

Modelling long-term effects of forest dynamics on the protective effect against rockfall

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Abstract

Forest dynamics have long-term impacts on the effectiveness of mountain forests in providing protection against natural hazards, but these are difficult to study because of the long time periods involved. We addressed this difficulty using simulation models, combining the forest patch model ForClim with the rockfall model RockFor^{NET}, and applying the combined simulation tool to a case study. Based on empirical data, we simulated the development of three mountain forests assuming different developmental scenarios over a period of 60 years. The protective effect of the simulated stands was then assessed using a site in the Swiss Alps where data on the terrain and rock characteristics were available. This enabled us to determine the factors that are important for maintaining the long-term protective effect of a mountain forest.

The long-term protective effect of the stands against rockfall was generally high for small rocks, but limited for larger rocks (diameter >0.8 m), indicating that there is a limit to the protective potential of stands on the slope. Key factors for effective protection over the 60 years were a high initial stand density and a relatively low mortality rate. A high density of tree regeneration in the initial stand was also found to increase the long-term protective effect against small rocks, but not against larger rocks.

The modelling approach used could be improved by extending the forest dynamics model beyond 60 years and by including a more detailed representation of tree diameter distributions in the rockfall model.

Keywords: mountain forest, protection forest, stand structure, mortality, ForClim, RockFor^{NET}

1 Introduction

Many mountain forests effectively protect people and their assets against natural hazards such as rockfall, snow avalanches, landslides, debris flow, soil erosion and floods (BRANG *et al.* 2001). The protective effect is mainly provided by the presence of mature trees. However, forest dynamics are constantly evolving, affecting not only stand density but also tree size and distribution. Therefore, the protective effect of a stand varies over time.

In the case of single rockfall events (<5 m³; BERGER *et al.* 2002), the focus of this study, stands with high stem density and large-diameter trees are the most effective in providing protection (OMURA and MARUMO 1988; CATTIAU *et al.* 1995). Such stands, however, are usually susceptible to storm damage (ROTTMANN 1985) and snow break (ROTTMANN 1986; OLIVER and LARSEN 1990). Moreover, they cannot maintain effective long-term protection as they generally have insufficient regeneration. Sufficient regeneration is crucial as it

ensures continuous forest cover, which in turn provides the long-term protective effects. Slow tree growth in mountain forests makes a lack of renewal particularly severe (OTT *et al.* 1997), since this lack will impair the protective effect only after decades. Consequently, the loss of protection may only be recognized when it is too late to take effective ameliorative actions. However, until now, the influence of different levels of tree regeneration on the future protective effect of mountain forests has not been studied.

The protection forest system is difficult to study, let alone to manage, because the constructive forces (e.g. tree regeneration) are very slow, and the destructive forces (e.g. windstorms) are sometimes sudden and violent. This makes it difficult to quantify the influence of forest dynamics on the long-term protective function of a stand. The same is true for the impact of many of the silvicultural measures used to influence natural forest dynamics (SCHÖNENBERGER and BRANG 2004; BRANG and SCHÖNENBERGER *this issue*). This, in turn, makes the successful management of protection forests difficult (BRANG *et al.* 2004). Simulation models can be very valuable tools to overcome these difficulties. They enable the investigation of the long-term dynamics of the protection forest system and to gain knowledge for optimizing the management of protection forests (DORREN *et al.* 2004). In relation to the problem in hand, simulation models can be used for: 1) projecting forest dynamics (JOHNSON *et al.* 2001), and 2) for assessing the level of protection provided by different stand structures (PENG 2000).

The main idea behind this study was to combine two existing models into a simulation tool that could be used to investigate the impact of forest dynamics on the long-term protective effect of mountain forests against single rockfall events. The models had to fulfill several requirements. The forest dynamics model had to accurately project over several decades the development of the key stand characteristics that determine the protective effect of the forest. These key characteristics include tree density, diameter distribution and species composition (DORREN *et al.* 2005). Additionally, the regeneration process had to be included in sufficient detail to reflect the most important features of mountain forest regeneration (e.g. the long regeneration period at high altitudes or constraints such as the impacts of browsing by ungulates).

The rockfall model (or the model of natural hazards in general) had to provide an accurate assessment of the protective effect of a stand. For rockfall, this means that the interaction of falling rocks and trees had to be reproduced with sufficient detail and in a realistic way.

Both processes, forest dynamics and rockfall, have frequently been modelled individually. Forest dynamics, in terms of the structural forest patterns described above, have been successfully reproduced with forest patch models (cf. LINDNER *et al.* 1997; SHUGART 1998; HUTH and DITZER 2000; RISCH *et al.* 2005; WEHRLI *et al.* 2005). The regeneration process, which is usually simulated without great detail (cf. PRICE *et al.* 2001), has recently been improved in the patch model ForClim (WEHRLI *et al.* 2006), and important features of tree regeneration in mountain forests have been included (e.g., individual sapling growth, impact of browsing ungulates). The protective effect that a stand can provide against rockfall can be assessed with sufficient accuracy using recently developed rockfall models, which include the interactions of falling rocks and trees (e.g. DORREN *et al.* 2004; BRAUNER *et al.* 2005; BERGER and DORREN submitted; STOFFEL *et al.* 2006; cf. DORREN 2003 for an overview of rockfall models). Thus, there are several promising models that fulfill the needs of a combined simulation tool.

In this paper, we have combined the forest patch model ForClim (BUGMANN 1994, 1996) with the rockfall model RockFor^{NET} (BERGER and DORREN submitted). We then applied the combined simulation tool to a case study to give an example of its use in investigating a protection forest system. Based on data from three mountain forests in the Swiss Alps, we

first simulated the potential development of the initial stands under several scenarios over a period of 60 years. The protective effect of the simulated stands against rockfall was then assessed by projecting the stands onto a site that had data available for terrain and rock characteristics. Finally, the factors that are important for the long-term protective effects of a stand were identified.

