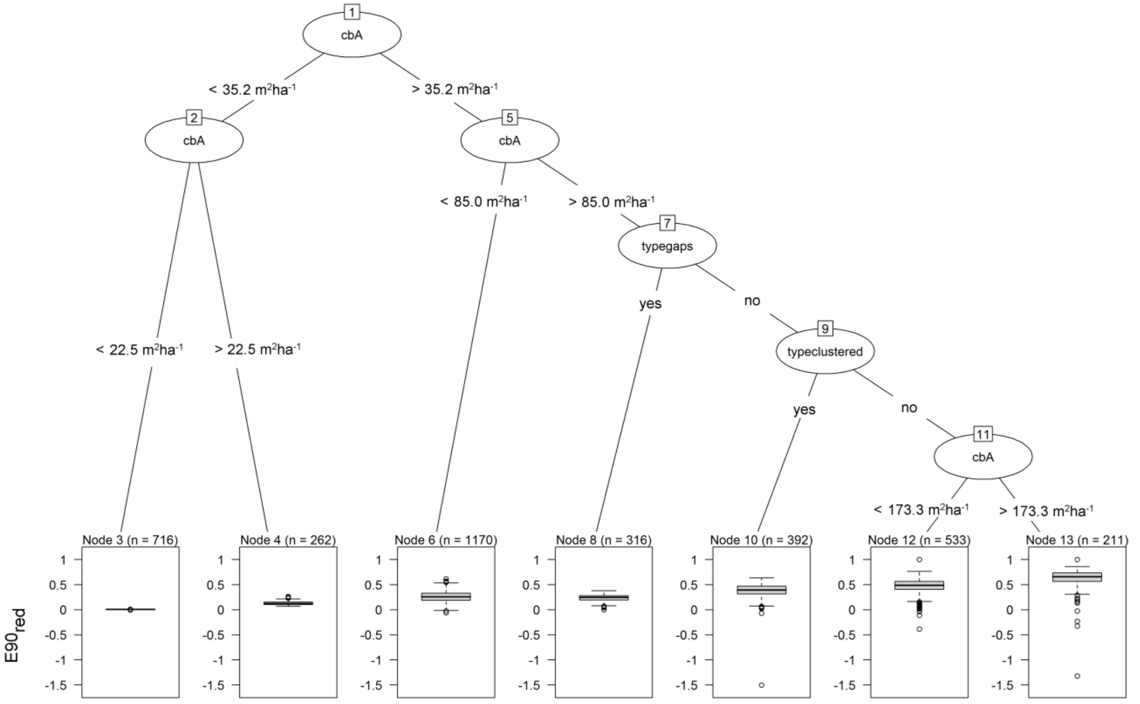

1
cbA
< 35.2 m^{2}ha^{-1}
> 35.2 m^{2}ha^{-1}
2
cbA
5
cbA
< 85.0 m^{2}ha^{-1}
> 85.0 m^{2}ha^{-1}
7
typegaps
yes
no
9
typeclustered
< 22.5 m^{2}ha^{-1}
> 22.5 m^{2}ha^{-1}
yes
no
11
cbA
< 173.3 m^{2}ha^{-1}
> 173.3 m^{2}ha^{-1}
Node 3 (n = 716)
Node 4 (n = 262)
Node 6 (n = 1170)
Node 8 (n = 316)
Node 10 (n = 392)
Node 12 (n = 533)
Node 13 (n = 211)
E90$_{red}$
1
0.5
0
-0.5
-1
-1.5

Figure 8: Regression tree models were used to predict the reduction in rockfall occurrence frequency (RT_{Freq}; above) and the reduction in rockfall intensity (RT_{Int}; below) by forests. The models were fitted with a training set representing 75 % of the entire dataset (n=3600) and by applying 3 times 10-fold cross-validation. The nodes represent the splitting variables followed by the applied threshold value. cbA = cumulative basal area [m^{2}ha^{-1}]; Vol = volume [m^3]; conif100 = coniferous percent [10, 100 %]; typegaps = gappy tree distribution [yes, no]; typeclustered = clustered tree distribution [yes, no].

