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Development and application of quantitative simulation tools for the analysis of rockfall protection forests

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Abstract

The protection of settlements and infrastructure against gravitational natural hazards such as rockfall is one of the key ecosystem services provided by forests in mountainous areas like the Alps. Knowledge about management strategies that allow the establishment of a permanent protection effect is therefore of high practical relevance. To explore future development of protective effects of forest vegetation and to identify trade-offs with other ecosystem services suitable predictive tools are required.

This study aims at providing such a tool: it describes the development, evaluation and application of a coupled rockfall and forest dynamics model. The rockfall model developed within this thesis is a three-dimensional rockfall model that simulates individual rock trajectories on a forested slope. In addition, the rockfall model has been coupled with a forest ecosystem model capable of simulating forest dynamics of managed and un-managed forests stands at individual tree resolution. Subsequently, the rockfall model has been tested thoroughly in a series of evaluation experiments, for example by comparing model results with data from empirical real-size rockfall experiments. The coupled model was then applied to a 40ha case study in Austria in order to assess the long-term effects of different management strategies with regard to rockfall protection and timber production indicators. A stripwise shelterwood business-as-usual (BAU) scenario was compared with protection forest management scenarios (PFM1, PFM2) and a no-management scenario (NOM). PFM1 and PFM2 were based on available recommendations for protection forest management and rely on slit-shaped small canopy openings along skyline tracks. Compared to PFM1 and PFM2, it was found that over 100 years the BAU management yielded slightly more timber (BAU: 6.7 $m^3ha^{-1}yr^{-1}$, PFM: 5.7–5.9 $m^3ha^{-1}yr^{-1}$), but lower contribution margins (BAU: 55 €$ha^{-1}yr^{-1}$, PFM: 113-115 €$ha^{-1}yr^{-1}$). Overall, depending on rock size and forest state, the forest was able to stop 30–70% of the rocks that would otherwise hit the road at the foot of the slope. While the PFM scenarios preserved high levels of rockfall protection over 100 years (protection efficiency (PE) between 45–64%) the BAU scenario suffered from periods of strongly reduced protection (PE between 26–65%). The NOM scenario maintained favorable conditions in the beginning, but showed declining protection in the last decades of the century (PE 49–63%).

It is concluded that such a coupled rockfall and forest modeling approach can provide useful insights for the management of protection forests. For the case study, it was found that rockfall protection management can outperform BAU with regard to both timber production and rockfall protection.

Keywords: rockfall, mountain forest management, simulation modeling, PICUS Rock'n'Roll

Kurzfassung

Der Schutz von Siedlungen und Infrastruktur vor gravitativen Naturgefahren wie Steinschlag ist eine der wichtigsten Ökosystemleistungen von Bergwäldern. Es ist daher überaus relevant zu analysieren, welche Form der Waldbewirtschaftung effizient eine langfristig hohe Schutzwirkung der Wälder ermöglicht. Angesichts des oft vorherrschenden Interesses an Holzproduktion sind aber auch Werkzeuge vonnöten, die Bewirtschaftungsstrategie nicht nur hinsichtlich der Schutzwirkung, sondern auch hinsichtlich ihrer ökonomischen Leistung beurteilen.

Diese Arbeit zielt mit der Entwicklung, Evaluierung und Anwendung eines gekoppelten Steinschlag- und Wald-Simulationsmodells darauf ab, ein solches Werkzeug bereitzustellen. Das Steinschlagmodell, das im Rahmen dieser Arbeit entwickelt wurde, erlaubt die Simulation von einzelnen Steintrajektorien auf einem drei-dimensionalen Hang und berücksichtigt dabei die Schutzwirkung von Bäumen. Dieses Modell wurde dann mit einem Waldökosystemmodell gekoppelt, das die dynamische Simulation von bewirtschafteten und unbewirtschafteten Waldbeständen erlaubt. In einer Reihe von Evaluationsexperimenten wurde das Steinschlagmodell ausführlich getestet, zum Beispiel wurden Simulationsergebnisse mit Daten empirischen Steinschlagversuchen verglichen. Schließlich wurde das gekoppelte Modell auf einer 40 ha großen Beispielsfläche in den österreichischen Alpen angewandt. Dabei wurden die Langzeitauswirkungen unterschiedlicher Bewirtschaftungsstrategien sowohl auf den Steinschlagschutz- als auch auf Indikatoren für Holzproduktion analysiert. Die verwendeten Bewirtschaftungsstrategien waren ein streifenweises Schirmschlag-verfahren (business-as-usual, BAU), zwei spezielle Steinschlagschutzszenarien (PFM1, PFM2) und ein Szenario ohne aktive Bewirtschaftung (NOM). Die Schutzszenarien wurden von Schutzwaldempfehlungen abgeleitet und basieren auf kleinflächigen Schlitzhieben entlang der Seilbahntrassen. In Summe über die 100 Jahre Simulation war die Holzerntemenge für BAU knapp höher (BAU: 6.7 $m^3ha^{-1}yr^{-1}$, PFM: 5.7–5.9 $m^3ha^{-1}yr^{-1}$), jedoch war der Deckungsbeitrag niedriger (BAU: 55 €$ha^{-1}yr^{-1}$, PFM: 113-115 €$ha^{-1}yr^{-1}$). Insgesamt wurden - abhängig von Steingröße und Waldzustand – 30-70% der Steine durch die Waldvegetation gestoppt, die ohne Vegetation die Straße am Hangfuß erreicht hätten. Während die Schutzwaldszenarien (PFM1, PFM2) eine hohe Schutzwirkung über 100 Jahre zeigten (Schutzwirkungsindikator PE zwischen 45-64%), war die Schutzwirkung im BAU Szenario über einen längeren Zeitraum deutlich reduziert (PE zwischen 26-65%). Das NOM Szenario zeigte zwar eine gute Schutzwirkung zu

Beginn der Simulation, die allerdings gegen Ende des Jahrhunderts nachließ (PE 49-63%).

Insgesamt zeigt die Arbeit, dass ein Ansatz der Steinschlag- und Waldsimulation verbindet, wertvolle Einsichten über die Möglichkeiten der Bewirtschaftung von Schutzwäldern erlaubt. Außerdem zeigt die Fallstudie, dass Bewirtschaftungsszenarien die speziell auf Schutz ausgerichtet sind, nicht nur eine bessere Schutzwirkung aufweisen, sondern auch hinsichtlich Holzproduktion überlegen sein können.

Schlagwörter: Steinschlag, Gebirgswaldbewirtschaftung, Simulationsmodelle, PICUS Rock'n'Roll

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But most of all, I thank Marlis – she keeps me keeping on. But also our two girls Emma and Frieda, who always remind me how important it is to get the future right.

Contents

1 Introduction

The protection against gravitational hazards (e.g., rockfall, avalanches, and landslides) is one of the key ecosystem services of mountain forests (Körner et al., 2005). Rockfall, here defined as the quick gravitational movement of individual rocks with a volume of up to 5 m^3, is typically endangering traffic infrastructure and settlements in valleys, especially in alpine areas with high population densities and abundant tourism. The protection against rockfall is given therefore in many areas a high priority by local stakeholders, administrators and civil protection officers (Volkwein et al., 2011). At the same time, the production of timber is very often the prime interest of landowners, especially when the forests are still sufficiently productive and accessible to allow cost effective management and thus provide income.

Rockfall slopes are often split into source, transit and deposition areas (Dorren et al., 2007). While forests play also a (negative) role during the release process of rocks (by roots widening existing joints and by promoting chemical weathering), the protective function lies mostly in the barrier effect of forests in the transit and deposition zones. Individual trees absorb, when hit by falling rocks, energy, thus decelerating or even stopping the moving rock. Properties such as forest structure (i.e., the number, species, size and spatial distribution of trees) and forest area (i.e., the length of the forested slope) influence the protection effect. Generally, the protection effect is known to increase with the number and the dimension of trees (e.g., Volkwein et al., 2011). Forests are, however, dynamic systems and it is therefore not sufficient providing good protection at one point in time, but it is important to maintain a favourable state over longer time frames. This is especially relevant as many protection forests in the Alps are overly mature and lack sufficient regeneration (BFW, 2011) putting them on risk from catastrophic break-downs when hit by disturbances. Thus, knowing which silvicultural strategies are most efficient in creating and maintaining protective forest structures is of high practical relevance. As is the question how efficient such management strategies perform with regard to the competing goal of timber production. In order to answer these questions a combined view on rockfall and forest processes is necessary, which can be provided by simulation modelling. During the last years, simulation modelling has been increasingly used for projecting forest development (Pretzsch et al., 2008), and also for the assessment of rockfall processes. With regard to rockfall modelling, a variety of tools have been proposed, reaching from landscape level tools to models that simulate detailed trajectories of single rocks (see Volkwein et al., 2011).

Acknowledging the significance of forests for rockfall protection (Dorren et al., 2005), several attempts were made to combine forest and rockfall simulation. Some of those studies concentrated on applying trajectory models on current forest states or yield table based extrapolations (Bigot et al., 2008; Stoffel et al., 2006; Wehrli et al., 2006). Other studies focused on forest development, and rockfall protection was assessed using simplified indicator-based approaches (e.g., Cordonnier et al., 2008).

A fully integrated rockfall- and forest-model that can be used to gauge long-term effects of forest management strategies on both rockfall- und other forest-related indicators was, however, lacking. This thesis aims at closing this gap, by providing such a coupled simulation tool.

2 Objectives

The overall aim of this thesis was the development, testing, and application of a coupled rockfall and forest model.

Specifically, this included (1) the development of a detailed, three-dimensional rockfall model that simulates individual rock trajectories on a forested slope taking into account the barrier effect of trees, (2) the integration of this rockfall model with an existing forest ecosystem model (PICUS, Lexer and Hönninger, 2001; Seidl et al., 2005), (3) testing and evaluating of model behaviour, and (4) the application of the combined rockfall and forest model to a case study in the Austrian Alps.

Papers I and II deal with model development as well as with model evaluation. Paper I focuses more on the basics of the rockfall model and its integration with the forest model and comes with a series of model comparison and simulation experiments. Paper II aims at testing the models performance against detailed empirical data and describes model improvements. Paper III features the application of the coupled models and highlights trade-offs between rockfall protection and timber production on slope scale.

The structure of the thesis is as follows. The Methods section introduces the rockfall and the forest model, followed by a description of the data used for evaluating and applying the combined simulation approach. Subsequently, the Results section presents selected results from the model development, evaluation and model application phases. Finally, the Discussion and Conclusions section scrutinizes the approach and highlights some main findings of this work. Three peer-reviewed scientific publications build the Appendix of the thesis. They are referenced as Paper I, Paper II, and Paper III in the text.

3 Material and methods

3.1 Methods

3.1.1 The rockfall model Rock'n'Roll

PICUS Rock'n'Roll is a three-dimensional trajectory rockfall model, i.e., the movements (rolling, jumping) of individual rocks are simulated on a detailed terrain model of a slope. The simulated rocks accelerate gravitationally on their way down and loose energy due to rolling friction and due to impacts on the ground and on trees.

The simulated slope is defined by a digital elevation model and several additional data layers representing surface properties and delineating rockfall source areas. Several input formats are possible, but the most versatile approach is to provide two raster grids (using the text-file based ESRI ARC/INFO ASCII grid format) and a data table with surface properties. The first grid specifies the digital elevation model; the second grid assigns unique numeric identifiers to areas with homogenous surface properties (polygons). These identifiers link to records in the data table which contain the actual property values (see Table 1).

Table 1. Input data for the rockfall model. The user needs to provide information about the terrain, details of the surface on the slope, and vegetation information.

Category	Variable	Description
Terrain	Digital elevation model	Provided as triangulated irregular network or as regular raster grid (ESRI ASCII raster)
Surface properties	Polygon map	Map of areas with homogeneous surface properties (ESRI ASCII raster)
	R_n, R_t	Coefficients of restitution in normal and tangential direction (rebound parameters).
	μ	Rolling friction of the surface in rolling mode
	Obs%	Percentage of the surface covered by obstacles
	ObsDim	Dimension of the largest obstacles on the surface
Vegetation	Stand map	Map of forest stands (ESRI ASCII raster)
	tree data	Tabular data of single trees for each stand (coordinates, diameter at breast height, tree height, species)

Forest vegetation is represented by individual trees with given species, dimensions (diameter at breast height, tree height) and location on the slope. Tree data is read from a single data file or from multiple files, if the forest is split into several forest stands. In the latter case, an additional data grid containing the stand polygons is required (see the example in Figure 1).

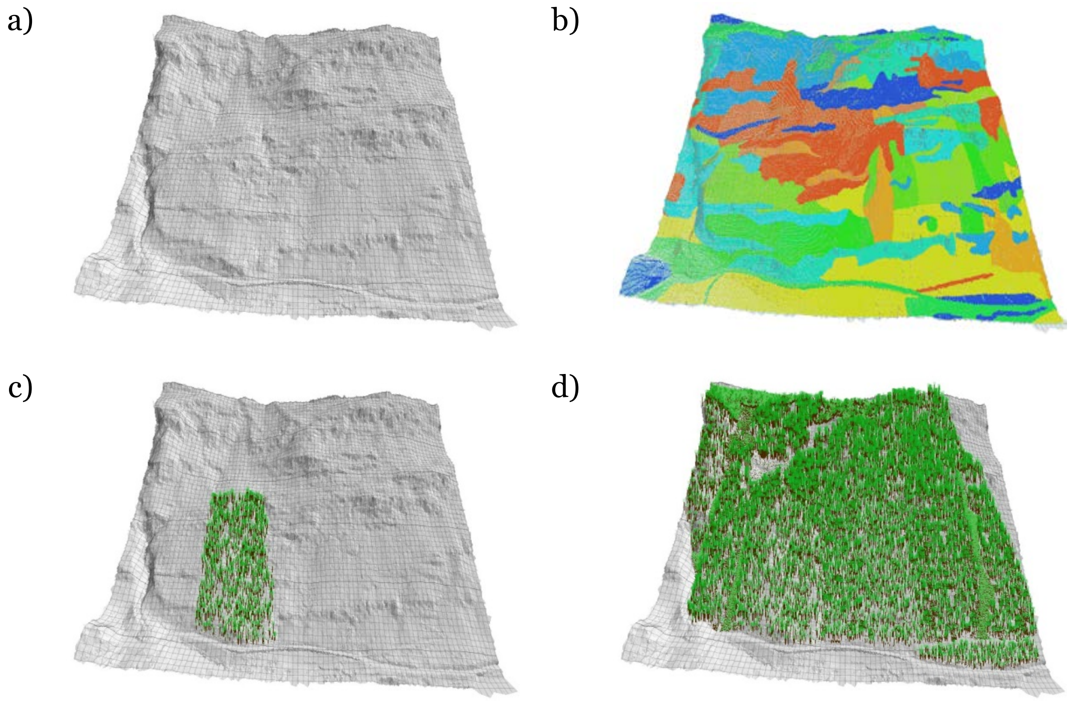


Figure 1. Various data layers are combined in setting up the rockfall model. (a) shows the terrain as given by the digital elevation model, (b) an example for a mapped surface property (the tangential coefficient of restitution R_t). The forest vegetation for the full slope (d) is composed of multiple single stands (c).

The simulated rocks are modelled as spheres with a given diameter and rock density. The model can start rock trajectories either from a predefined point, line or polygon with specified starting conditions (rolling or jumping, velocity, direction, and height). Within source polygons the starting positions are randomly selected and start directions are aligned to the line of greatest slope.