2 Methods

2.1 Description of the simulation models and model combination

The forest patch model ForClim

ForClim was originally developed to assess the impacts of climatic change on the tree species composition and biomass of forests in the Swiss Alps (BUGMANN 1994, 1996). Even though ForClim was not originally designed to simulate structural forest patterns, such as diameter distributions, it has been shown to accurately reproduce such patterns in simulations over several decades (RISCH *et al.* 2005; WEHRLI *et al.* 2005). A detailed description of ForClim can be found in BUGMANN (1996). The model version used in this study, ForClim V2.9.4, is documented in detail in WEHRLI *et al.* (2006).

The rockfall model RockFor^{NET}

RockFor^{NET} was recently developed by BERGER and DORREN (submitted) to provide a tool for assessing the probable residual hazard beneath a protection forest. The residual hazard is thereby a measure of the protective effect of a stand. It is defined as the percentage of rocks passing down a forested slope (i.e. the percentage that cannot be stopped by the forest stand).

RockFor^{NET} is based on the results of more than 100 real-size rockfall experiments and has been validated at several sites (DORREN and BERGER 2006; BERGER and DORREN submitted). It enables realistic assessments of the protective effects of different stand structures. Consequently, it has been frequently applied in the assessment of the residual hazard for different sites in the European Alps.

To assess the residual hazard, RockFor^{NET} calculates the energy balance of a falling rock on a forested slope (i.e., it calculates the energy a falling rock can develop on a given slope, and compares this to the energy that can be dissipated by the stand on the slope). The model requires only a few input parameters which characterize the stand (species composition, stand density, a representative diameter at breast height (DBH), i.e. a measure of location that is representative of the DBH distribution), the terrain (cliff height, slope length between the foot of the cliff and the foot of the forested slope, slope length of the forested slope, and mean slope gradient) and the rocks (mean rock diameter and rock density).

The terrain and rock parameters are used to determine the energy developed by a falling rock. The calculation is based on the energy line angle – the angle of the straight line between the starting point and the maximum stopping point (HEIM 1932; TOPPE 1987; GERBER 1994).

The forest stands are considered as spatially-distributed “rockfall curtains” – i.e. the stand input parameters are used to generate virtual rows of trees standing next to each other (BERGER and DORREN submitted). The trees in a row have the same diameter, equal to the given representative DBH. This diameter, in combination with the tree species, determines the effectiveness of a tree row in dissipating energy during a rockfall impact.

To calculate the probable residual hazard, the model determines the number of tree rows required for full protection on the foot of the slope (i.e., 100 % of the rocks are stopped). Finally, RockFor^{NET} compares the required number of trees with the existing number of trees in the stand and translates the difference between the two into a probable residual hazard, ranging from 0 to 100 %.

Model combination

For the present study, the two models were not physically combined, but joined together by file exchange. Thus, the stand input data needed for the RockFor^{NET} model was derived from the projected stand structures simulated by ForClim.

2.2 Model input data and modelling scenarios

Stand and regeneration data

We modelled several scenarios based on empirical stand and regeneration data from three mountain forests in the Swiss Alps. The forests are dominated by Norway spruce (*Picea abies* [L.] Karst.) and silver fir (*Abies alba* Mill.) and situated between 700 and 1000 m above sea level. Figure 1 and Table 1 give an overview of the current regeneration and stand structure of the three forests.

The first stand is fairly even-aged (EA), and is referred to as the EA-stand. It consists of 561 trees ha⁻¹ >4 cm DBH, and only minor timber harvesting has taken place during in recent decades. Tree regeneration (from 1 cm height and up to 3.9 cm DBH) is rather scarce, with approximately 2230 saplings ha⁻¹ (Table 1). The second stand is currently being converted

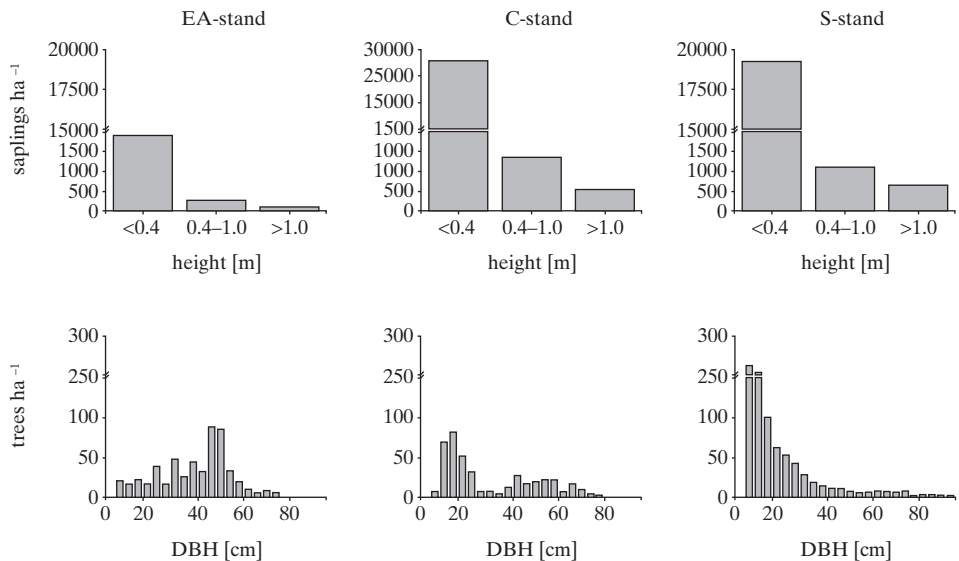


Fig. 1. Size distributions of tree regeneration (above) and DBH (below) for the three initial stands.

Table 1. Stand and regeneration characteristics of the three initial stands used in the simulation of forest dynamics.