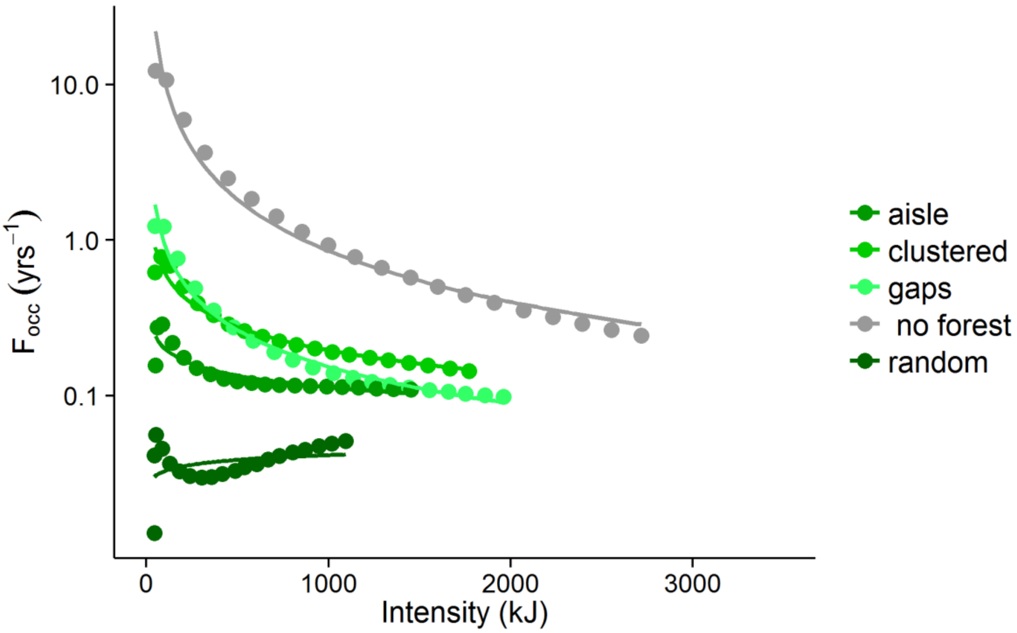


Figure 9: Frequency-intensity distributions with fitted power laws at a distance of 300 m from the release area for forest type 1 with different horizontal forest structures and without forest. The intensity is expressed as the 90th percentile of the maximum kinetic energy of the simulated blocks (50 blocks per source cell) passing through the evaluation line.

Tables

Table 1: Soil types and roughness used for the different simulation scenarios according to the classification of Dorren (2015). The release area and the forest road were set to no roughness and soil types 5 and 7, respectively, in all scenarios.

	Slope scenarios			**Release area**
Soil types	soil type **3:** scree ø < ~10 cm or medium compact soil with small rock fragments	soil type **3:** scree ø < ~10 cm or medium compact soil with small rock fragments	soil type **4:** talus slope ø > ~10 cm or compact soil with large rock fragments	soil type 5: bedrock with thin weathered material or soil cover
Roughness	**Rough:** 0.15 (10 %), 0.05 (20 %), 0.01 (70 %)	**No:** 0 m (100 %)	**Rough:** 0.15 (10 %), 0.05 (20 %), 0.01 (70 %)	**No:** 0 m (100 %)

Table 2: Characteristics of the different forest types used for the rockfall simulations. Values have been taken form the Swiss National Forest Inventory (NFI) datasets published in Messmer (2014).

Forest type	**Definition**	**Mean number of trees ha^{-1} (with DBH > 12 cm)**	**Mean DBH [cm] (DBH > 12 cm)**	**STD DBH [cm]**	**Percentage of conifers [%]**
1	Fagus sylvatica 1	460	33	8.36	10
2	Pinus sylvestris-Larix decidua	304	40	10.85	100
3	Fagus sylvatica 2	200	33	8.36	10
4	Pole-stand F. Sylvatica	500	21	5.00	10

Table 3: Estimated regression coefficients, standard errors, Z-values (i.e. ratio of estimate and standard error), and p-values of the parametric explanatory variables of the general linear model (GLM) for the reduction in rockfall occurrence frequency by forests ($\mathrm{GLM}_{\mathrm{Freq}}$) and the GLM for the reduction in rockfall intensity ($\mathrm{GLM}_{\mathrm{Int}}$) by forests. The models were fitted with a training set representing 75 % of the entire dataset (n=3600) applying 3 times a 10-fold cross-validation. Note that R^2 $\mathrm{GLM}_{\mathrm{Freq}}$ = 0.80 and R^2 $\mathrm{GLM}_{\mathrm{Int}}$ = 0.69.