Simulated movements of rocks fall in two categories, namely rolling and jumping. Rocks gain energy gravitationally; in "rolling" mode energy is dissipated by rolling friction, and in "jumping" mode energy is lost during ground impacts. In both modes rocks dissipate energy when hitting trees. Internally, the model calculates rock movements not using a fixed step size, but rather simulates a series of (analytically solved) movements that reach from the respective rock position to either the next triangle of the slope (representation) or an obstacle (e.g., a tree). This approach is both accurate (e.g., when deciding whether a tree is hit) and computationally efficient.

In the context of rockfall protection forests the implementation of the rock-tree interaction is crucially important. Rock'n'Roll builds upon knowledge gained from real-size rockfall experiments conducted in the French Alps (Dorren et al., 2006; Dorren and Berger, 2006). The used algorithm estimates (as a species-specific function of the diameter at breast height) the maximum amount of energy that can be dissipated by a tree during a head-on impact. This capacity is reduced for lateral tree hits. The rock´s energy is reduced accordingly and the rock gets – if it is not stopped - horizontally deviated. Trees are assumed to break when they are centrally hit with energies exceeding their dissipation potential.

The ground impact algorithm is a key ingredient of any rockfall model; here Rock'n'Roll uses a "classical" inelastic point-rebound, where coefficients of restitution in normal and tangential to the contact plane are used for calculating the reduction of velocity in the respective direction before/ after the impact (Volkwein et al., 2011). These crucial parameters depend on ground properties such as ground material or soil depth and can be derived from the literature (e.g., Azzoni et al., 1995; Schweigl et al., 2003). After finding this algorithm failing to reproduce empirically observed pattern in rock jumps, two modifications were applied: first, a velocity-dependent plastic deformation of the ground material was assumed, i.e. faster rocks use more kinetic energy for building deeper impact craters (Johnson, 1985). The second modification aimed at improving simulated rebound heights and jump length by facilitating an empirical relationship between the rebound angle and the velocity of a rock (see Paper II for more details on the rationale and consequences of these modifications).

Simulated rocks stop, when the kinetic energy is fully depleted (i.e. the velocity falls to zero), or when the simulated area is left. In reality, however, rocks are sometimes stopped by obstacles on the ground such as blocks or large debris. In order not to over-estimate simulated run-out-distances, a relationship was established between the distribution and size of obstacles and the probability that a rock of a given size is stopped by those obstacles during an impact. These stopping probabilities were estimated by simulating a large number of (simplified) rebounds on virtually generated talus surfaces with varying obstacle size and ground coverage (see Paper II for details).

Rock'n'Roll saves various data of the simulated rock trajectories (e.g., velocities, jump length and height, kinetic energy, run out distances) and provides output variables on different aggregation levels. One important class of outputs are distribution metrics over all simulated trajectories, e.g., the 90th percentile of the maximally achieved velocity, or the median of the run-out-distance. In addition, data is collected on a grid of 10x10m cells allowing the creation of maps of e.g., the number of rocks reaching each pixel, or the mean velocity of rocks within each pixel. In addition, velocity and jump height are recorded when rocks enter specifically marked polygons (e.g., some protection target, or the location of rockfall fences).

The computationally efficient implementation of the rockfall process - the model can simulate thousands of trajectories per second on current (2015) office computers - allows running a large number of trajectories (replicates) for securing statistically valid results for a number of different scenarios (i.e. management, climate).

3.1.2 The forest ecosystem model PICUS

PICUS is a hybrid forest gap model that combines the abilities of a 3D gap model (Lexer et al., 2001) with process-based estimates of stand level primary production (J.J. Landsberg and Waring, 1997). The basic spatial element of PICUS is a horizontal grid of "patches" with a size of 10 x 10 m. Vertically, the leaf area of all trees sharing a patch is simulated in 3D crown cells with a height of 5 m. The positions of trees within a patch are assigned in a stochastic process (ensuring that biomass is distributed relatively homogenous within a patch), but are not used explicitly in PICUS. Tree population dynamics emerge from growth, mortality and reproduction (Lexer et al., 2001; Seidl et al., 2005). PICUS simulates the distribution of seeds within a stand spatially explicit and consequently the establishment of seedlings in the lowest of four regeneration cohorts per patch (Woltjer et al., 2008). Trees reaching a height >=1.3 m are recruited into the main model. The annual growth potential of individual trees is derived from a species-specific growth potential for a tree of the given size, which is then reduced accounting for sub-optimal conditions with regard to the availability of light, water and nutrients. The stand level productivity is calculated for species groups facilitating the radiation use efficiency approach by Landsberg and Waring (1997) running with monthly time steps. At the end of the year, both growth estimates are coupled: each tree is assigned the amount of stand level primary production that is proportional to the share of the tree on the sum of the biomass growth of the individual trees. Thus, the process-based productivity estimate is partitioned according to the competitive strength of the individual trees (Seidl et al., 2005). The mortality of trees is simulated stochastically, combining an intrinsic low-level background mortality with a heightened probability of death when diameter growth falls short of species-specific thresholds for a number of consecutive years. Additional tree mortality from disturbance events can be accounted for: PICUS includes a thermo-energetic process module of European spruce bark beetle disturbance (Seidl et al., 2007), as well as empirical disturbance modules for spruce bark beetle and wind storms (Pasztor et al., 2014a, 2014b). Especially relevant for mountain forestry applications is the sophisticated management module. Facilitating a custom script language, forest management interventions can be defined with a high level of detail – including options to implement spatially explicit management, e.g., gap sized cuts along sky line tracks.

The model requires climate and soil data, using time series data of temperature, precipitation, radiation and VPD at monthly or daily resolution, and data on the water holding capacity (mm) and available nitrogen (kg $ha^{-1}yr^{-1}$) as a proxy for nutrient supply. PICUS has been extensively tested and applied in several studies. For instance, previous studies found realistic responses to climatic gradients in the complex terrain of the European Alps with regard to species dynamics (Didion et al., 2009; Lexer et al., 2001) and productivity (Seidl et al., 2005).

Both the rockfall model (see section 3.1.1) and the forest model can be operated individually or “coupled”. Both models share a common technical framework, thus meeting a precondition for a tight coupling. The model version used in Paper I allowed fully coupled forest and rockfall simulations for a single forest stand. The integration level of the current version (Paper III) is lower. The reason for this is the difference in the relevant spatial scale in both models: while the forest module is designed and well suited for simulating forest development at stand level (i.e. areas of a few hectares), the relevant spatial scale for rockfall processes is typically much larger and contains several forest stands (i.e. areas of typically tens to hundreds of hectares). The solution for bridging the spatial scales is to run the rockfall model on the larger spatial extent (tens to hundreds of hectares), but with forest vegetation composed from several individual stand level simulations. To that end, in each forest simulation the state of the forest (i.e., the location, species and dimension of every simulated tree) is exported to data files multiple times, for example every 10 years. This approach allows running rockfall simulations with a consistent vegetation snapshot derived from multiple stand level simulations (see Figure 1).

3.1.3 Model evaluation

Before a model can be successfully applied to answer specific questions, it is vital to establish an appropriate level of confidence about the performance of the model (Bennett et al., 2013). Confidence is gained by comparing the outcomes of the model against our understanding and empirical observations. Many approaches exist for this task, ranging from mere plausibility checks and sensitivity analysis to tests against empirical data.

Sensitivity analysis is an approach that aims at determining the importance of model parameters and is as much a way of increasing model understanding as it is a means for model evaluation (Vanclay and Skovsgaard, 1997). The typical approach ("one at a time") is to systematically alter one parameter after another and analyse the changes in model outcomes with regard to selected indicators. Although sometimes criticized for being perfunctory (Saltelli and Annoni, 2010), sensitivity analysis proved to being informative (see Paper I).

Model comparison can be seen as a second type of sensitivity analysis, focusing on the data space rather than the parameter space. Both approaches also play an important role in the model development process, especially for the technical validation (i.e., if the model software works as expected). In Paper I a model comparison had been employed to learn from comparing predictions for the average trajectory length between tree hits, and the dissipated kinetic energy during tree impacts from structurally different formulations from the literature. Inter-model tests can be run on a much broader range of potential inputs as can be typically provided by empirical data, thus allowing analysing model behaviour also for much less frequent corner cases. In addition, some indication on model uncertainty can be derived from model comparison experiments (van Oijen et al., 2013).

Another type of evaluation technique is to gauge the plausibility of outcomes of dynamic simulation experiments. For instance, in Paper I a model experiment was conducted where different forest management strategies implemented in forest simulations over 100 years and tested whether important rockfall indicators such as the mean run-out-distance responded as expected to forest management.

A central step of model development and evaluation is to compare model outcomes with empirical data (Jakeman et al., 2006). Consequently, an extensive model evaluation with empirical data is presented in Paper II, where predictions of the rockfall model are tested against empirical data from rockfall experiments in France, and against two rockfall trajectories from Switzerland and Austria.

3.2 Material

3.2.1 Evaluation experiments

In order to gauge the sensitivity of the rockfall model to model parameters a "one at a time" sensitivity analysis was conducted (Paper I). Starting from a forested slope (400 Norway spruce trees/ha, mean DBH 40cm, slope angle 30°) both model parameters and stand variables where changed systematically by +-10% and the effect of these changes on simulated run-out-distances (boulder diameter: 50cm, 1000 trajectories) was evaluated.

A second test compared the simulated average distance between tree hits (ADC) with an theoretical approach from the literature (Gsteiger, 1993), the latter taking into account stem number, mean tree diameter, and boulder size (Paper I). Forest development was simulated over 100 years, starting from pole stage (1800 Norway spruce trees/ha, mean diameter 10cm) and simulated run-out-distances as well as the number of tree hits per rock (rock diameter: 50cm, 1000 trajectories) were recorded for every simulation year. A third test focused on the energy dissipation due to tree hits and was based on the same simulation setup as the previous test. Here, the simulated energy dissipation was compared with a theoretical approach from the literature (Brauner et al., 2005), that estimates the energy dissipation potential for a given stand composition.

3.2.2 Evaluation data

Model evaluation experiments included tests against empirical rockfall data: First, it made use of data of real-size rockfall experiments, conducted from 2001-2003 in the Forét Communale de Vaujany in France by Dorren et al. (2006). They released on both a forested and a non-forested slope a total number of 218 rocks with a mean diameter of 0.95 m and analysed their trajectories thoroughly. In addition to recording coordinates of tree hits and rock rebounds on the ground, rock velocities were assessed by video analysis. In Paper II the Vaujany sites were virtually re-established using the available high resolution digital elevation model and the tree coordinates within the rockfall model. A large number (10,000) of rockfall trajectories were then simulated starting from the original release point (rock diameter 0.95m).

The second source of evaluation data was a set of two two-dimensional rock trajectories that were recorded after rockfall events in Austria (Bad Ischl) and Switzerland (Steg). In this case, the data consisted of profiles informing about ground conditions and locations of rebounds along the trajectory. From these trajectories slope profiles were derived and a large number of rockfall trajectories with the boulder properties of the incident rocks were simulated.

3.2.3 Model application

3.2.3.1 The case study Penken

The case study used to demonstrate the integrated rockfall and forest modelling approach (Paper III) was situated at the slope of the Penken, a mountain along the valley of the Ziller in the province of Tyrol, Austria (lon: 47.16°/ lat: 11.16°). The study area extends over 38 ha and on a south-facing slope at elevations between 650 m and 1100 m a.s.l. (Figure 2).

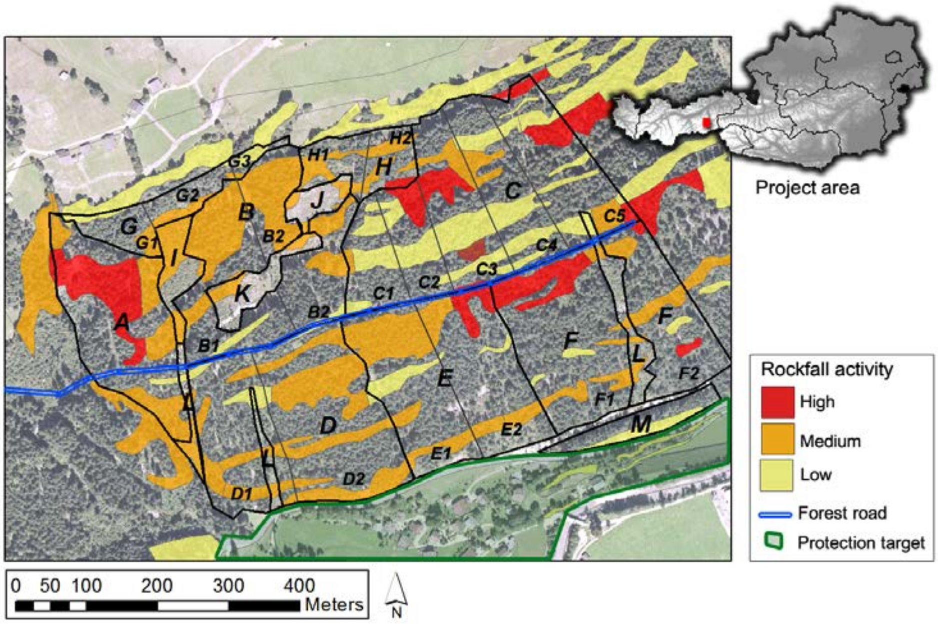


Figure 2. The case study area „Penken“. Forest stands are annotated with capital letters. The total area of the project area is 38 ha. Colors (Red, Orange, Yellow) indicate rockfall source areas. The road and settlements at the valley bottom are endangered by rockfall.

The project area is a typical rockfall slope in the Alps, with inclinations between 35° and 40° and a length of (projected) approx. 500 m. The area is dominated by mature to overly mature Norway Spruce stands with admixed Larch and Silver fir. Table 2 provides an overview over the current situation of the forests in the study area.

The project area is owned by multiple agricultural land owners and managed by an agricultural community focusing on timber production and income generation.

Table 2. Current stand characteristics of the forest stands in the Penken case study. Two smaller areas covered by shrubs were combined to stand L (1.0 ha) which was not actively simulated.

Stand	**Area** [ha]	**Stems** [stems ha^{-1}]	**Standing volume** [m^3 ha^{-1}]	**Share of Picea abies** [% volume]
A	3.4	514	448	100
B	4.2	559	880	98
C	8.0	632	709	99
D	5.9	584	543	99
E	5.0	564	516	97
F	5.4	821	633	100
G	1.2	3841	294	99
H	1.2	3016	301	96
I	0.6	558	30	48
J	0.4	0	0	-
K	0.6	528	0	0
L	1.0	12807	-	-
M	0.7	1120	535	95

3.2.3.2 Forest management scenarios

For the Penken case study the long-term effects of current management and alternative silvicultural concepts were assessed. All scrutinized concepts had to rely, due to slope steepness, on skyline cable yarding systems. For all concepts, slope-level management plans were derived, aiming at both efficient placement of skyline tracks and at avoiding large non-forested areas.

Specifically, four management scenarios were assessed:

a) The Business-As-Usual-Management (**BAU**) resembles a shelterwood-concept targeting at natural regeneration within an age-class-forestry context. It includes a seeding cut and the removal of the overstorey 20 years later, as well as two thinnings in the pole stage phase. Such a shelterwood approach is widely used in the Austrian Alps.

b) The protection forest management scenario 1 (**PFM1**) is based on recommendations for sustainable protection forest management (Frehner et al., 2005). This concept aims at transforming the current forest to a unevenaged forest structure by applying transversal slit-cuts with a length of 20-30m and a width of 6-10m along the skyline track. In course of time, existing slits are enlarged and new slits are added. Structural thinnings increase stand heterogeneity in pole stands.

c) A second protection forest management scenario is **PFM2** that was derived from a trial marking in the field with local foresters. While generally similar to PFM1, it includes larger and more lateral cuts, covering a larger area at each entry.
d) A "Do nothing" scenario (**NOM**) was included for benchmark purposes. Here, forest dynamics unfold undisturbed by human activities.