Stand	Stand characteristics (main tree species, stand basal area (BA), median DBH and tree density at beginning of simulation [trees > 4 cm DBH])	Regeneration characteristics (main tree species, and sapling density up to 4 cm DBH at beginning of simulation)
EA-stand (even-aged stand)	Norway spruce (83 %), Silver fir (13 %) BA = 73.8 m ² ha ⁻¹ , DBH _{med} = 42.3 cm, 561 trees ha ⁻¹	Norway spruce (20 %), Silver fir (44 %) 2230 saplings ha ⁻¹
C-stand (stand under conversion)	Norway spruce (32 %), Silver fir (62 %) BA = 44.5 m ² ha ⁻¹ , DBH _{med} = 36.6 cm, 430 trees ha ⁻¹	Norway spruce (42 %), Silver fir (57 %) 31 090 saplings ha ⁻¹
S-stand (selection stand)	Norway spruce (43 %), Silver fir (52 %) BA = 35.1 m ² ha ⁻¹ , DBH _{med} = 26.4 cm, 901 trees ha ⁻¹	Norway spruce (49 %), Silver fir (51 %) 22 170 saplings ha ⁻¹

into a selection forest (plentering according to SCHÜTZ 2001). It is referred to as the C-stand (stand under conversion). The stand consists of 430 trees ha⁻¹ >4 cm DBH, and there is ample tree regeneration, with more than 30 000 saplings ha⁻¹ (Tab. 1). The third stand has been managed as an uneven-aged selection forest for several decades. It is referred to as the S-stand. The stand consists of 901 trees ha⁻¹ >4 cm DBH, and there is abundant tree regeneration, with more than 20 000 saplings ha⁻¹ (Table 1).

Scenarios for the simulation of forest dynamics

The forest dynamics scenarios were based on: i) different initial stand and regeneration structures (variation of input data), and on ii) different model parameters (variation of growth constraints). An overview of the different scenarios for the simulation of the forest dynamics is given in Table 2.

We used the three initial stand and regeneration structures described above as input data. Additional scenarios for tree regeneration were included by varying sapling density and species composition in the regeneration input data. Three levels of sapling density were used, low, intermediate and high (Table 3), and species composition was varied to include the initial composition, 100 % Norway spruce regeneration, and 100 % silver fir regeneration.

The range of input data established alternative growth constraints, as stand structure strongly affects stand dynamics. Additional growth constraints were included by variation of two model parameters – browsing impact on saplings and the mortality rate of trees. Browsing impact was varied in terms of browsing intensity, which led to a species-specific reduction in sapling growth (Table 4; for details see WEHRLI *et al.* 2006). Tree mortality was varied between a standard mortality rate and an increased mortality rate. The standard mortality rate is the standard value of age-related tree mortality in patch models, which implies that 1 % of all established saplings survive to their species-specific maximum age (SHUGART 1984; BUGMANN 1994). In contrast, the increased mortality rate enables the depiction of

processes that are not explicitly modelled, such as a coarse reproduction of a thinning regime or increased tree mortality due to injuries from falling rocks. The mortality rate was thereby increased to reflect the assumption that only 0.1 % of the established saplings reach their maximum age. The same increased mortality rate was used in the study by RISCH *et al.* (2005).

Table 2. Scenarios for the simulation of forest dynamics for each initial stand.

	Species composition of tree regeneration		
	Initial composition	100 % Norway spruce	100 % silver fir
Levels of sapling density	3	3	3
Levels of browsing impact	5	2	2
Levels of mortality rate	2	2	2
<i>Total scenarios per initial stand</i>	<i>30</i>	<i>12</i>	<i>12</i>

Table 3. Variation of tree regeneration. Bold figures denote the initial level of tree regeneration. Regeneration levels were varied by factors of 5 (medium) and 10 (high) for the EA-stand, and by factors of 0.5 (medium) and 0.1 (low) for the C- and the S-stand, respectively.

Regeneration level	EA-stand	C-stand	S-stand
Low	2230	3109	2217
Medium	11150	15545	11085
High	22300	31090	22170

Table 4. Variation of browsing impact on the main tree species. Browsing impact is determined by multiplying the species-specific browsing susceptibility included in ForClim (Norway spruce = 0.25, silver fir = 0.75) by browsing intensity. Together with canopy shading, browsing impact then determines the species-specific reduction of sapling growth (reduction factor for sapling growth within a range of 0–1, whereby 0 denotes optimum height growth and 1 denotes no more height growth; for details see WEHRLI *et al.* 2006).

Species	Browsing intensity				
	0	0.67	1	1.33	2
silver fir	0	0.5	0.75	1	1
Norway spruce	0	0.166	0.25	0.333	0.5

Terrain and rock characteristics

The terrain and rock input data needed for RockFor^{NET} (Table 5) were derived from empirical terrain and rock characteristics from the site with the EA-stand. This site, called Stotzigwald, is a steep forested slope in the Swiss Alps (46°45' N and 08°39' E) with a mean slope gradient of more than 40° and multiple interspersed cliffs (THALI 1997). The forest provides protection for one of the most important highways connecting northern and southern Europe.

Scenarios for the assessment of the protective effect

The protective effect of the simulated stand structures was assessed for six different rock size classes (S1–S6), ranging from a rock diameter of 0.2 m (S1) up to 1.2 m (S6; Table 5). For each rock size class, the residual hazard of each simulated stand structure was calculated.

Table 5. Terrain and rock characteristics for the assessment of the protective effect derived from Stotzigwald site.

	Site Stotzigwald
Cliff height	40 m
Slope length between cliff and forested slope	0 m
Slope length of the forested slope	325 m
Mean slope gradient	45°
Mean rock diameters	0.2, 0.4, 0.6, 0.8, 1.0, 1.2 m
Rock density	2700 kg / m ²

2.3 Simulation set-up

Simulation of forest dynamics

Starting from one of the three initial stands, each forest scenario was simulated for a period of 60 years, which is currently considered to be the limit of accurate predictions of structural forest patterns with the ForClim model (cf. WEHRLI *et al.* 2005). Only the current tree regeneration data were used in the simulations, and additional seedling regeneration during the simulation period was excluded since data for reliable parameterizations and corroborations were not available. As evident from the study by WEHRLI *et al.* (2006), this simplification did not significantly affect the simulated stand structure after 60 years in terms of the protective effect against rockfall.