	Estimate		Std. Error		Z-value		p (>|z|)	
	$\mathrm{GLM}_{\mathrm{Freq}}$	$\mathrm{GLM}_{\mathrm{Int}}$	$\mathrm{GLM}_{\mathrm{Freq}}$	$\mathrm{GLM}_{\mathrm{Int}}$	$\mathrm{GLM}_{\mathrm{Freq}}$	$\mathrm{GLM}_{\mathrm{Int}}$	$\mathrm{GLM}_{\mathrm{Freq}}$	$\mathrm{GLM}_{\mathrm{Int}}$
(Intercept)	-0.46	-0.38	0.014	0.01	-32.54	-35.99	<2*10-16	<2*10-16
Vol	-0.26	0.02	0.005	0.003	-55.91	6.52	<2*10-16	7.85*10-11
log(cbA)	0.30	0.17	0.003	0.002	100.56	80.40	<2*10-16	<2*10-16
type clustered	-0.09	-0.0.13	0.007	0.007	-13.60	-24.55	<2*10-16	<2*10-16
type gaps	-0.04	0.-0.18	0.007	0.007	-6.06	—31.14	1.51*10-09	<2*10-16
soil type 4	-0.02	0.01	0.006	0.004	-2.95	3.00	0.003	0.009
Roughness 2	-0.07	0.03	0.006	0.004	-12.09	7.89	<2*10-16	3.92*10-15
Conifer percent 100	-0.03	-0.06	0.007	0.005	-4.76	-11.72	1,97*10-16	<2*10-16

Table 4: Normalized Root Mean Squared Error (nRMSE) of the generalized linear models (GLM) and the regression tree models (RT) predicting Nrp_{red} (GLM_{Freq}, RT_{Freq}) and $E90_{red}$ (GLM_{Int}, RT_{Int}) with 3 times 10-fold cross-validation (cv) and for predictions of the test dataset (25 % of the data) and linear slopes with varying slope angle (slope 2-5).

Model	**nRMSE cv**	**nRMSE test**	**nRMSE slope 2 (32°)**	**nRMSE slope 3 (35°)**	**nRMSE slope 4 (38°)**	**nRMSE slope 5 (40°)**
GLM_{Freq}	16 %	16 %	20 %	17 %	12 %	11 %
RT_{Freq}	16 %	17 %	21 %	17 %	11 %	10 %
GLM_{Int}	6 %	9 %	14 %	14 %	13 %	14 %
RT_{Int}	10 %	9 %	10 %	7 %	7%	10 %

Table 5: Model input parameters and predicted values of Nrp_{red} with the GLM and the RT model as well as the measured value for Nrp_{red} for the study site in Vaujany where (Dorren et al., 2006) performed real-size rockfall experiments.

Position	**Vol [m^3]**	**cbA [m^2 ha^{-1}]**	**Forest type**	**Soil type**	**Roughness**	**Nrp_{red} (true)**	**Nrp_{red} (pred, GLM)**	**Nrp_{red} (pred, RT)**
Middle slope	0.5	70.5	Random	4	Rough	0.64	0.55	0.61
Bottom slope	0.5	102.4	random	4	rough	1.0	0.66	0.73

Table 6: α and ß coefficient and adjusted R^2 of the with least-squares fitted power-laws of the non-cumulative frequency-intensity distributions at a distance of 300 m from the release area for forest type 1 with different horizontal forest structures and without forest.

Forest structure	**α**	**ß**	**R^2**
No forest	7.38	1.09	0.98
Random	-3.69	-0.10	0.08
Clustered	1.81	0.5	0.95
Aisle	-0.45	0.25	0.75
Gaps	3.54	0.78	0.98