A detailed description of the management scenarios and further assumptions are provided in Paper III (Appendix).

3.2.3.3 Experimental setup

The experimental setup of the study is shown in Figure 3. The planning of the silvicultural alternatives (see previous chapter) was carried out on the slope level (Figure 3a). The management plans were broken down for each of the 13 forest stands and simulated over 100 years with PICUS. The simulated forest states were extracted and stored for six points in time (t_1 to t_6, Figure 3b). Within the Rock'n'Roll-model, the vegetation state on slope level was reconstructed from these previously stored data for each of the 24 combinations of time and management scenario. On the thus forested slope (Figure 3c) rockfall simulations (three rock sizes, spherical rocks with a diameter of 0.3 m, 0.5m, and 1 m) were conducted.

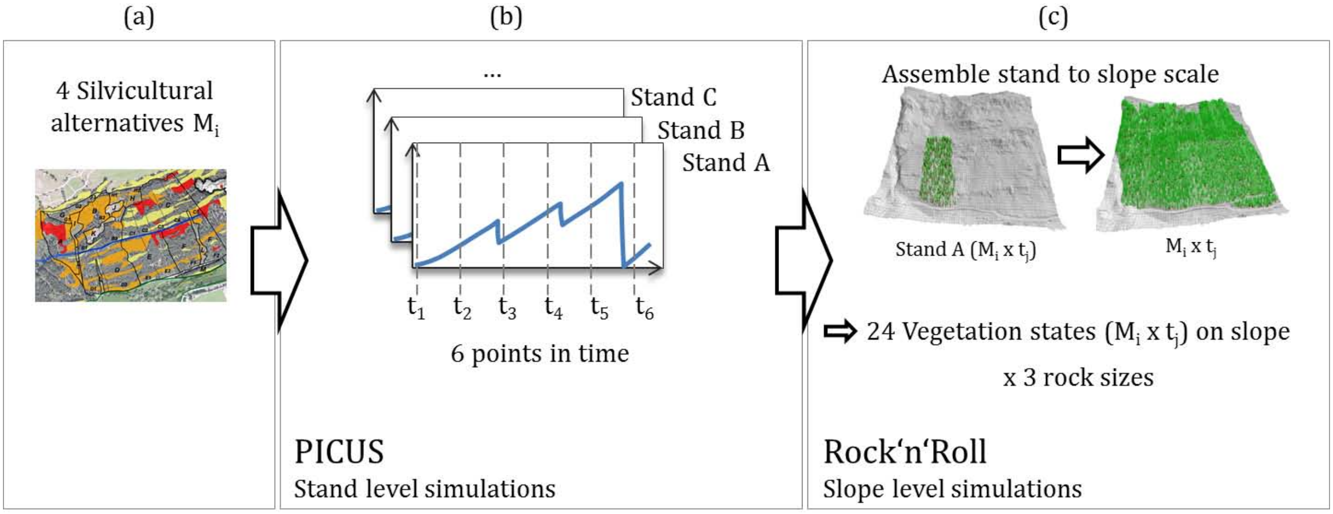


Figure 3. Simulation workflow for the case study application. Slope level silvicultural alternatives (a) are broken down to stand level management and simulated (b). For the rockfall simulations (c), the forest state on slope scale is constructed from the stand level simulations.

The forest simulations yielded various state and flow-indicators such as standing and harvested timber, or stem numbers. The contribution margin 1 (CM1) was calculated by subtracting harvesting costs from timber revenues. Harvesting costs were based on Stampfer et al. (2006) and revenues were derived from a regional timber price mix.

The main rockfall protection indicator was the protection efficiency (PE), defined as 1 minus the ratio of rocks that reach the road below the slope (see Figure 4) for a given vegetation state compared to simulations with no trees at all. For example, an extraordinary high value of 90% indicates that the forest cover is able to stop 90% of the rocks that would reach the road if no forest vegetation was present on the slope. In addition to PE, additional rockfall indicators (rock velocities, rebound heights) were recorded.

More details on the setup are provided in Paper III.

4 Results

4.1 Model development

The development of the rockfall model (Rock'n'Roll) - both conceptually and technically - is a key result of this thesis. The development process followed an iterative approach, where the model has been improved and extended over time. This iterative process (sensu Grimm and Railsback, 2005), involves cycles of model development and model testing – in the case of the rockfall model, three main loops were performed, that are represented by the three papers of this thesis (Figure 4).

	(a)	**(b)**	**(c)**
Version	Paper I	Paper II	Paper III
Slope	Flat	3D-slope	3D-slope
Scale	Stand	Stand	Slope

Visual-ization

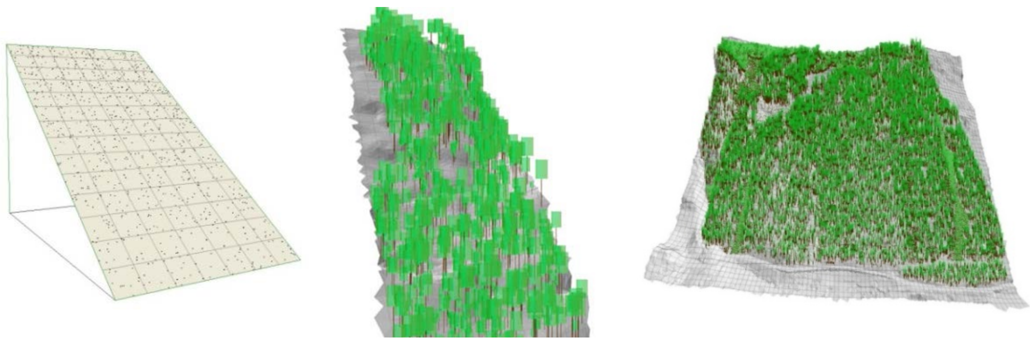


Figure 4. Main milestones of the development of the rockfall module, represented by screen shots. Version (a) simulated rockfall on a flat surface. In version (b), real digital elevations could be used to simulate rockfall trajectories on stand-scale. This spatial scale was extended in version (c).

The Paper I-version of the model featured a fully functional rockfall model capable of simulating rockfall trajectories (rolling and jumping) within a forested slope. The slope itself, however, was represented by a tilted flat plane. The simulation of tree-hits comprised already energy dissipation and the deviation of the rock trajectory, but was based on theoretical considerations only. This version included a detailed sub-module of the protection effect of the regeneration layer. As this version showed both a promising performance and potential for improvement, work on the model continued.

Consequently, the Paper II version (Figure 4 (b)) was developed. On the one hand, new features were included, with the implementation of a digital terrain model being most prominent. On the other hand, key algorithms of the model were revised and improved. For instance, the tree-hit algorithm was reformulated and is now based on empirical data (Dorren and Berger, 2006). Furthermore, the formulation of the ground impact was modified as the first rendering failed to reproduce the patterns found in empirically observed data. Since attempts to empirically testing the protection effect of the regeneration layer could not be realized, and therefore proper evaluation data was lacking, this sub-module was deactivated.

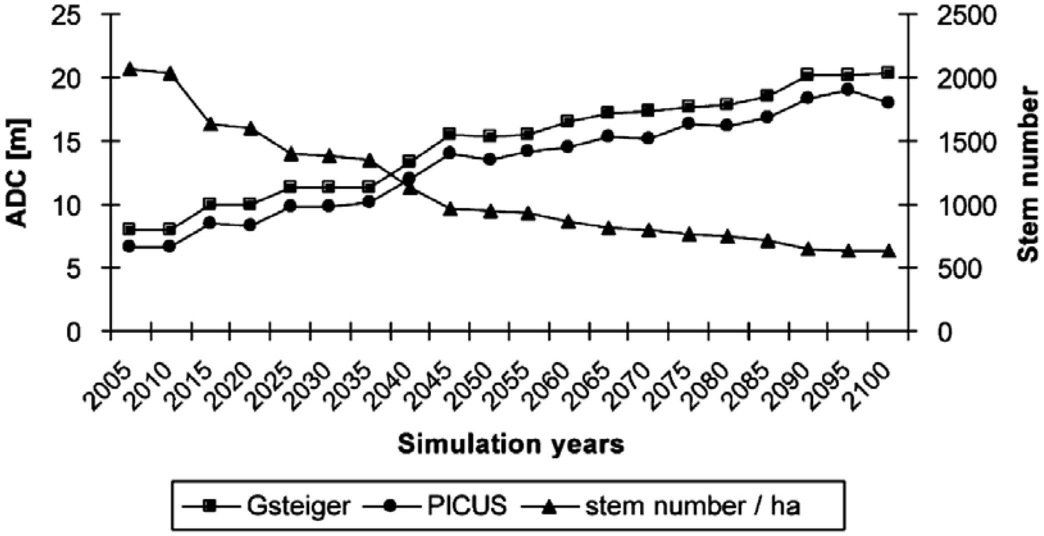
The next major development loop (Paper III) focused on extending the spatial scale of the model, as it became increasingly evident, that rockfall processes need to be addressed on larger spatial entities, such as a slope comprised of multiple stands.

4.2 Model evaluation

Paper I contains a series of model evaluation experiments examining various aspects of model behaviour. The sensitivity analysis (Paper I, Fig. 5) showed, that 10% changes of stand characteristics such as stem number or mean diameter have less influence on mean run-out-distances compared to the slope and values for rolling friction and the rebound coefficients.

When comparing the simulated average distance between tree hits (ADC) with a theoretical approach from the literature (Figure 5a), a highly correlated response of both approaches to stand development was found. The simulated ADC showed, however, slightly higher values. The simulated energy dissipation during tree hits (Figure 5b) was consistently lower than the energy dissipation potential of Brauner et al. This difference could be attributed to conceptual differences between the two approaches, and it was concluded that the approach of Brauner et al. overestimates rockfall protection effects for stands with higher standing volume, as it always assumes maximum energy dissipation (i.e., stem breaking energy) at each impact.

a)



b)

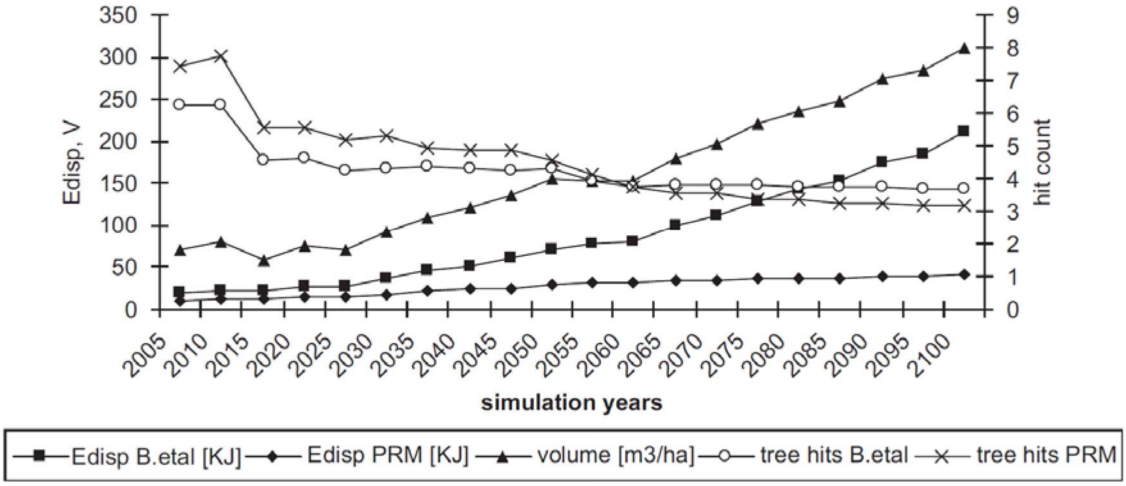


Figure 5. Results of model evaluation experiements. Panel (a) compares simulated mean trajectory length between tree hits of PICUS Rock'n'Roll with a theoretical approach by Gsteiger (1993). Panel (b) compares the energy dissipation and the number of tree hits per rock as predicted by PICUS Rock'n'Roll (E.disp PRM) compared to an approach by Brauner et al. (2005) (E.disp B.etal).

In Paper II, simulated rockfall trajectories were compared with measured ones. Figure 6 shows the distribution of run-out-distances before and after modifications of rockfall algorithms for the two experimental sites in Vaujany. In both cases the update of key algorithms increased the match of observed and simulated run-out-distances.

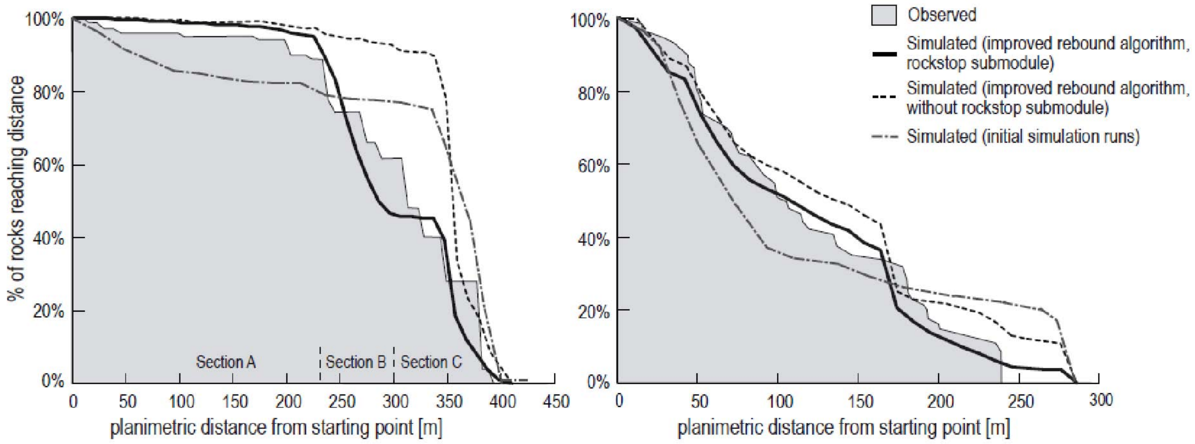


Figure 6. Percent of rocks that reach a certain distance for the two test sites in Vaujany. After improvements of the model formulation (black solid line), the fit to empirical data (grey area) was improved considerably.

With the updated rockfall model, the two-dimensional rockfall trajectories in Switzerland and Austria were simulated. The comparison of simulated and observed jump length (Figure 9) showed a generally good match.

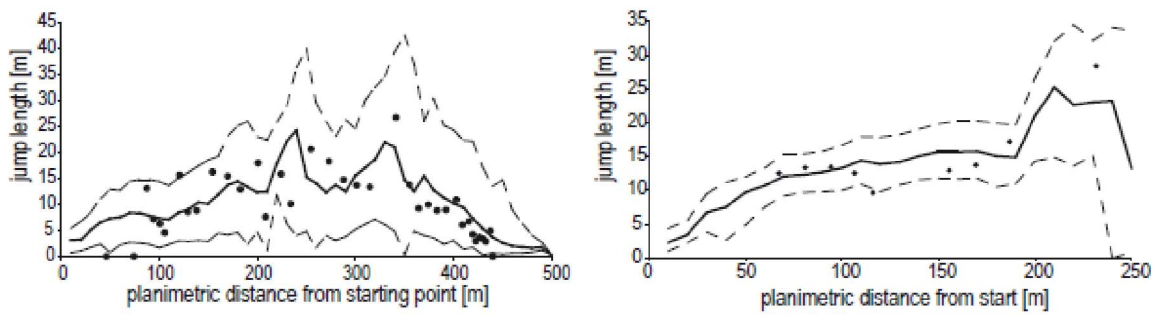


Figure 7. The jump length for the two simulated 2d-trajectories (left: Steg, right: Bad Ischl). Dots indicate observed jumps, the solid line is the mean and the dashed lines are min/max of 10000 simulated trajectories.