For the simulations based on the C- and S-stands, the parameterization of the tree growth module of ForClim was slightly modified because preliminary simulation runs with the standard parameterizations over-estimated tree growth compared to empirical growth data from long-term data series from these stands (Table 6). This overestimation is probably due to the parameterization of the dynamic crown structure implemented in ForClim V2.9.4, which is mainly based on data from stands that tend to be even-aged (cf. WEHRLI *et al.* 2006). We therefore introduced a correction factor in terms of a multiplier for the leaf area index for the C-stand (a correction factor of 1.2) and the S-stand (a correction factor of 1.3), which led to more realistic growth rates (Table 6).

The initialization of ForClim with stand and regeneration data was performed at the scale of individual patches, whereby the patch size was set to 225 m² (15 m × 15 m) for the present study. To reduce the stochastic “noise” in the simulation results, the simulation experiments were performed with numerous repetitions ($n = 237\text{--}320$ patches, depending on the area covered by the initial stand; cf. BUGMANN 1996; PRETZSCH and DURSKY 2001).

The input for the weather generator included in ForClim was derived from time series of monthly precipitation sums and monthly mean temperatures from the weather station at Gurtzellen (739 m a.s.l.), approximately 2.5 km from the site with the EA-stand (Stotzigwald).

Table 6. Growth rates simulated with ForClim with and without CF for the C- and S-stand, and comparison with empirical data from long-term data series for both stands. CF denotes the correction factor included in ForClim to modify the leaf area index (see text). Growth rates are measured in terms of increment of basal area ha^{-1} over 60 years. na: not available.

	empirical growth	No CF	CF 1.2	CF 1.3	CF 1.4
C-stand	42.0	50.1	42.5	na	na
S-stand	47.7	64.6	50.9	47.0	42.0

Assessment of the protective effect

For the assessment of the protective effect of the simulated stands, we only considered trees with a DBH >8 cm because the role of smaller trees in rockfall protection is unknown. Species composition and stand density were derived from the output file of ForClim and included in RockFor^{NET}. The measure of location for the DBH needed as input for RockFor^{NET} was set to the median, since most of the simulated DBH distributions were rather asymmetric. For such distributions, the median is more representative than other measures of locations (SOKAL and ROHLF 1995), and the median was therefore considered to deliver more accurate results. This assumption was confirmed by preliminary tests with other measures of location such as the mean quadratic DBH. The latter yielded poor results, with most of the scenarios for S1–S4 having no residual hazard at all. This, however, seems very unlikely on the Stotzigwald site.

2.4 Analysis of simulation results

Assessment of the residual hazard under different simulation scenarios

The protective effect provided by the different scenarios was compared graphically for all stands together and for each initial stand using boxplots (SOKAL and ROHLF 1995; SPSS Inc. 2001). The range of the residual hazards over all scenarios and the mean residual hazard over all scenarios were calculated for each rock size class. The parametric (Pearson correlation, cf. STAHEL 2000) and non-parametric (Spearman correlation, cf. STAHEL 2000) correlations between the simulated stand structures and the residual hazards were determined.

Derivation of indicators for a high long-term protective effect

We used logistic regression models to identify the most important determinants of a long-term protective effect for each rock size class. The different levels of residual hazards for each rock size class were divided into two classes, representing a high and a low protective effect, respectively, to provide the necessary binary target variable. The threshold for the allocation into these classes was fixed for each rock size class, based on qualitative observations of the frequency of rockfall events for each size class at the Stotzigwald site (Table 7). Since these events are rather frequent for smaller rocks, the thresholds for those rock size classes were set to low levels. In contrast, the threshold for S3–S6 rock classes was set to considerably higher values, to account for the lower frequency of these events.

Continuous variables (SOKAL and ROHLF 1995, p.11) were first transformed following the Tukey first aid transformations (cf. STAHEL 2000) and then included in the logistic model, whereas the categorical variables (browsing impact and mortality rate) were included as categorical co-variables based on the indicator contrast method (SPSS Inc. 2001). The most important variables for each rock size class were then determined with a backward

selection method based on Wald-values (SPSS Inc. 2001; SOKAL and ROHLF 1995). The model assumptions were verified by examining the residuals (STAHEL 2000).

In addition to the logistic models, the boxplots were examined visually and the parametric and non-parametric correlations between all variables were determined.

Table 7. Limits for the binary target variable for the logistic regression models. Stands that delivered a residual hazard up to the limit values are considered to have a high protective effect, the others are allocated to the class with a low protective effect.

	Rock size class					
	S1 (d = 0.2 m)	S2 (d = 0.4 m)	S3 (d = 0.6 m)	S4 (d = 0.8 m)	S5 (d = 1.0 m)	S6 (d = 1.2 m)
Limit	0.1 %	10 %	30 %	50 %	50 %	50 %

3 Results

3.1 Residual hazards of different stands

Residual hazard of the initial stands

The initial stands differed markedly in their protective ability against the six rock size classes (Table 8). Whereas the EA-stand, which corresponds to the current stand at the Stotzigwald site, yielded an acceptable residual hazard for all rock size classes, the performance of the C- and in particular of the S-stand were very limited for rocks with a diameter >0.2 m. From size class S4 on, the residual hazard for these two stands was >90 % – indicating that their protective effect was only marginal.

Table 8. Range of residual hazards and mean residual hazard per rock size class for all simulated stands as well as mean residual hazard and initial residual hazard per initial stand. RH: Residual hazard in %.