4.3 Model application

The application of the coupled rockfall and forest model to a case study in Tyrol, Austria is the central topic of the third paper of this thesis.

4.3.1 Timber production

Figure 8 gives an overview over the simulated forest development under the different forest management scenarios for the full project area. The BAU management scenario led to a sharp decrease in standing timber volume as mature stands were successively clear cut. Contrastingly, the rockfall protection management scenarios resulted in a more gentle decrease in standing timber. In all three actively managed scenarios the stem numbers increased due to on-setting wide-spread regeneration.

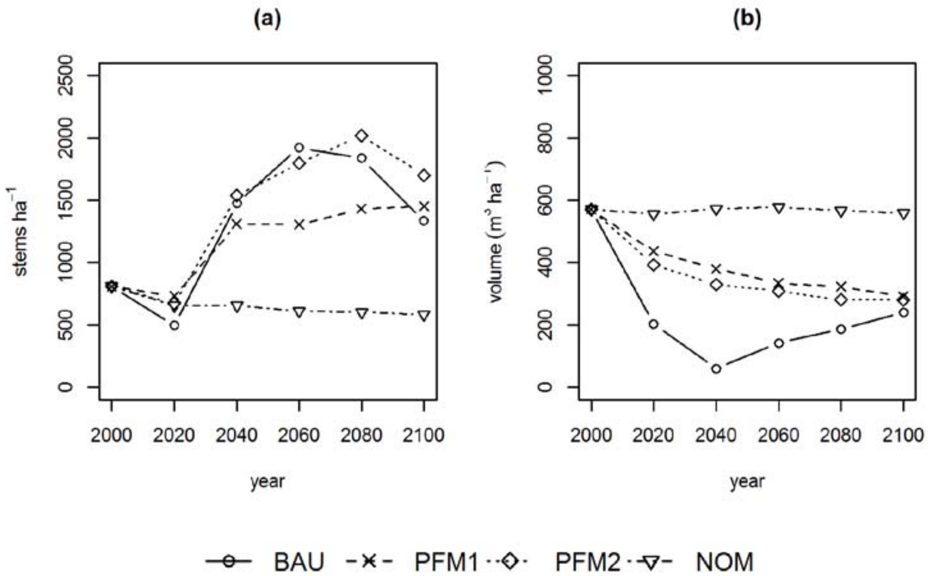


Figure 8. Simulated mean number of trees per ha (a) and standing timber volume (b). Stem numbers increase and standing timber volumes decrease for all active management scenarios.

Harvested timber volume and contribution margin (CM1) of the three evaluated active management regimes is presented in Table 3. The contribution margin – the difference between revenues and costs – became negative during the second half of the simulation period under BAU management, as cost intensive tending of the mostly juvenile stands led to lower revenues. This was not the case for the protection management scenarios PFM1 and PFM2, which avoided widespread early stand development phases and the resulting need for costly stand tending measures. The mean harvested timber over the full simulation period of 100 years was highest for BAU with 6.7 m^3 ha^{-1} yr^{-1} and lower for PFM1 (5.7 m^3 ha^{-1} yr^{-1}) and PFM2 (5.9 m^3 ha^{-1} yr^{-1}). The higher productivity of BAU can be attributed to the faster transformation of the overly mature, less productive initial stands into productive young stands.

Table 3. Mean harvested volume [m^3 ha^{-1} yr^{-1}] and contribution margin CM1 [€ ha^{-1} yr^{-1}] in five 20-year periods and for the full simulation period. BAU= business as usual shelterwood system, PFM1 and PFM2 = rockfall protection management.

	BAU		PFM1		PFM2	
period	harvest	CM1	harvest	CM1	harvest	CM1
2000-2019	12.6	209	6.5	136	8.0	168
2020-2039	11.4	94	6.7	147	6.4	121
2040-2059	1.1	-9	6.3	122	4.9	101
2060-2079	3.6	-25	3.3	68	5.3	105
2080-2099	5.0	-2	5.9	108	4.9	75
2000-2099	6.7	53	5.7	116	5.9	114

4.3.2 Rockfall protection

The protection efficiency (PE), the percentage of rocks stopped by the forest that would reach the road if no forest were present, was found to being sensitive to forest management (Figure 9). In all actively managed scenarios the PE generally responds negatively to the removal of biomass in the first decades of the simulation. This negative effect was markedly stronger for the BAU scenario and for the larger rocks (1m). In the second half of the century the PE of the NOM scenario started declining, while the other three scenarios bounced back to and partially exceeded initial protection levels. The protection scenarios showed generally a similar pattern; PFM2, having larger gaps compared to PFM1, performed slightly inferior, especially for large rocks.

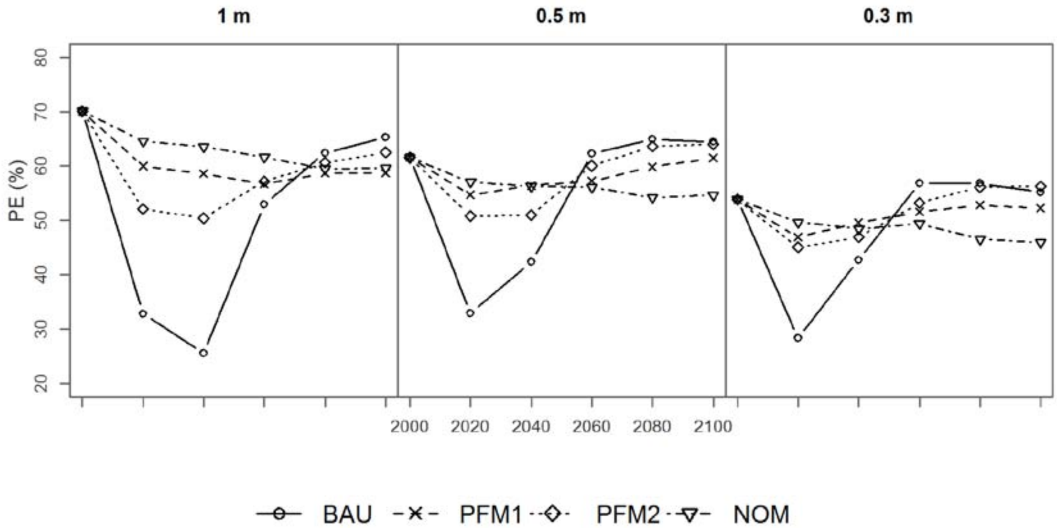


Figure 9. Protection efficiency (PE) over time for three simulated rock sizes (1m, 0.5m, 0.3m) . The BAU-management shows phases of strongly reduced PE.

Other relevant rockfall processes, such as rock velocities or rock rebound heights, showed a similar pattern (see also Fig. 3 in paper III). For instance, the rebound height (mean of the maximum rebound heights per trajectory) for 1m rocks in the year 2020 was with 2.72m for BAU 18% above the mean of the other three scenarios for this year.

4.3.3 Trade-off analysis

In order to detect potential trade-off relationships between timber production and rockfall protection, a joint analysis of an indicator for economic success (CM1) with an indicator for rockfall protection (PE) for all periods and rock sizes (Figure 10) was performed. The protection forest management scenarios PFM1 and PFM2 showed relatively little variation, with all periods and rock sizes located in an area with both positive revenues (68 to 168 €·ha^{-1}·yr^{-1}) and high protection efficiencies (45% to 64%). In contrast, the results for the business as usual scenario varied strongly: the CM1 ranged from -25 to 209 €·ha^{-1}·yr^{-1}, while the protection efficiency was found lying between 25% and 65%. The no management scenario generated no revenues and showed PE values between 49% and 63%.

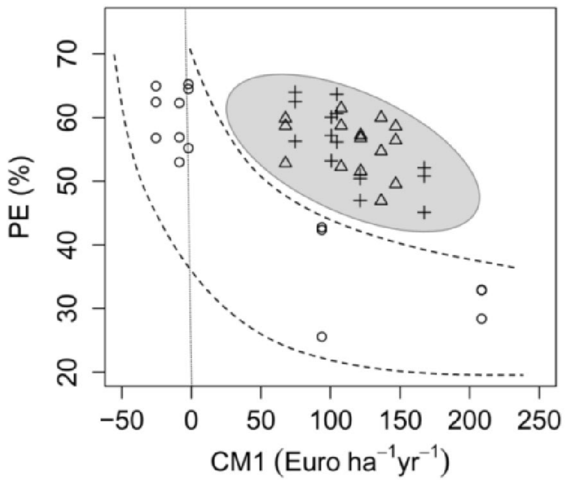


Figure 10. Integrated comparison of rockfall protection (PE) and timber production (CM1) indicators for all time periods and rock sizes. Circles: BAU, Triangles: PFM1, Crosses: PFM2. Both the PE and CM1 remain in a limited area (grey shape) for the protection forest management (PFM1, PFM2). The BAU scenario includes phases of high CM1 at the cost of low PE, and vice versa.

When aggregated over the full simulation period (and over all rock sizes), the BAU scenario had a PE of 50%, which was 5 to 6% less than the other three scenarios. Similarly, the average CM1 over the full simulation period was 55 €·ha^{-1}·yr^{-1} for BAU, as compared to 113 and 115 €·ha^{-1}·yr^{-1} for the protection management scenarios.

5 Discussion and conclusion

This thesis introduces a newly developed rockfall simulation model and its coupling with an existing forest model. It furthermore presents comprehensive model evaluation exercises along iterative model improvements, and ends with presenting a model application in a real-world case study to assess the long-term effects of different forest management scenarios on both timber production and rockfall protection.

Before potential implications for protection forest management are discussed, the modelling approach as such and its consequences for model applications are highlighted.

5.1 Model development and testing

The ultimate properties of a model, including both strengths and limitations, depend strongly on early design decisions in the development process, which are influenced by intended application scenarios, research interests, available conceptual and technical skills, and more mundane factors such as project deadlines. Some early imposed limits may persist forever, while others can be stretched in iterative development cycles (Grimm and Railsback, 2005). There are, however, themes such as scales, feedbacks, and data requirements that are continuously re-occurring during model development and improvement.

Scale. An integrated assessment of the protection function of forests against natural hazards requires a view beyond the stand scale (Maroschek et al., 2014). The forest model PICUS was created as a stand level patch model (Lexer et al., 2001), but treats, unlike traditional gap models, patches as spatially explicit elements, and is thus able to simulate spatially explicit forest management (e.g., creation of gaps along a skyline track) and its consequences for forest development (e.g., regeneration establishing in gaps). Both the forest model and early versions of the rockfall model (Papers I and II) were, however, limited to single rectangular stands. In order to overcome this shortcoming, the “landscape”-approach was developed (presented in paper III), that allowed treating rockfall processes at the appropriate scale.

Feedback of rockfall processes on forest development. Currently, rockfall impacts have no effect on the impacted trees. Trees do not die immediately when impacted with stem-breaking energy, nor do they suffer from an increased probability of mortality caused by fungal infections that may enter trees through rockfall wounds (Vospernik, 2002). For one, such feedback would be a technically difficult task, since rockfall and forest development are simulated at two different scales and at two different logical “spaces” within the model. A second reason relates to the low incident frequency of real rockfall events, that is usually unknown (but see Trappmann et al (2014) for a recent attempt to integrate tree-ring based estimates of rockfall frequencies into rockfall modelling). In addition, real rockfall frequencies are of limited use for simulation designs that aim at estimating (probabilistic) protection efficiencies as they require a very large amount of events. Thus, the limitation seems therefore acceptable.

Parameter and data parsimony. An often-found topic whenever processes of the natural world are being modelled is the trade-off between parsimony in both required parameters and input data versus accuracy and biophysical realism (Seidl et al., 2005). PICUS Rock’n’Roll was from the beginning primarily designed as a simulation environment for conducting experiments with regard to the effect of forest dynamics on rockfall processes *in silicio* (Peck, 2004), rather than a tool for supporting designing and dimensioning technical protection measures. Therefore, a broadly applicable design was implemented that avoids site specific parameterization/ calibration and uses input that is either increasingly available at larger scales (digital elevation models) or relatively easy to obtain from a combination of field work and parameters from literature. It has been shown in extensive model evaluation experiments that the presented general approach is well able to capture the main rockfall processes over a broad gradient of slope conditions.

In addition, the model responds realistically to changes in the forest structure, which was demonstrated inter alia with the Penken case study (Paper III).

Data requirements of the coupled approach. The Penken case study can serve as a realistic example for an application of the coupled rockfall and forest model with the goal of assessing the effects of forest management on rockfall and timber related indicators. In this case, the data requirements were quite substantial, given the relatively large area, the longterm time horizon of simulated forest development, and the number of forest management scenarios. In addition to the relatively modest general input data required by the rockfall model (Table 1), a variety of input data had to be provided for the forest model, ranging from climate and soil data over detailed information about the initial forest conditions to detailed full scale operational management plans. This all-in-all high effort clearly hampers a broad application of this approach in a decision support context. There are, however, some available options to alleviate this problem: One option could be a two phase approach, with the first phase being an initial screening, resulting in dedicated rockfall hot spots, and consequently a second phase with an analysis focused on smaller areas. Another potential improvement is to tap into the increasingly available pool of remote sensing data, which could be used to, e.g., speeding up the preparation of the initial forest state. If these simplifications do not suffice, a simpler approach to gauge rockfall hazards could be utilized (e.g., the NaiS approach (Frehner et al., 2005)). This route of combining a simplified rockfall assessment framework and remote sensing data was followed for example by Maroschek et al. (2014).

5.2 Implications and Conclusions

Implications for forest management. In this work it has been demonstrated that forest management regimens that are particularly designed for protection forests provide better long-term rockfall protection and at the same time can provide better contribution margins in timber production than a business as usual scenario based on a shelterwood approach that is typical for commercial forests. Relying only on spatially aggregated small interventions, PFM1 and PFM2 succeeded in maintaining a mostly continuous forest cover while initiating a continuous regeneration process that improved the long-term stability and resilience of the forest. The BAU scenario did also succeed in rejuvenating the forest, but at the cost of re-occurring phases with reduced rockfall protection potential. In this study the large scale forest management plan of the BAU scenario already considered the spatial context of the stands and tried to avoid continuous areas with low volume and stem numbers. This plan could, however, be improved further, thus reducing the loss of rockfall protection in phases of intensive harvest activities. But, given the small-scale ownership structure of the area, it remains unclear whether the owners are able and willing to fully coordinate their management activities. Most stands in the area are today in a mature or overly mature state, which led to parallel stand regeneration cuts after management activities were assumed to start. Such imbalance in the forest age structure is not specific to the Penken case study, but is a wide spread phenomenon in the Alpine region (BFW, 2011).

The NOM scenario maintained high protection efficiency over several decades despite the aforementioned initial age structure. It has to be noted, that in our simulations the effect of browsing by ungulates was not considered, which likely led to an overestimation of regeneration success in all scenarios. Similarly, disturbances such as bark beetle infestations were also disregarded in our simulations. Yet, disturbances are expected to increase under climate change (e.g., Seidl et al., 2014), posing a particular threat for the overly mature stands in the NOM scenario.

Relationship to technical protection measures. This thesis corroborates the notion, that forests are a key factor in protecting settlements and infrastructure against rockfall (e.g., (Frehner et al., 2005; Volkwein et al., 2011). Specifically, it was found that the effect or forests mainly consisted in a reduction of run-out-distances, and, less pronounced, a reduction of rock velocities and rebound heights. Thus well stocked forests act as a relatively cheap means of rockfall protection for large areas. But also those areas at high risk that need to be protected by additional technical measures, benefit from the protective effect of forests: Forests greatly reduce the number of rocks that reach the rockfall nets or dams as well as their kinetic energy, thus help decreasing maintenance costs for technical infrastructure.

Concluding remarks. Mountain forests in the Alps provide a wide range of services to our society, ranging from recreation and hunting to the supply of clean drinking water. The broad set of services and diverging stakeholder interests complicate the management of these resources. This thesis focuses on the protection service against rockfall, and its interactions with the biomass and timber supply function of forests. It could be shown, that simulation tools particularly designed to integrate both mountain forest dynamics and rockfall processes, can help to gain a better understanding of the intricacies of these processes and their relationships. Likewise, scenario analysis allow exploring a wide range of possible developments that may arise from changes in natural systems (e.g., climate change), changes in human systems (e.g., alternative forest management), or both. Attempts to bridge scientific fields and to promote system understanding, as described in this thesis, may become even more important in a world of accelerating change and increasing complexity, and may provide the tools for tackling upcoming challenges in the management of our natural resources.

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7 Full list of publications

Werner Rammer

Number of publications: 26, Citations: 345, h-Index: 10 (Source: Scopus, June 2015)

2015

Rammer, W., Brauner, M., Ruprecht, H., Lexer, M.J., 2015. Evaluating the effects of forest management on rockfall protection and timber production at slope scale. Scand. J. For. Res. 00000, 1–25. doi:10.1080/02827581.2015.1046911

Silva Pedro, M., Rammer, W., Seidl, 2015. Tree species diversity mitigates disturbance impacts on the forest carbon cycle. Oecologia 619–630. doi:10.1007/s00442-014-3150-0

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8 Appendix

The Appendix consists of three scientific publications in the original layout of the journals the papers were published in.

Paper I

Woltjer, M., Rammer, W., Brauner, M., Seidl, R., Mohren, G.M.J., Lexer, M.J., 2008. Coupling a 3D patch model and a rockfall module to assess rockfall protection in mountain forests. J. Environ. Manage. 87, 373–88. doi:10.1016/j.jenvman.2007.01.031

Paper II

Rammer, W., Brauner, M., Dorren, L.K. a., Berger, F., Lexer, M.J., 2010. Evaluation of a 3-D rockfall module within a forest patch model. Nat. Hazards Earth Syst. Sci. 10, 699–711. doi:10.5194/nhess-10-699-2010

Paper III

Rammer, W., Brauner, M., Ruprecht, H., Lexer, M.J., 2015. Evaluating the effects of forest management on rockfall protection and timber production at slope scale. Scand. J. For. Res. 00000, 1–25. doi:10.1080/02827581.2015.1046911

8.1 Appendix - Paper I

Woltjer, M., Rammer, W., Brauner, M., Seidl, R., Mohren, G.M.J., Lexer, M.J., 2008. Coupling a 3D patch model and a rockfall module to assess rockfall protection in mountain forests. J. Environ. Manage. 87, 373–88. doi:10.1016/j.jenvman.2007.01.031

Journal of Environmental Management 87 (2008) 373–388

Journal of Environmental Management

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Coupling a 3D patch model and a rockfall module to assess rockfall protection in mountain forests

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Abstract

Many forests in the Alps are acknowledged for protecting objects, such as (rail) roads, against rockfall. However, there is a lack of knowledge on efficient silvicultural strategies and interventions to maintain these forests at optimal protection level. Therefore, assessment tools are required that quantify the rockfall protection effect of forest stands over time, and thereby provide the ability to evaluate the necessity and effect of management interventions. This paper introduces such a tool that consists of a 3D rockfall module embedded in the patch based forest simulator PICUS. The latter is extended for this study with a new regeneration module. In a series of experiments the new combined simulation tool is evaluated with regard to parameter sensitivity, model intercomparison experiments with recently proposed algorithms from the literature, and the ability to respond realistically to different management regimes in rockfall protection forests. Results confirm the potential of the new tool for realistic simulation of rockfall activity in heterogeneous mountain forests, but point at the urgent need to improve the knowledge base on the interaction of understory and rockfall activity. Further work will focus on model validation against empirical rockfall data, and include reduced tree vitality due to damage from boulder collisions as well as the explicit consideration of downed dead wood.

Keywords: PICUS; Protection forest; 3D rockfall simulation

1. Introduction

A particularly important function of forests in the Alps is to provide protection against natural hazards such as snow avalanches, debris flows and rockfalls. Therefore, many forest stands in the Alps have, next to a site-protection function in which forest cover stabilizes the slope itself, an object-protection function, which means that forest cover can protect objects and infrastructure located further down a slope from natural hazards (Motta and Haudemand, 2000). Taking into account the increasing pressure from emerging tourism and increasing infrastructure needs in the Alps (Kräuchi et al., 2000), the object-protection function of mountain forests in Central Europe will only gain importance in future. However, there is a lack of knowledge on efficient silvicultural strategies and interventions to maintain protection forest structures, i.e. how to best overcome periods of decreased protection which may occur in managed stands as well as during natural forest development (Dorren et al., 2004; Perret et al., 2004). In the near future, such development is expectable on a large scale, as for instance in Austria, many protection forest stands enter their old growth phase and regeneration is in many cases lacking (BFW, 2004).

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Efficient management is most needed, while low productivity, difficult terrain and therefore high harvesting costs are often keeping owners and managers from intervening in protection forest stands.

In the current study focus will be on protection function of mountain forests against rockfall. Rockfall is defined here as a quick gravitational movement of rock boulders, rolling, tumbling or sliding down a hillslope (Selby, 1995). The boulders rather act independently and rockfall total mass lies typically below 5 m^3 (Berger et al., 2002). Since interest in this study is on sustainable forest resource management, sufficient tools are needed that quantify the rockfall protective effect of forest cover over time, and thereby provide the ability to evaluate the necessity and effect of management interventions. Among the first attempts to characterise and quantify the protection effect of forest cover against rockfall are studies done by Jahn (1988), Gsteiger (1989) and Zinggeler (1989). While Jahn (1988) analysed empirical rockfall experiments while releasing boulders down a slope, Zinggeler (1989) mathematically analysed data sets of rockfall trajectories and thereby proved the influence of slope relief, soil condition and standing trees on the rockfall trajectory. In addition, Gsteiger (1989) developed the now widely applied, tested and adapted concept of the "mean tree free distance" or "average distance between contacts" (e.g., Gsteiger, 1993; Brauner et al., 2005; Dorren et al., 2005), which indicates the mean distance between two collisions of boulders with trees, or in other words: how often, on average, a boulder dissipates its energy by impacting a tree on its way down the slope.

The above-mentioned studies prove that an increasing amount of quantitative knowledge is available on the relation between the process of rockfall and forest structures in the Alps. Several assumptions on ideal forest structures have been tested in experimental studies, following Jahn (1988); e.g. Perret et al. (2004) and Dorren et al. (2005). In contrast, knowledge regarding the temporal relation between forest management interventions and rockfall is lacking (Dorren, 2002). Decision support tools are called for, which can predict this dynamic relation in a plausible manner (Dorren, 2002; Dorren et al., 2004; Kräuchi et al., 2000). Based on biomechanical considerations, Brauner et al. (2005) developed such a dynamic modelling tool for decision support in protection forest management. Two rockfall quantification models were coupled and implemented in an empirical distance-independent forest growth simulator. While the results of Brauner et al. (2005) are promising, there is still potential to improve the approach on spatial explicitness of both rockfall and forest vegetation simulation approaches. Similarly, Wehrli (2005) attempts to combine the forest gap model FORCLIM (Bugmann, 1996) and an existing rockfall simulation tool, and concludes that a spatially explicit representation of forest structure would enhance the approach.

Based on these considerations the objectives of this paper are:

(1) the introduction of a new rockfall module, embedded in the patch-based forest simulator PICUS (e.g., Lexer and Hönninger, 2001). It is hypothesized that with this spatially explicit simulator the consequences of heterogenizing silvicultural interventions, typical for mountain forest management (Mayer and Ott, 1991; Ott et al., 1997; Pitterle, 1993), on rockfall protection can be considered with a higher level of accuracy and reliability;
(2) the preliminary evaluation of the presented tool with regard to parameter sensitivity, comparison against model formulations from the literature with regard to key output variables, and the ability to respond realistically to different management regimes in rockfall protection forests.

2. Methods and material

2.1. The forest model PICUS v1.3

The model used in this study is the hybrid forest patch model PICUS v1.3 (Seidl et al., 2005), which incorporates elements of a classical patch model (PICUS v1.2, Lexer and Hönninger, 2001) as well as a stand level production model based on physiological principles (3-PG, Landsberg and Waring, 1997). The spatial structure of PICUS v1.2 (Lexer and Hönninger, 2001) is retained in the current model version. PICUS arranges tree biomass in space based on $10 \times 10\,m^2$ patches with vertical resolution of 5 m. Within a patch the position of a tree is not known. A three-dimensional light model, allowing for explicit consideration of direct and diffuse radiation within the canopy, is used to model inter- and intra tree species competition. The incorporation of a production model that is based on the concept of radiation-use efficiency (Landsberg and Waring, 1997) enhanced accuracy in prediction of growth and yield. It also improved the physiological foundation of the model with regard to varying environmental conditions (Seidl et al., 2005). PICUS v1.3 requires input of incoming radiation, temperature, precipitation and vapour pressure deficit of the air in at least monthly resolution. The mortality submodel within PICUS follows the classical patch model approach (e.g., Keane et al., 2001) and has been complemented by a submodule of bark beetle induced mortality in *Picea abies* (L.) Karst. (Lexer, 2001). So far, regeneration in PICUS has been simulated with a recruitment submodel (e.g., Vanclay, 1994; Price et al., 2001).

2.1.1. Extended regeneration submodel

For the realistic inclusion of a rockfall module in PICUS v1.3 the recruitment component required a major update since the regeneration layer plays an important role in the rockfall process. In designing the new regeneration module three core requirements had been set: (i) due to high uncertainties in modelling mountain forest regeneration (e.g., Kindermann et al., 2002), the model structure was kept as simple as possible, (ii) biological processes were considered whenever possible, and (iii) key parameters as well as flow and state variables should be observable to allow model validation against empirical data. In the following section a brief outline of the new regeneration module within PICUS is given. For further details on model logic and structure we refer to Lexer and Hönninger (2001), Lexer (2001) and Seidl et al. (2005).

As in previous model versions, seeds produced by mature trees are distributed in the simulated forest mimicking zoochorous and anemochorous processes. According to the model concept the probability of regeneration establishment on a particular patch in a given year is calculated per species based on the available light on the forest floor, the stockable relative area per patch, and the effective number of seed of a species on a patch. A prerequisite for the new module was the enhancement of the light model within PICUS because in recent model versions trees had not been initialized explicitly below 1.3 m height, and subsequently were not considered in modelling light levels at the forest floor:

$$\mathrm{avL_{floor}} = \mathrm{avL_{bottom}}\,\mathrm{e}^{-0.7\,\mathrm{BM}}, \quad (1)$$

where $\mathrm{avL_{floor}}$ is the relative available light at the forest floor incl. regeneration $\leqslant$130 cm [0–1], $\mathrm{avL_{bottom}}$ the relative available light in the lowest crown cell (without regeneration $\leqslant$130 cm) [0–1], 'e' the base of natural logarithm, and BM the aboveground dry mass of regeneration $\leqslant$130 cm [kg m^{-2}].

Eq. (2) estimates the probability of establishment in a given year, per patch and per species. $S_{\mathrm{eff}(ij)}$ is the seed of a species (j) on patch (i) after applying the species-specific germination rate and the environmental filters of the temperature regime, soil moisture and nutrient supply (see Lexer and Hönninger, 2001):

$$P(\mathrm{est})_{ij} = \left(1 - \mathrm{e}^{(-a\,S_{\mathrm{eff}(ij)}\,SA(i)\,\mathrm{Lresp}(ij))}\right)^{(1-\mathrm{Lresp}(ij))}, \quad (2)$$

$P(\mathrm{est})_{(ij)}$ is the probability of establishment for species (j) on patch (i) [0–1], $S_{\mathrm{eff}(ij)}$ the effective number of seed of species(j) at patch(i) [nm^{-2}], $SA_{(i)}$ the proportion of stockable area of patch(i) [0–1], Lresp(ij) the light response of species (j) at patch (i) on forest floor [0–1], and a the empirical coefficient.

The coefficient a can be estimated from field data. In the current study it was set to 0.0005. The rationale was that based on explorative simulation experiments under unlimited seed supply the model produced realistic results with regard to number of seedlings along both a site and light gradient which could be confirmed by qualitative literature data (Ruhm, 2004; Müller, 2003). A random number decides whether new individuals of a species are added to the lowest of four height classes ($H_1 = 0$–10 cm, $H_2 = 10$–30 cm, $H_3 = 30$–80 cm, $H_4 = 80$–130 cm). Growth of established seedlings is modelled within that size-class frame. Per size-class a representative individual is defined. Currently, all conifers and all broadleaf species respectively are pooled. The relationship of dry mass and height of individual seedlings shown in Fig. 1 is used to calculate BM in Eq. (1).

A species-specific height growth potential per height class is modified with the light response of the species as a process-based proxy of competition by vegetation of the same height or taller as the target height class to get an estimate of actual height growth $ih_{\mathrm{sim}(ijk)}$ (Eq. (3a)). The

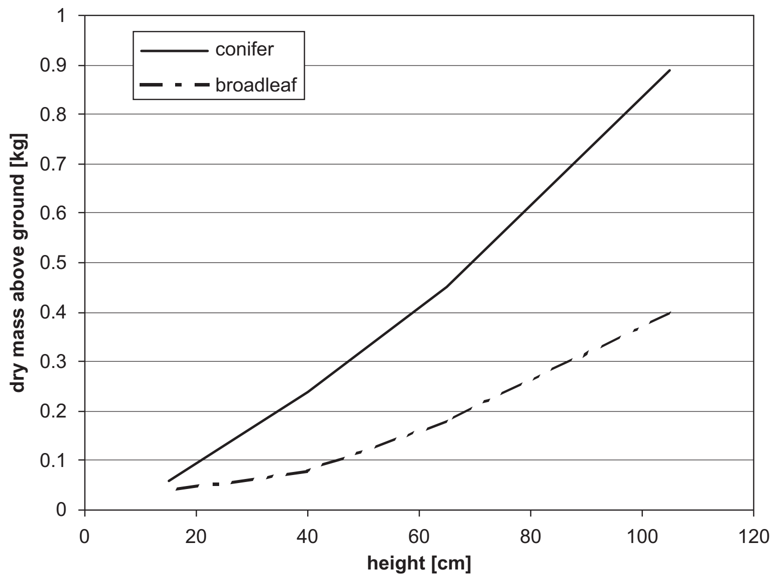

Fig. 1. Relationship of dry mass of aboveground biomass and height for pooled conifer and broadleaf seedlings (Hochbichler, unpublished data).

number of individuals per species (j) growing from height class (H_k) into height class (H_{k+1}) is calculated with Eq. (3b):

$$ih_{\text{sim}(ijk)} = ih_{\text{pot}(ijk)}\,\text{Lresp}(ijk), \tag{3a}$$

$$A_{ijk} = n_{ijk}\,\frac{ih_{\text{sim}(ijk)}}{b}, \tag{3b}$$

where A_{ij} is the number of individuals of species (j) at patch (i) growing from $H(k)$ to $H(k+1)$ [n ha^{-1} yr^{-1}], N_{ijk} the stem number of species (j) at patch (i) in $H(k)$ [n ha^{-1}], $ih_{\text{pot}(jk)}$ the potential annual height growth of species (j) in $H(k)$ [cm yr^{-1}], Lresp(ijk) the light response of species (i) at patch (j) in height class (k) [0–1], $ih_{\text{sim}(ijk)}$ the actual height growth of species (j) at patch (i) in height class (k) [cm yr^{-1}], and b the width of $H(k)$ [cm].

If a species fails to achieve a minimum height growth for a specified number of successive years a percentage of individuals per height class dies. Outgrowth from H_4 is initialized as individual trees within the PICUS simulation environment. Further growth, seed production and mortality are then simulated as described in Seidl et al. (2005).