Rock size class	All sites		EA-stand		C-stand		S-stand	
	mean RH	range of RH	initial RH	mean RH	initial RH	mean RH	initial RH	mean RH
S1 (d = 0.2 m)	1	0–24	0	1	4	1	2	0
S2 (d = 0.4 m)	24	0–76	0	24	17	37	51	10
S3 (d = 0.6 m)	61	0–97	0	54	60	82	90	47
S4 (d = 0.8 m)	78	0–99	6	67	91	95	98	74
S5 (d = 1.0 m)	89	2–100	36	76	97	98	99	91
S6 (d = 1.2 m)	93	31–100	51	84	99	99	100	97

Residual hazards of simulated stands after 60 years

The residual hazard of the simulated stands after 60 years was low for rocks with a diameter of 0.2 m (rock size class S1, cf. Fig. 2). In most of the scenarios, the residual hazard was close to zero, but a few scenarios produced residual hazards of up to 24 % (i.e., 24 % of the rocks passed through the simulated stand) (Table 8). With increasing rock diameter, the mean residual hazard over all scenarios rapidly increased from 24 % (S2) to 61% (S3) and 78 % (S4), respectively (Table 8, Fig. 2). For the largest rock size classes (S5 and S6), the protective effect was even smaller (Table 8). Still, the range of the residual hazards for these classes

indicated that under a few scenarios, the simulated stands were able to yield a residual hazard <50% (Fig. 2). Those scenarios only occurred in the EA-stand, and generally involved the standard mortality rate and a relatively low regeneration density.

The residual hazard under different scenarios depended strongly on the initial stand (Fig. 3). Simulations based on the EA- and S-stands generally resulted in a higher protective effect than those based on the C-stand, as shown by the mean residual hazards for each initial stand (Table 8). The latter only provided a low residual hazard for rock size class S1 ($d = 0.2$ m), and a rather low residual hazard for rock size class S2 ($d = 0.4$ m, mean residual hazard: 37 %, cf. Fig. 3 and Table 8).

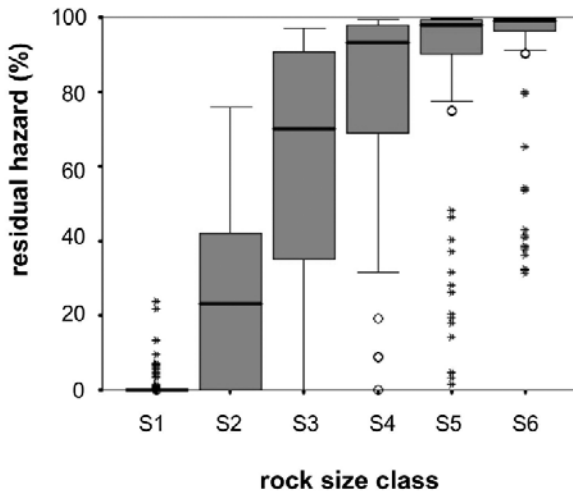


Fig. 2. Residual hazards over all scenarios for each rock size class. Circles denote outliers (1.5–3 box lengths from the end of the box), asterisks mark extremes (> 3 box lengths from the end of the box).

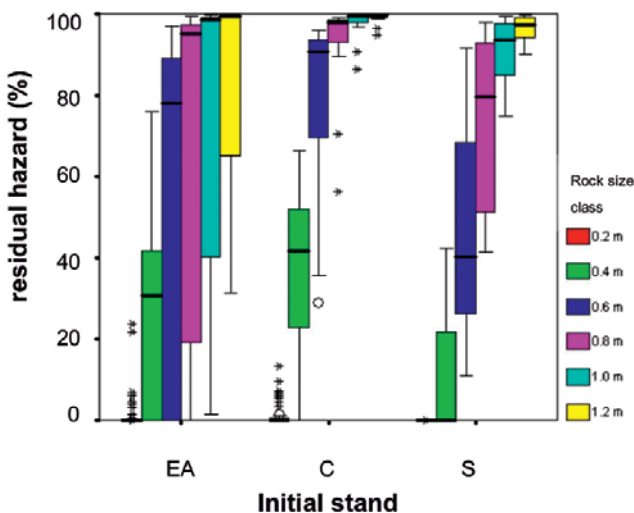


Fig. 3. Residual hazards over all scenarios for each rock size class and initial stand. Box plot symbols are explained in the legend to Figure 2.

Development of the residual hazards during the simulation period

The EA-stand, which initially provided a relatively high protective effect (Table 8), showed an increase in the residual hazard under several simulation scenarios. For the smallest rock size class, S1, 13 scenarios yielded an increase in the residual hazard when compared to the initial stand. For rock size classes S2 to S6, the residual hazards increased in 32 (S2) to 44 (S4–S6) of the 54 scenarios. Most of the scenarios leading to an increased residual hazard included an increased mortality rate.

In the scenarios based on the C-stand, which initially showed rather high residual hazards (Table 8), the residual hazard increased in comparison to the EA-stand. For S2 to S6, almost all scenarios led to an increased residual hazard compared to the initial stand. For S1, however, the residual hazard only increased under seven scenarios that had increased mortality rates.

In contrast to the C-stand, the residual hazards decreased in the S-stand, which showed relatively high residual hazards at the beginning (Table 8).

3.2 Key factors for the assessment of the residual hazard with RockFor^{NET}

The simulated stand density, and for larger rocks particularly the simulated median DBH, showed the highest correlations with the residual hazard for each rock size class, and can thus be seen as key factors for assessing the residual hazard with RockFor^{NET} (Table 9). The two key factors were negatively correlated (parametric: -0.66, non-parametric: -0.52, $p < 0.01$).

The simulated median DBH and the residual hazard were negatively correlated for all rock size classes, with very high correlations for S3 to S6 (Table 9). In contrast, the simulated stand density (stem number) and the residual hazard were only negatively correlated for rock size class S1. For all larger rocks, the correlations were found to be: i) positive, and ii) at a lower level than the correlations between the simulated median DBH and the residual hazard.

Table 9. Important correlations between simulated stand structure and residual hazard. Values denote parametric (Pearson) and non-parametric correlations (Spearman, in brackets). Negative signs indicate a negative correlation. All correlations are significant at the 0.01 level (2-tailed).