2.2. The rockfall submodule

2.2.1. General layout

In PICUS, the initial forest conditions regarding the distribution of trees can be established by (i) randomly allocating the trees of a population over the patches, or (ii) manually allocating each tree individually to a particular patch. By the latter approach any forest structure can be realized within the 100 m^2 resolution of the patch array. Gaps can be simulated by leaving patches out of the tree distribution. Once allocated to a patch, the trees are randomly assigned a position within the patch considering minimum neighbourhood distances. This feature was included to specifically address the needs of the rockfall module. However, for simulating forest dynamics the patch is still the basic spatial modelling entity. Currently, PICUS v1.3 simulates forest dynamics on a horizontal patch array. For the rockfall simulation the patch array is tilted according to slope. Every simulated year the rockfall module can be called and the effect of vegetation on rockfall activity can be estimated. To eliminate the stochastic component of forest dynamics on rockfall activity, the same tree positions are repeatedly used during each rockfall simulation. Embedded in PICUS, the rockfall module is conceptually based on several core rules:

(1) a boulder is defined as a sphere of variable size (diameter) and mass,
(2) each rockfall trajectory starts either at a random or fixed location at the upper limit of the simulated forest stand,
(3) the model distinguishes individual tree contacts (for trees higher than 1.3 m) and the energy dissipating effect of the regeneration layer, the so-called "understory",
(4) for the understory, vegetation is considered as distributed homogeneously over the patch in four height classes ($H_1 = 0$–10 cm, $H_2 = 10$–30 cm, $H_3 = 30$–80 cm, $H_4 = 80$–130 cm),
(5) the boulder can change between rolling and jumping mode along its trajectory,
(6) boulder trajectories are modelled in 3D space and
(7) the trajectory ends when (i) the boulder leaves the simulated forest, or (ii) the boulder stops.

A moving boulder looses kinetic energy through (i) surface roughness (in rolling mode), (ii) movement through understory (in rolling or jumping mode), (iii) tree hits (in rolling or jumping mode), and (iv) through ground contact in jumping mode. Whether the boulder is jumping or rolling depends on a jumping criterion. A boulder starts jumping from the moment when the rotational velocity exceeds the translational velocity (compare Dorren et al., 2004).

Based on Meißl (1998), the acceleration of a rolling boulder without vegetation contact (a_g) is calculated as a function of current slope and surface roughness:

$$a_g = \frac{5}{7}\,g(\sin(\text{slope}) - \mu\cos(\text{slope})), \tag{4}$$

where a_g is the acceleration of a rolling boulder without vegetation contact [m s^{-2}], g the earth acceleration of gravity (constant 9.81 m s^{-2}), μ the parameter that defines surface roughness [0–1], and slope the inclination [°].

If the boulder is jumping the path of the boulder is described by a ballistic parabola without consideration of air mass resistance. To account for the inclined slope the classical formulation was extended (Eqs. (5)–(7)). The height over ground ($h(t)$) of the boulder depends on the initial conditions of velocity (v_0), height (h_0) and the vertical dip angle relative to the horizontal (α_0) (compare Fig. 2a). Eq. (5) presents the jumping boulder without understory ("free jump"):

$$h(t) = -\frac{g}{2}t^2 + (\sin(\alpha_0) - \cos(\alpha_0)\tan(\text{slopeg}))v_0 t + h_0, \tag{5}$$

where $h(t)$ is the height over ground at time t [m], v_0 the velocity at $t = 0$ [m s^{-1}], α_0 the boulder dip angle at $t = 0$ [°], h_0 the height over ground at $t = 0$ [m], slopeg the current slope in boulders direction [°], and t the time [s].

As the time needed for reaching a specific height over ground (h_{above}) can be determined using Eq. (6), the jump distance can be calculated with Eq. (7):

$$t_h = \frac{1}{g}\Big(v_0(\sin(\alpha_0) - \cos(\alpha_0)\tan(\text{slopeg})) + \sqrt{v_0^2(\sin(\alpha_0) - \cos(\alpha_0)\tan(\text{slopeg}))^2 + 2g(h_0 - h_{\text{above}})}\Big), \tag{6}$$

$$d = v_0 t_h \cos(\alpha_0), \tag{7}$$

where t_{h} is the time needed for reaching h_{above} [s], h_0 the height over ground at $t = 0$ [m], h_{above} the height over ground [m], v_0 the velocity at $t = 0$ [m s^{-1}], α_0 the boulder

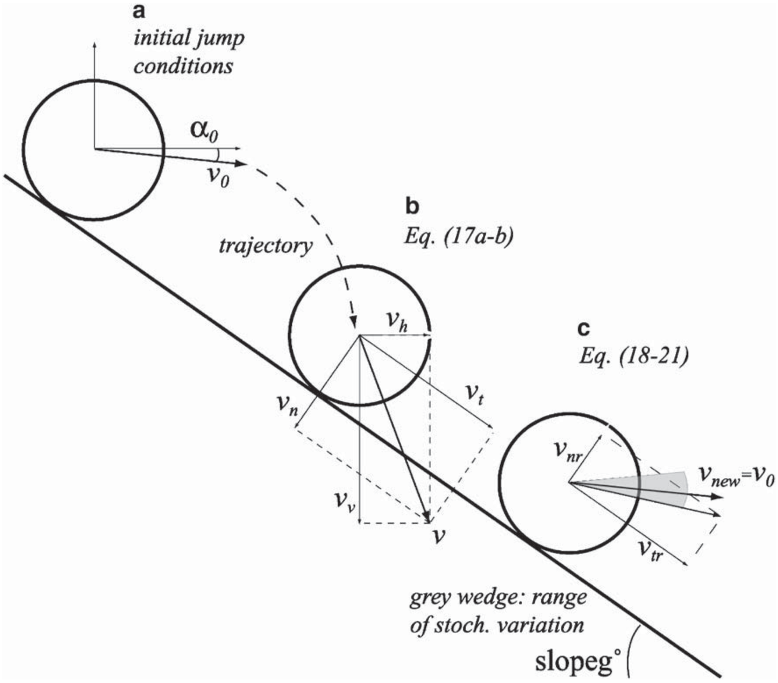

Fig. 2. Scheme for initial jump conditions (a) and ground contact (b, c). (a) Indicates the reference frame for boulder jumps (see Eqs. (4)–(7)), (b) shows the transformation of velocity components from the reference frame to the local slope coordinate system, and (c) the situation after the application of rebound parameters. The vector v_{new} describes the initial conditions for the next jump.

dip angle at $t = 0$ [°], and d the projected distance at time t [m].

2.2.2. Trajectory calculation through understory vegetation

In PICUS, trees that have a height lower than 1.3 m are not treated as individual trees but subsumed as understory. On each patch these small trees are grouped in four height classes: 0–10 cm, 10–30 cm, 30–80 cm, and 80–130 cm. The biomass within each height class is assumed as homogeneously distributed throughout the patch area (compare Section 2.1.1). In the rockfall module each of these height classes has a distinguishing energy dissipation value. For a given movement, distance d, biomass BM converted to its volume equivalent using specific density factors for small understory trees (Hochbichler, unpublished) V_{BM} and its attached fracture work U_{fr} (Berger et al., 2004) are accumulated within the corridor of the boulder, as defined by the boulder diameter. Currently, no empirical data on the fracture work of understory vegetation is available. As a preliminary solution the fracture work per unit volume U_{fr} has been derived from stress–strain diagrams of fresh wood (e.g., Berger et al., 2004).

For the boulder's rolling-mode, this distance-dependent energy loss is calculated as a constant negative acceleration a_s in Eq. (8a), in which F_s is the breaking force (Eq. 8(b)), and m the boulder mass. The resulting effective acceleration (Eq. (9)) in rolling mode is the sum of Eqs. (4) and (8a):

$$a_{\text{s}} = \frac{F_{\text{s}}}{m}, \tag{8a}$$

$$F_{\text{s}} = -V_{\text{BM}}\, U_{\text{fr}}\, B, \tag{8b}$$

$$a_{\text{eff}} = a_g + a_s, \tag{9}$$

where a_{s} is the constant negative acceleration due to vegetation contact [m s^{-2}], F_{s} the constant breaking force [kg m s^{-2}], m the boulder mass [kg], V_{BM} the volume equivalent of dry mass of understory [m^3 m^{-2}], U_{fr} the fracture work [J m^{-3}], B the boulder diameter [m], a_{g} the velocity of a rolling boulder without vegetation contact [m s^{-2}], and a_{eff} the effective acceleration (including vegetation contact) [m s^{-2}].

Movement through the understory in the jumping mode is solved iteratively. For each iteration step (step length 0.2 m) the jump height-specific biomass density is retrieved from the understory height classes and the derived deceleration is calculated, resulting in reduced movement velocity and jump length, where the decelerating effect of the understory is inversely proportional to boulder diameter.

2.2.3. Effect of tree hits and ground contact on boulder trajectory

2.2.3.1. Tree hits. Energy loss due to boulder-tree collision is calculated in the same manner for the jumping and the rolling mode. As long as neither trees nor ground surface are hit, the boulder trajectory direction stays constant. Therefore, it is possible to identify the next tree hit deterministically. While this calculation is carried out in a vector approach, the eccentricity of the boulder-stem impact is stochastically determined within the range set by the tree diameter under bark, accounting also for the not perfect spherical form of boulders under real world conditions. Assuming only limited elastic reaction of the stem during impact, the new deviation angle can be calculated based on eccentricity of the contact point relative to the stem axis and the tree's DBH.

Depending on the eccentricity of the collision, part of the boulder's energy is directed to the centre of the tree. The kinetic energy of a boulder immediately before a tree contact is fractioned by splitting the velocity vector v_0 into its radial (v_r) and tangential (v_t) component, respectively (Eqs. 10(a) and (b)). As a prerequisite the angle between the boulder's direction and the tree centre is calculated with Eq. (11) (see Fig. 3):

$$v_r = v_0 \cos(\delta), \quad (10a)$$

$$v_t = v_0 \sin(\delta), \quad (10b)$$

$$\delta = \arcsin\left(\frac{e}{\mathrm{DBH}\,0.5}\right), \quad (11)$$

$$W_r = \frac{m}{2} v_r^2, \quad (12)$$

where e is the randomly selected impact position related to tree diameter under bark [cm], δ the angle between boulder direction and tree centre [°], v_0 the velocity of boulder before impact [m s^{-1}], v_r the component of velocity in radial direction [m s^{-1}], v_t the component of velocity in tangential direction [m s^{-1}], and W_r the kinetic energy in radial direction [J].

The radial component of the kinetic energy W_r (Eq. (12)) is compared to the energy dissipation potential of the tree (Eq. (13)). Tree volume is calculated according to Pollanschütz (1974). After the radial energy component

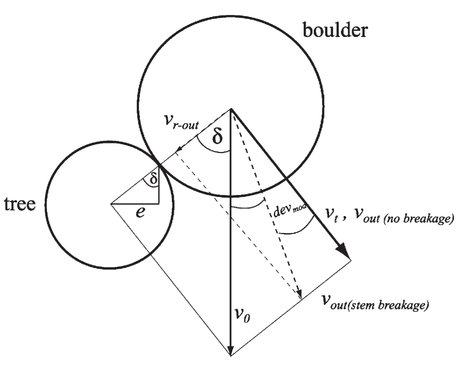

Fig. 3. Geometric scheme of the boulder-tree impact. If the tree does not break, the resulting $v_{r\text{-out}}$ is zero. In that case the outgoing velocity vector is v_t. Otherwise the outgoing velocity is the sum of v_t and $v_{r\text{-out}}$.

W_r is reduced up to that limit (Eq. (14)), the remaining velocity after the impact is calculated with Eqs. 15(a) and (b). Friction loss of v_t is currently not considered:

$$W_{\mathrm{tree}} = V_{\mathrm{tree}} U_{\mathrm{fr}}, \quad (13)$$

$$W_{\text{r-out}} = \max(0;\ W_r - W_{\mathrm{tree}}), \quad (14)$$

$$v_{\text{r-out}} = \sqrt{\frac{2 W_{\text{r-out}}}{m}}, \quad (15a)$$

$$v_{\mathrm{out}} = \sqrt{v_t^2 + v_{\text{r-out}}^2}, \quad (15b)$$

where W_{tree} is the energy dissipation potential of the tree [J], V_{tree} the tree stem volume [m^3], U_{fr} the fracture energy per 1 m^3 wood [default: 90000 J m^{-3} (Berger et al., 2004)], $W_{\text{r-out}}$ the kinetic energy in radial direction after impact [J], $v_{\text{r-out}}$ the velocity in radial direction after impact [m s^{-1}], and v_{out} the velocity of boulder after impact [m s^{-1}].

If the energy dissipation potential of the tree is exceeded by W_r, the stem breaks and the outgoing horizontal deviation angle is reduced according to Eq. (16a) (compare Fig. 3). The final deviation angle 'dev' is calculated with Eq. (16b):

$$\mathrm{dev}_{\mathrm{mod}} = \arctan\left(\frac{v_{\text{r-out}}}{v_t}\right), \quad (16a)$$

$$\mathrm{dev} = \begin{cases} \delta < 0 : -90 - \delta + \mathrm{dev}_{\mathrm{mod}}, \\ \delta \geqslant 0 : 90 - \delta - \mathrm{dev}_{\mathrm{mod}}, \end{cases} \quad (16b)$$

where $\mathrm{dev}_{\mathrm{mod}}$ is the reduction of horizontal deviation due to stem breakage [°], and 'dev' the resulting deviation after tree hit [°].

2.2.3.2. Ground contact. Energy dissipation by ground contact after jumping is calculated based on empirical rebound factors (Chau et al., 2002; Azzoni et al., 1995; Pfeiffer et al., 1993) that reduce boulder velocity (Eqs. (17) and (18)). The rebound factors comprise of a normal (reboundN) and a tangential (reboundT) component relative to ground surface, where an impact without energy loss (e.g., a rubber ball on concrete) has a value of 1 and a total reduction of the boulder energy has a value of 0. The new boulder velocity v_{new} is then calculated with Eq. (19). The outgoing angle relative to the slope dip angle (Eq. (20)) is adjusted by a stochastic component to account for deviating effects of micro-topography, e.g. rocks or dead wood. Following Pfeiffer et al. (1993) the maximum adjustment is set by a roughness parameter for deviation, here 20° (Eq. 21). Figs. 2(b) and (c) give a schematic representation of these geometrical components. The natural tendency of a boulder to approach the slope direction is taken into account through bisection of the outgoing horizontal trajectory direction deviation angle plus a randomly chosen angle. Based on empirical findings by Berger et al. (2004) this horizontal deviation after surface contact is evenly distributed and varies between

$+20^\circ$ and -20°. In the current model version boulders that leave the simulated area on the sides are not tracked any further.

$$v_n = v_v \cos(-\text{slopeg}) - v_h \sin(-\text{slopeg}), \quad (17a)$$

$$v_t = v_v \sin(-\text{slopeg}) + v_h \cos(-\text{slopeg}), \quad (17b)$$

$$v_{nr} = v_n \,\text{reboundN}(-1), \quad v_{tr} = v_t \,\text{reboundT}, \quad (18a-b)$$

$$v_{new} = \sqrt{v_{nr}^2 + v_{tr}^2}, \quad (19)$$

$$\theta = \arctan\left(\frac{v_{nr}}{v_{tr}}\right), \quad (20)$$

$$\alpha_0 = -\text{slopeg} + \theta + \text{nrandom}(0,\ \text{rough}), \quad (21)$$

where slopeg is the slope in current boulder's direction [°], v_n the boulder velocity normal to slope [m s^{-1}], v_t the boulder velocity tangential to slope [m s^{-1}], v_v the vertical boulder velocity [m s^{-1}], v_h the horizontal boulder velocity [m s^{-1}], v_{nr} the v_n reduced with rebound parameter [m s^{-1}], v_{tr} the v_t reduced with rebound parameter [m s^{-1}], v_{new} the new boulder velocity after ground contact [m s^{-1}], θ the outgoing boulder angle relative to slopeg [°], α_0 the adjusted outgoing boulder angle relative to horizontal plane [°], reboundN the rebound parameter normal to slope [0–1], reboundT the rebound parameter tangential to slope [0–1], and rough the maximum outgoing jump angle (here: 20°).