Rock size class	All sites	
	simulated median DBH	simulated density
S1 (d = 0.2 m)	-0.20 (-0.37)	-0.24 (-0.3)
S2 (d = 0.4 m)	-0.69 (-0.95)	0.46 (0.45)
S3 (d = 0.6 m)	-0.88 (-0.98)	0.62 (0.55)
S4 (d = 0.8 m)	-0.96 (-0.98)	0.61 (0.55)
S5 (d = 1.0 m)	-0.96 (-0.98)	0.56 (0.55)
S6 (d = 1.2 m)	-0.93 (-0.98)	0.52 (0.55)

3.3 Important factors for a long-term protective effect

The most important factors associated with a high long-term protective effect were determined for the rock size classes S1 to S4 using logistic regression models for each rock size class. Rock size classes S5 and S6 were excluded from these analyses because the protective effect was generally low for large rocks. An overview of the four logistic regression models is presented in Table 10. Variables with a negative B-value denote factors that helped to reduce the residual hazard, and thus to increase the protective effect.

For the rock size class S1 ($d = 0.2$ m), a low residual hazard was associated with high initial stand density, high regeneration density and a low mortality rate (Table 10). These findings were confirmed by boxplots for the three factors over all simulation scenarios (Fig. 4), although this is barely visible given the overall low residual hazard for S1.

For the rock size classes S2 to S4, ranging from 0.4 to 0.8 m in diameter, the same factors had a significant influence. A low residual hazard was associated with high initial stand density and a low mortality rate as for the smallest rocks, but with a low regeneration density (Table 10). Moreover, for rock size class S3, a high initial median DBH was associated with a low residual hazard (Table 10). Again, these findings were confirmed in the boxplots (Fig. 4).

Table 10. Logistic regression models for the rock size classes S1 to S4. Negative signs indicate variable that lead to a reduced residual hazard.

All variables significant at the $p < 0.01$ level. $n = 162$ scenarios (54 per initial stand)

Rock size class	Parameter	Multiple logistic regression model		
		limit	B-value	Wald
S1 ($d = 0.2$ m)	Regeneration density 2005	0.1 %	-0.023	16.3
	Initial stand density 2005		-0.821	25.4
	Standard mortality rate		-1.605	10.0
	Constant		20.034	26.3
S2 ($d = 0.4$ m)	Regeneration density 2005	10 %	0.022	15.0
	Initial stand density 2005		-0.824	30.7
	Standard mortality rate		-2.644	25.3
	Constant		18.751	28.9
S3 ($d = 0.6$ m)	Regeneration density 2005	30 %	0.029	17.9
	Initial stand density 2005		-1.114	10.6
	Initial median DBH 2005		-0.166	7.2
	Standard mortality rate		-2.284	15.6
	Constant		32.030	10.2
S4 ($d = 0.8$ m)	Regeneration density 2005	50 %	0.028	17.2
	Initial stand density 2005		-0.453	9.5
	Standard mortality rate		-2.076	13.1
	Constant		10.868	9.6

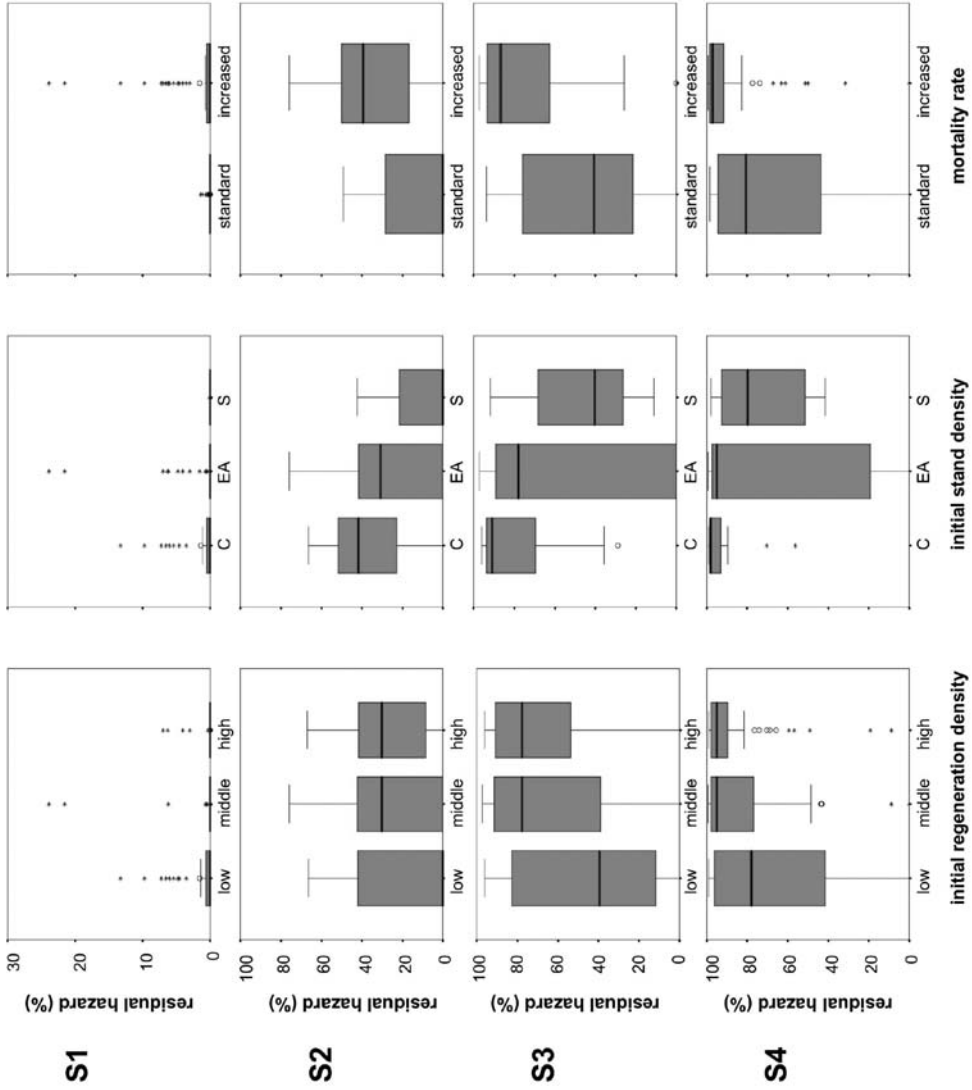


Fig. 4. Relationship between residual hazard and initial regeneration density (first column), initial stand density (second column) and mortality rate (third column) for rock size class S1 (first row), S2 (second row), S3 (third row), and S4 (fourth row). Box plot symbols are explained in the legend to Figure 2.

4 Discussion

4.1 Residual hazards of different stands

The residual hazards under the different simulation scenarios were essentially different for the six rock size classes. For the smallest rocks included in this study (S1 with $d = 0.2$ m), all initial stands and almost all simulated stands showed low residual hazards; they had a high protective function. Additional assessments of the protective effect against rocks smaller than S1 ($d < 0.2$ m) always yielded a residual hazard of zero. As there is empirical evidence for very small rocks passing through the forests on the very steep slope studied, we believe that a rock diameter of about 0.2 m represents the lower boundary of the applicability of the RockFor^{NET} model. The approach of the RockFor^{NET} model, which only accounts for the forest when calculating the energy balance of a moving rock, is probably too simplistic for smaller rocks. For such rocks, factors neglected in the model (e.g. surface roughness or dampening effects of the surface) are likely to influence the energy balance of falling rocks significantly. In particular, surface roughness (e.g. woody debris, branches, shrubs, or stationary rocks) can slow down or even stop falling rocks (JAHN 1988; MEISSL 1998; DORREN 2002; SCHÖNENBERGER *et al.* 2005). The impact of these additional factors on the energy balance of falling rocks is very difficult to quantify, and these factors are therefore not included in RockFor^{NET}.

For rocks with $d > 0.8$ m, our results indicate the limitations of any forest on the present, relatively short slope (325 m). On this slope, and under the given terrain characteristics, larger rocks can develop energy that cannot be dissipated by most of the simulated stand structures. This finding is in agreement with RICKLI *et al.* (2004) who state that the mitigating effect of stands on rockfall is limited by the mass and velocity, and thus energy, of the falling rocks. As a consequence, technical counter-measures against large rocks are needed to reduce the residual hazard for the highway at the Stotzigwald site. Such counter-measures have indeed been installed, including restraining nets that can dissipate up to 500 kJ (FREI 2003).

For all rock size classes, the initial stand conditions had a considerable impact on the long-term protective effect. This was confirmed by the four logistic regression models. The C-stand, which is currently being converted into a selection forest, is the most limited of the three initial stands in terms of long-term protective effects. This stand only shows acceptable low residual hazards for S1- and, partially, for S2-sized rocks (Fig. 3). The reasons for this are probably: i) the low initial tree density, and ii) the initial bimodal DBH distribution, which shows a nadir between 24 to 36 cm DBH (Fig. 1). After 60 years, this initial nadir has moved to larger DBH classes, leading to a lack of such trees. Without large trees in sufficient numbers, the high-energy developed by rocks in size classes S3 to S6 cannot be dissipated sufficiently.

The S-stand which, together with the C-stand, only showed a very limited protective effect in its initial condition (see above), yields a better performance in the long term, as is evident from the development of the residual hazards compared to the initial residual hazard. This is very probably due to a considerable initial tree density with DBH < 36 cm in the S-stand (Fig. 1), leading to a higher number of large trees after 60 years compared to the C-stand.

The best protective effect after 60 years, however, is generally still provided by the EA-stand, which initially shows a high number of larger trees (both $>$ and < 36 cm DBH). In the beginning, the EA-stand probably provides an almost optimal protective effect for the Stotzigwald site. Over a period of 60 years, however, the protective effect decreases slightly, as indicated by the increase of residual hazards under several simulation scenarios for all

rock size classes (see page 70). Over periods longer than 60 years, the protective effect of the EA-stand is likely to decrease further since the initial DBH distribution shows a rather low density of small trees (Fig. 1). In combination with the rather sparse level of current tree regeneration in the EA-stand (Table 1), this will probably lead to a lack of large trees in the long term, which in turn will induce an increase in the residual hazard (see page 70). Thus, when looking at a time period >60 years, the S-stand with its abundant tree regeneration and its high stand density is likely to perform better than the EA-stand. This is already indicated by the mean residual hazards for the S-stand after 60 years, which for S1 to S4 are either already lower or at least very close to the values for the EA-stand. However, these assumptions cannot reliably be verified with the present simulation tool because the accuracy of the projected stand structures obtained with the present ForClim version declines after several decades (WEHRLI *et al.* 2005). Consequently, accurate simulations with ForClim over periods longer than 60 years were not possible in this study.

4.2 Key factors for the assessment of the residual hazard with RockFor^{NET}

As can be seen from the strong correlations, the assessment of the residual hazard on a given site with RockFor^{NET} highly depends on two key factors – the simulated stand density and the simulated median DBH. The influence of these two factors on the residual hazard is closely related to rock size, and changes with increasing rock size. For small rocks, stand density and DBH reduce the residual hazard, with the influence of both factors appearing similar. This is in agreement with JAHN (1988), who reports a significant influence of both DBH and stand density on the protective effect against small rocks.

For larger rocks, the negative influence of the median DBH increases to very high values, whereas the simulated stand density is positively correlated with the residual hazard (i.e., the more trees, the higher the hazard). We think, however, that this positive correlation is not causal but mainly due to the strong negative correlation between simulated median DBH and simulated stand density (parametric correlation of -0.66 , non-parametric correlation of -0.52). A high simulated stand density is mainly caused by the recruitment of many young trees, which in turn leads to a decrease of the median DBH. This suggests a weakness in the current RockFor^{NET} version: RockFor^{NET} uses one single key indicator to represent the DBH distribution of a stand. This indicator in turn determines the energy that can be dissipated by a tree row. Therefore, the model outcome, and by this the “performance of the stand,” is very sensitive to this indicator.

Nevertheless, our simulation results are in agreement with findings from empirical field studies, which report a similar change in importance of the key factors determining the protective effect of a stand against rockfall: from stand density to stem size (DBH) with the progression from small to larger rocks (DORREN *et al.* 2005; KALBERER *et al.* 2005).