2.3. Model evaluation experiments

2.3.1. Experiment 1: Sensitivity analyses

Sensitive model parameters can guide applications and model improvement (Vanclay and Skovsgaard, 1997). Furthermore, awareness of parameter sensitivity can add interpretive value to the evaluation results and highly sensitive parameters can be varied in the evaluation experiments in order to explore their influence on the simulation results. In the current study the sensitivity of the rockfall module output to parameters which are either crucial to determine or of obvious relevance to rockfall processes is evaluated in a comprehensive sensitivity analysis (Table 1). The effect of a 10% change of a single parameter on the target value "mean run out distance" (ROD_m) over the simulated area will be compared to a base scenario. This scenario consists of a forest stand with a ground surface of 300 m downslope times 100 m in width on which 400 trees ha^{-1} (*Picea abies*), each with a DBH of 40 cm, are randomly placed. The simplified stand characteristics for this experiment are chosen based on former work of Wasser and Frehner (1996). ROD_m is calculated over 1000 boulder trajectories, repeated 50 times on the same tree pattern ($n = 50$). Boulders leaving the simulated forest at the sides are not taken into account. The tree positions are fixed and kept for all runs.

Table 1
Parameters of the rockfall module and their base value for the sensitivity analyses

Parameter	Base value	Unit
Slope	30	[°]
RebounceN	0.7	Dimensionless
RebounceT	0.8	Dimensionless
Rough	20	[°]
μ	0.5	Dimensionless
Boulder size	50	[cm]
Stem density	400	stems ha^{-1}
DBH	40	[cm]
Enter velocity (1)	0.8	[m s^{-1}]
Enter velocity (2)	10.0	[m s^{-1}]

Slope = hillslope, RebounceN = restitution coefficient normal to the slope (dampening effect), RebounceT = restitution coefficient tangential to the slope (dampening effect), Rough = range of stochastic variation of the outgoing vertical angle after ground contact, μ = surface roughness for rolling mode, boulder size = boulder diameter, DBH = tree diameter at 1.3m height, enter velocity = initial boulder velocity.

Table 2
Stand initialization characteristics for model inter-comparison Experiments 2 and 3

Species	DBH-class [cm]	Age [years]	Trees [n ha^{-1}]	H/D
Picea abies	8–9	40	600	85
Picea abies	9–10	40	600	75
Picea abies	10–11	40	600	70

H = mean tree height [cm], D = mean tree diameter [cm].

2.3.2. Experiments 2 and 3: Model intercomparison

In order to compare the rockfall module with existing modelling approaches, the development of two key output variables of the new tool is compared in a 100 year simulation with recent formulations from the literature. For both experiments the initial stand is a pole stage stand (Table 2) which develops over the 100-year simulation period without active management intervention. The regeneration module is deactivated. Climate and soil conditions represent a site in the Eastern Alps at an altitude of 1450 m a.s.l.

First, in Experiment 2, a key parameter to evaluate rockfall protection efficiency, the Average Distance between Contacts (ADC), as simulated with 1000 rockfall trajectories in the rockfall module, is compared with the ADC following Gsteiger (1993). Thereby the calculation formula of Gsteiger (1993) is applied to the simulation output according to Eq. (22). The ADC in the rockfall module is calculated as the mean trajectory length, divided by the average number of tree hits over 1000 simulated trajectories. The simulated stand extends 300 m downslope and has a width of 100 m:

$$ADC_{Gsteiger} = \frac{A}{[(N\,B) + \Sigma DBH]}, \quad (22)$$

where A is the simulated area [m^2, horizontal area], N the stem number [on simulated area], B the boulder size [m], and DBH the diameter at breast height [m].

Next, in Experiment 3, the energy dissipation (Edisp) by trees along the boulder's trajectory, calculated as a mean over 1000 trajectories in the rockfall module, is compared to the calculation method of Brauner et al. (2005). In their approach, Edisp by trees is calculated as the dissipation potential of n average trees that are fully hit along a complete trajectory through the simulated stand (Dpath) (compare Eq. (23)). The dissipation potential of an average tree represents the maximum boulder impact the tree can withstand without breaking. The number of tree hits along the trajectory is calculated by dividing the horizontal trajectory length (Dpath) with the expected distance between tree hits assuming a regular tree pattern. According to Brauner et al. (2005) this distance represents a boulder's travelling distance within which a tree impact occurs with a probability of 90%. For details we refer to Brauner et al. (2005). Stand data for the calculations were taken from the PICUS simulator.

In the PICUS rockfall module the dissipated energy by the trees is summed individually over the energy radially directed to the tree centre, as calculated in Section 2.2.3.1. The simulated stand extends over 100 m × 100 m:

$$\mathrm{Edisp}_{\mathrm{Potential}} = \frac{\mathrm{Dpath}}{D90}(V_{\mathrm{tree}}U_{\mathrm{fr}}), \tag{23}$$

where Dpath is the horizontal trajectory length of the boulder [m], $D90$ the boulder travelling distance till first hit with passing probability 0.9 [m], V_{tree} the volume of average tree [m^3], and U_{fr} the fracture work [$\mathrm{J\,m^{-3}}$].

2.3.3. *Experiment 4: Sensitivity to forest management*

To evaluate how sensitive the new modelling approach responds to realistic forest management, three stands under three different management regimes each are evaluated for their rockfall protection function. Each scenario run extends over a simulation period of 100 years. The target variable is $\mathrm{ROD_m}$. The study stands are located in Tyrol, central Alps in Austria. Notwithstanding the broad diameter distributions (compare Fig. 4) all stands are mono layered. In none of the stands active management interventions have been implemented over the last 20 years. Stand data and observations were provided by the NAB-project ''Natural Potential of Alpine Regions''. Representative soil data was taken from the Austrian Forest Soil Survey (Englisch et al., 1991), monthly climate data were interpolated from nearby weather stations. Table 3 gives major stand characteristics. In all stands regeneration is lacking, in stands A and B mainly due to low light levels at the forest floor. In stand C, several large gaps occur with gap diameter as large as 30 m. Local forest managers report severe browsing impact of cattle and ungulates. *Picea abies* is the dominant species in all stands.

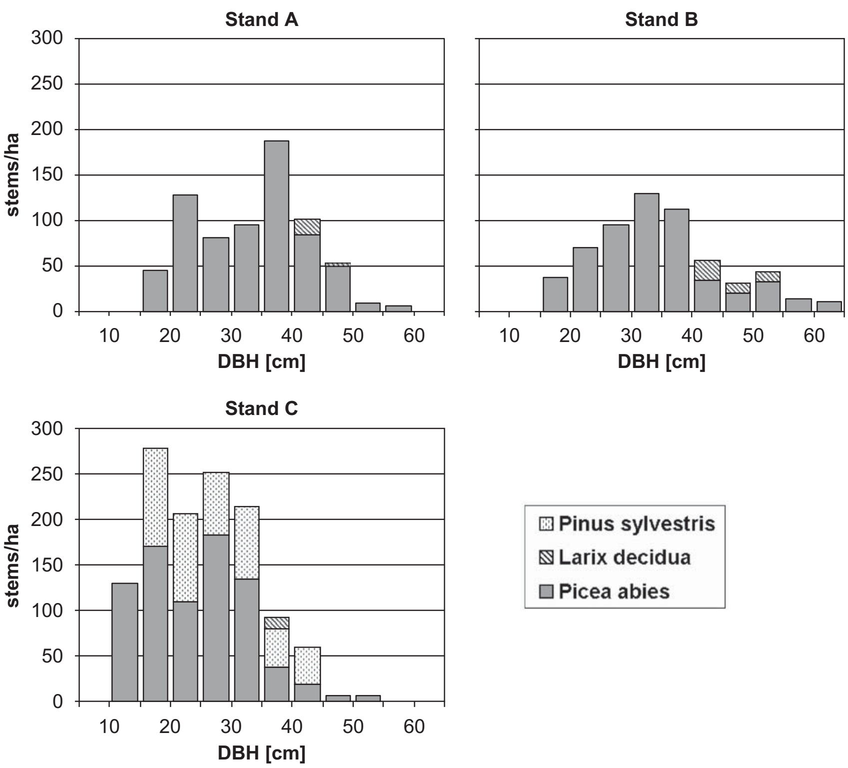

Fig. 4. Initial DBH distribution for stands A, B and C (Anonymous, 2005).

Table 3
Stand characteristics for stands A, B and C

Stand characteristics	Stand A				Stand B			Stand C			
	PA	PS	LD	Total	PA	LD	Total	PA	PS	LD	Total
Slope [°]	—	—	—	27	—	—	35	—	—		39
Age [years]	170	125	195		175	158	—	194	158	145	—
Mean height [m]	25.8	25.0	27.0		30.0	33.3	—	21.3	15.7	19.0	—
MAI_{150} [$m^3 ha^{-1}$]	4.9	—	—		6.2	—	—	2.6	—	—	—
Basal area [$m^2 ha^{-1}$]	64.0	1.0	3.0	68.0	58.0	10.0	68.0	41.3	26.7	1.3	69.3
Stem number per ha	689	5	20	714	558	61	619	801	434	12	1247
Stocking density	1.26	0.02	0.10	1.38	1.11	0.24	1.35	0.88	0.55	0.04	1.47
Volume [$m^3 ha^{-1}$]	722	11	34	767	762	135	897	386	207	11	604

PA = *Picea abies*, PS = *Pinus sylvestris*, LD = *Larix decidua*, MAI_{150} = mean annual increment at stand age 150, stocking density = stand basal area relative to basal area of yield tables (Anonymous, 2005).

The stand data had been sampled spatially non-explicit. For stand C a qualitative description of gap distribution was available. In the simulation, in stands A and B trees are randomly distributed over all patches, whereas in stand C no trees were assigned to patches that represent gaps. The initially assigned position of the trees was kept for all simulation runs. For all simulations the patch array consists of 10×30 patches (3.0 ha).

To analyse the response of the new rockfall module to stand structures as affected by management three-stand treatment programmes (STP) are applied to each stand over a simulation period of 100 years, starting in year 2005. STP1 is a "no intervention" regime, STP2 is a "business as usual" regime, and STP3 represents a "rockfall protection management" regime (compare Tables 4a and b). The passive "no intervention" regime is used here as a natural benchmark scenario with which the protective effect of the active management regimes can be compared. STP2 is a regime commonly applied to regenerate mature mountain forests managed for timber production. First, a regeneration cut opens up the stand to initialize regeneration, and later a final cut removes the shelter. In the simulation trees with a DBH smaller than 12 cm are retained. During the early stem exclusion phase (sensu Oliver and Larson, 1996) a pre-commercial thinning is applied. In STP3 the stands are managed according to Wasser and Frehner (1996) with a focus on stand stability. In general, the mature single layered, homogenous stands are to be transformed into stands with at least groups of trees of different ages and size classes. Such a transformation towards enhanced stability is best accomplished with slight interventions (Ott et al., 1997). STP3, therefore, includes several thinning with intervals of 20 years. Furthermore, gaps are created and successively enlarged in stands A and B to enhance natural regeneration. Treatment of stand C differs from stands A and B with regard to several features. As productivity in stand C is considerably lower, the shelter period of STP2 extends over 35 years compared to 20 years for stands A and B. The eight initial gaps in 2005 are already 4–12 patches in size and not enlarged in STP3. Tables 4a and b give a complete list of silvicultural interventions (see Appendix A).

Table 4(a)
Stand Treatment Programmes (STP2 = business as usual management, STP3 = protection forest management) for stands A and B

Simulation year	STP2		STP3		
	Type	Removal [%]	Type	Removal [%]	Gaps × patches
2010	Regeneration cut	40	Thinning/gap	25/10	4 × 8
2030	Clearing	100	Thinning	25/10	
2050	—	—	Thinning/gap	25/10	4 × 16
2070	—	—	Thinning	25/10	
2075	Pre-thinning	50	—	—	
2090	—	—	Thinning/gap	25/10	4 × 24

The intensity for thinnings in STP3 distinguishes a removal percentage (related to stem numbers) for the stability thinning (DBH: 12–41 cm), respectively the overhead thinning (DBH > 41 cm). The 4 gaps created in 2010 (STP3), each 8 patches in size, are enlarged every 40 years with another 8 patches. Start of the simulation in year 2005. Simulated area: 3.0 ha.

Table 4(b)
Stand Treatment Programmes (STP2 = business as usual management, STP3 = protection forest management) for stand C

Simulation year	STP2		STP3	
	Type	Removal [%]	Type	Removal [%]
2010	Regeneration cut	40	Thinning	20/10
2030	—	—	Thinning	20/10
2045	Clearing	100	—	—
2050	—	—	Thinning	20/10
2070	—	—	Thinning	20/10
2075	—	—	—	—
2090	Pre-thinning	50	Thinning	20/10

The intensity for thinnings in STP3 distinguishes a removal percentage (related to stem number) for the stability thinning (DBH: 12–41 cm), respectively the overhead thinning (DBH > 41 cm). Start of the simulation in year 2005. Simulated area: 3.0 ha.

3. Results

3.1. Parameter sensitivity and model comparison

In Experiment 1, the influence of the parameters initial velocity of the boulders and *rough,* the range of variation of the vertical outgoing angle after ground contact, on the mean run out distance (ROD_m), calculated over 1000 simulated trajectories, is indifferent according to Fig. 5. With an initial velocity of $0.8\,m\,s^{-1}$ ROD_m is 118 m, a 10% increase in v_{init} results in an increase in ROD_m by 0.8%, while a 10% decrease reduces ROD_m by 1.4%. The same experiment with an initial base velocity of $10\,m\,s^{-1}$ yields a mean runout distance of 229 m, and a sensitivity of +0.9% and −3.0%, respectively. In a Kolmogoroff-Smirnoff-Test for independent samples, for both initial base velocities the ROD_m distributions for ±10% initial velocity proved to be not significantly different ($\alpha = 0.05$) from the distribution of the base scenario. Without a regeneration layer the parameter ROD_m is highly sensitive to *slope* and μ (surface roughness in rolling mode) which meets expectations. ROD_m is intermediate sensitive to the other tested parameters with relative sensitivity of ROD_m between 10% and 20% compared to the baseline. The stem number per ha is more influential than the mean tree diameter.

Fig. 6 shows the comparison of the ADC according to Gsteiger (1989) and the corresponding parameter as calculated from the output of the PICUS rockfall module (Experiment 2). The two parameters are highly correlated ($r_P = 0.998$**) but the ADC after Gsteiger is moderately larger. As shown in Fig. 7 the dissipated energy ($Edisp_{Betal}$) as estimated with the approach of Brauner et al. (2005) has an increasingly higher value compared to the values from the PICUS rockfall module ($Edisp_{PRM}$) (Experiment 3). Obviously, $Edisp_{Betal}$ is closely related to increasing stand volume (V), while $Edisp_{PRM}$ is not. Initially, the two estimates have similar values. As stem number decreases, the difference in the number of tree hits between the two approaches first approaches zero, then the number of tree hits in PICUS is slightly lower compared to the calculation according to Brauner et al. (2005).