4.3 Important factors for a high long-term protective effect

In all of the logistic regression models, initial stand density, regeneration density, and mortality rate had a significant influence on the long-term protective effect for rockfalls. For S3, an additional factor, the initial median DBH, also had a significant influence.

In all models, high initial stand densities as well as a relatively low mortality rate led to a high long-term protective effect. Thus, in contrast to the simulated stand density, which only had a negative influence on the residual hazard for the smallest rock size class, the initial stand density appeared to have a reducing effect on the residual hazard over all rock size

classes. This is not surprising as, after a period of 60 years, the number of surviving large trees is closely related to the initial stand density. The density of large trees however, is a key factor for the assessment of the protective effect of a stand in reality (large trees in the DBH distribution) as well as in RockFor^{NET}.

Low tree mortality is essential to maintain the protective function of a forest, and its influence is even more significant for larger rocks, as indicated by the higher B-values for S2 to S4 compared to S1 (Table 10). A stand can only maintain a high protective effect in the long term if few trees are injured by falling rocks, because such injuries are thought to increase tree mortality (RICKLI *et al.* 2004). In addition tree mortality should only be moderately increased by selective cutting, and large clear cuts should certainly be avoided. However, the association of a low mortality rate with a high long-term protective effect, as shown by this study, may be slightly over-estimated. The simplistic combined simulation tool does not take into account any protective effect of dead trees because it simply eliminates such trees. In reality, dead trees (e.g. snags, KUPFERSCHMID ALBISETTI 2003), and even stumps of trees felled at a height of 1.3 m or higher, can at least temporarily provide a certain protective effect and thereby reduce the residual hazard on a site (DORREN *et al.* 2005; FREHNER *et al.* 2005; SCHÖNENBERGER *et al.* 2005).

In contrast to the initial stand density and standard mortality rate, the influence of the regeneration density was different in the four logistic regression models. While being negative for S1, as expected (higher initial regeneration density leads to a higher stand density and thus, to a lower residual hazard), the influence was found to be positive for the other rock size classes. This positive influence is rather surprising and warrants further explanation.

One reason is the relatively short simulation period (60 years). As previously stated, ForClim currently does not allow accurate simulations over longer periods. However, a period of 60 years is apparently too short for tree saplings, growing under shelter, to become large enough to effectively dissipate energy from large falling rocks. Therefore, we could expect tree regeneration to have no significant influence on the residual hazard for larger rocks until some point beyond 60 years.

Tree regeneration was found to have a positive influence for rock sizes S2 to S4, indicating that the residual hazard increases with increasing initial regeneration density. The reason for this is likely to be the same as for the positive correlation found between simulated stand density and residual hazard. The simulated median DBH shows a significant negative correlation with the initial regeneration density (parametric: -0.39 , non-parametric: -0.44 , $p < 0.01$), that is, a higher initial density leads to a decrease of the median DBH due to the recruitment of more young trees. A lower median DBH in turn increases the residual hazard estimated by RockFor^{NET}. Thus, the positive influence found in the logistic regression model is probably an artefact. The median of the DBH distribution, which in this study denotes the representative DBH needed in RockFor^{NET}, is relatively sensitive to the recruitment of many young trees. The use of alternative measures of location is unlikely to improve the model performance since it would not allow a better representation of skewed DBH distributions.

Consequently, we propose that initial stand density and a relatively low mortality rate are two key factors for a high protective effect for a given rock size over a period of 60 years. In contrast to this, other variables such as browsing impact or species composition of tree regeneration did not seem to significantly influence the protective effect over the relatively short simulation period. For longer simulation periods, however, these variables, as well as the regeneration density of the initial stand, could become more important.

4.4 Modelling approach

The combined simulation tool as well as the underlying simulation models include a number of simplifications that need further investigation and could be improved in future studies.

The forest dynamics model should be improved to enable more accurate predictions of stand structures for periods exceeding 60 years. Additional data for the parameterization of the recruitment module would be necessary in order to use this module for a continuous supply of tree regeneration over the whole simulation period. Moreover, the representation of the light regime and of tree mortality would probably benefit from further investigation and improvements.

The rockfall model requires a refinement of its underlying principle – the virtual representation of stands as distributed “rockfall curtains”. The representation of the DBH distribution in the model as well as the relationship between the energy which can be dissipated by the real stand and by virtual tree curtains, should be included with more detail. By doing so, RockFor^{NET} will become a more useful tool for forest managers, given that it currently performs accurate reproductions of important features of rockfall processes, and of the interaction with protection forests for certain stand structures.

Finally, the improved models for forest dynamics and rockfall could be combined physically in a single simulation tool that could be applied by forest managers. The effects of falling rocks on trees, such as injuries leading to higher mortality rates or stem breakage, could be included in the tool, as suggested by DORREN (2002).

5 Conclusions

A combination of models of forest dynamics and rockfall has been demonstrated to be useful for investigating the effect of forest dynamics on the long-term protective effect of mountain forests against rockfall. However, mountain forest dynamics are known to be slow. Our study suggests that a time period of 60 years is too short for investigating long-term effects of forest dynamics on the protective effect against rockfall.

Over a period of 60 years, initial stand density and a relatively low mortality rate are particularly important for creating effective protection. Silvicultural measures, such as selective cutting or regeneration cuts, in protection forests should therefore be moderate. To reduce the residual hazard in stands with a low tree density such as the stand undergoing conversion to an uneven-aged structure (c-stand), alternative measures might be necessary (e.g. cut trees left on the slope, diagonally to the slope direction, cf. DORREN *et al.* 2005; FREHNER *et al.* 2005).

The approach presented in this study requires further investigation and improvement. Once improved, a combined simulation tool is likely to enable the determination of the factors that are relevant to the maintenance of protective functions over 100 years or longer. Target values for these factors could eventually be delivered, which in turn could be used for the more effective and efficient management of protection forests.

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