3.2. Sensitivity to forest management

The effects of the stand treatment programs on the rockfall protection function in Experiment 4 were char-

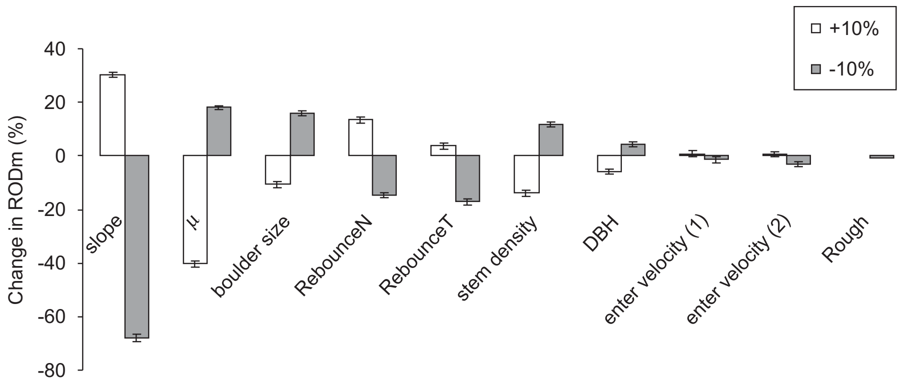

Fig. 5. Percentage change in mean run out distance (ROD_m; based on 1000 boulders) of 50 cm diameter boulders as a result of either 10% increase or decrease of the selected parameters (compare Table 1). The confidence intervals are calculated with $\alpha = 0.05$. (Experiment 1). ($n = 50$).

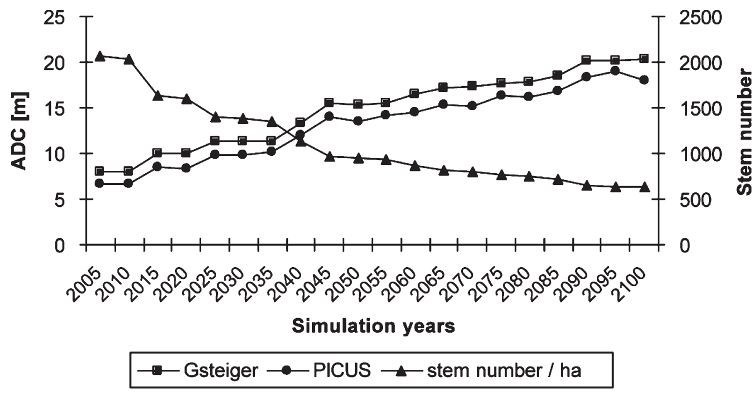

Fig. 6. Average Distance between Contacts (ADC) calculated with two approaches for 50 cm boulder diameter (1000 repetitions) over 100 years of forest development (Experiment 2).

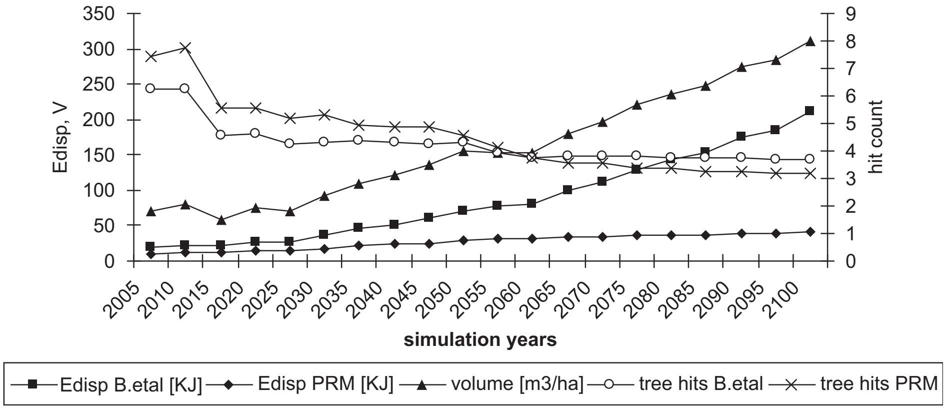

Fig. 7. Kinetic boulder energy [KJ] dissipated by tree hits along the trajectory, calculated as a potential (Edisp B.etal) based on Brauner et al. (2005), and simulated with the rockfall module of PICUS (Edisp PRM). The number of tree hits over which Edisp is calculated is shown on the secondary y-axes. (Experiment 3).

acterized by the mean run out distance (ROD_m). When comparing the ROD_m between the stands, the run out distances in stand A are considerably shorter than in the other stands mainly due to the steeper slope in stands B and C (compare Table 3). When comparing the effect of the management regimes between the stands, there are similar patterns for all STPs in stands A and B, but different effects for STP1 (''no intervention'') and STP3 (''protection forest management'') in stand C (compare Fig. 8).

In all stands the ''business as usual'' management regime STP2 causes the largest variability in ROD_m over time. At first, when regeneration is missing and the canopy is opened, the mean run out distances under STP2 more than double. Then, when natural regeneration emerges in considerable densities as simulated with the regeneration module, ROD_m decreases strongly. Only when tree density decreases after the pre-commercial thinning, ROD_m increases again. At least for stands A and B, STP1 gives stable run out distances and even decreasing distances later on when natural regeneration emerges due to a reduction of stem numbers through natural tree mortality. However, in stands A and B over most of the simulation period ROD_m under STP1 is substantially higher than under any of the other treatments.

Contrary to the ''no intervention'' strategy (STP1), the ''protection regime'' (STP3) allows for more natural regeneration due to the actively initialized gaps and the regular thinnings. STP3 first causes an increase in ROD_m after the first interventions, but soon results in stable and lower values of ROD_m. The mean run out distance is then shorter than under STP1.

More complicated is the analyses for stand C, in which under STP2 and in the ''no intervention'' strategy (STP1) the initial gaps in the simulation are soon filled with regeneration, and therefore, no significant difference in ROD_m for STP1 and STP3 can be found until simulation year 2085 (compare Fig. 8). From 2085 on STP3 shows clearly lower ROD_m than STP1. Due to rapid and abundant regeneration after the first shelterwood cut ROD_m under STP2 drops to very low values, which then slowly increase again due to reduced stand density. Under the assumption that no regeneration would emerge in stand C, STP1 has a constant shorter ROD_m than STP3, caused by the thinnings in the latter treatment which reduce stem numbers faster than natural mortality in STP1 without substantially affecting ROD_m via enhanced individual tree growth. Consequently, STP2 with a 40% reduction in stem numbers in year 2010 without any regeneration establishment provides the least protection against rockfall.

While ROD_m is not giving much information on the probability that a boulder can reach a specific distance within the simulated stand, as an example the result of STP3 in stand B is also presented in run out distance classes (Fig. 9). It can be seen that, for instance, in 2005 approximately 60% of the boulders were stopped within the first 100 m after entering the simulated forest stand. This figure increased to 68% of the boulders being stopped after 200 m trajectory length.

4. Discussion and conclusions

Through integration of the newly developed 3D rockfall module in the forest simulator PICUS, including an extended regeneration module, a new research tool has been developed. It bears the potential of assessing the development of the protective effect of a forest ecosystem against rockfall events over longer time periods in managed and unmanaged forests. Thereby, it answers to the call for a tool that takes explicitly into account both, rockfall and forest development. PICUS operates at the spatial scale of $100\,m^2$ patches where the position of the trees within a patch is not known. This approach allows the application of simplified competition and light models in simulating forest dynamics, while on the other hand it lacks information required for the spatially explicit simulation

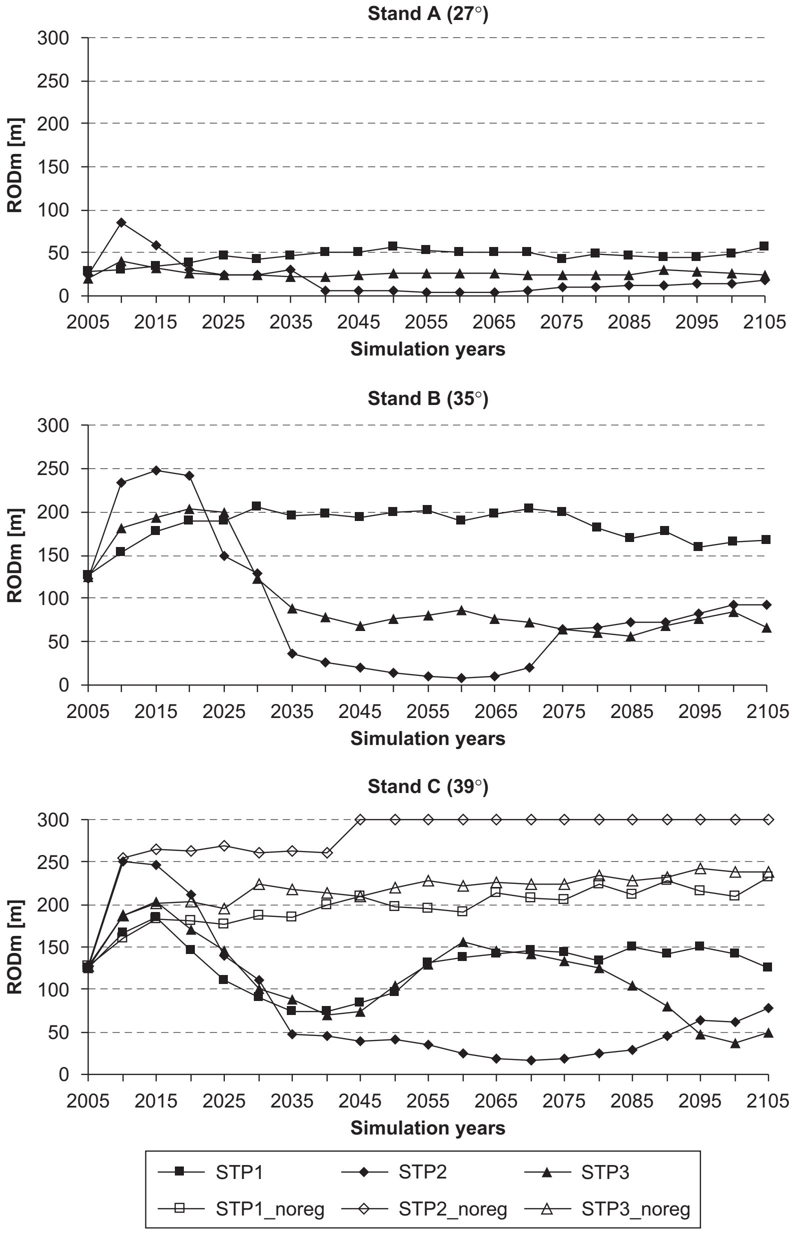

Fig. 8. Effect of forest management on the mean run out distance (ROD_m) for stands A, B and C over a period of 100 years. Boulder size is 50 cm. STP1 = "no intervention" regime, STP2 = "business as usual" regime, STP3 = "protection forest management" regime. For stand C the simulations are also presented for a situation where regeneration is lacking (noreg). (Experiment 4).

of rockfall activity. To bridge this gap, in the presented approach the trees within a patch are either assigned random positions or measured tree coordinates are provided which are then exclusively utilized by the rockfall module while forest dynamics are still simulated at $100 m^2$-resolution. The approach allows the 3D simulation of single boulder trajectories, which in turn makes stochastic components in the rockfall module inevitable. This stochasticity makes an individual boulder trajectory a chance event and an appropriate number of repetitions are needed in order to evaluate rockfall and protection effect. The variability of simulated indicators for rockfall activity depends on the interplay of site, stand and boulder characteristics and may differ among applications. The relationship of an increase in rockfall process indicator variability with decreasing stand density can be used as a general guideline. A detailed analysis was beyond the scope of this contribution which focused on model development and preliminary model evaluation experiments, and will be covered elsewhere.

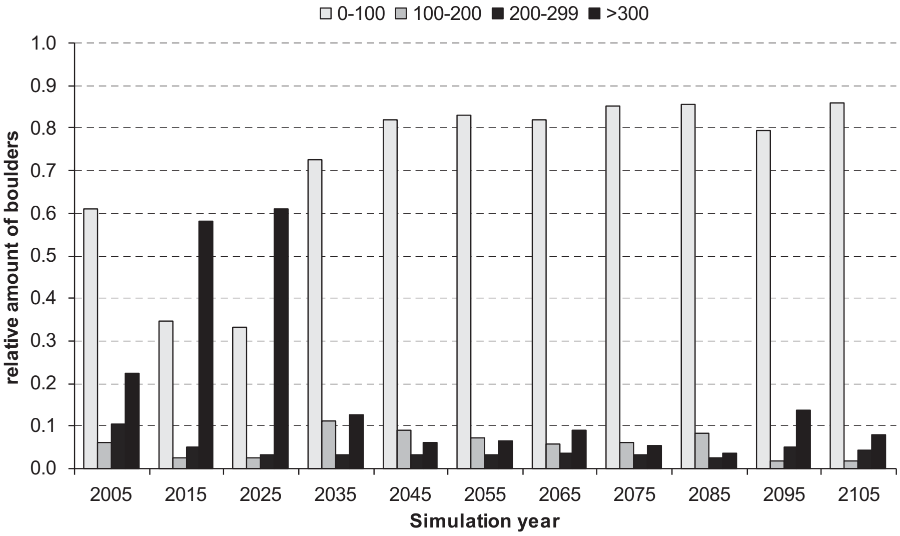

Fig. 9. Relative distribution of run out distances in stand B represented in run out distance classes [m], for a simulation period of 100 years under protection forest management (STP3) in Experiment 4.

In the new rockfall module, most of the processes that describe a rockfall trajectory through a forest stand are incorporated. These processes are modelled as a mix of physics and empirical formulations as expressed by ''black box'' parameters. The empirical algorithms concern mainly the events where boulder energy is absorbed by ground contact. These algorithms are parameterised from findings of empirical studies (e.g., Berger et al., 2004). Processes that are not yet taken into account are the explicit consideration of dead wood on the forest floor (Schönenberger et al., 2005), and snags including stumps with decreasing potential to dissipate energy due to decay processes. Another feature particularly relevant in longterm simulations of rockfall protection forests is reduced tree vitality due to damage from hits by rocks which very likely affect tree mortality (compare Vospernik, 2002) as well as energy dissipation potentials.

That refining the empirical components may be an efficient approach to improve the reliability of the rockfall module is further supported by the results of the sensitivity analysis in Experiment 1 where, for instance, the empirical rebound parameters showed substantial impact on simulated run out distances. In the presented experiment the effects of selected key stand attributes on ROD_m are of similar magnitude with stem numbers being slightly more influential than mean tree diameter Dorren et al. (2005) report that the influence of stand density and mean tree diameter on the protection effect varies over the range of boulder sizes with mean tree diameter being more important for larger rocks. The fairly small differences in ROD_m sensitivity for stand density and mean tree diameter respectively indicates that the tested boulder size of 50 cm may just be of that intermediate size beyond which stand density becomes less influential compared to mean diameter.

In relative terms both levels of initial boulder velocities tested in Experiment 1 just slightly affect simulated ROD_m. Thus, given the difficulties in estimating initial boulder velocity for a specific model application in transit zones robust model results can be generated. However, care has to be taken in extrapolating the results of the sensitivity experiment to other conditions due to the complex interplay of site, stand and boulder characteristics.

To better understand the behaviour of the new rockfall module it was compared to two approaches from the literature which do not simulate explicitly rockfall trajectories but instead apply simplifying static assumptions. First, the widely used ADC concept indicating the average distance between boulder-tree contacts calculated after Gsteiger (1989) was compared with equivalent simulation output of the rockfall module. Results of the two approaches correlated closely. However, ADC after Gsteiger was consistently 1–3 m larger than the corresponding figure from the PICUS simulation. Notwithstanding that the divergence in the average distance among tree hits among the two approaches were quite small, to better understand the conceptual differences among the approaches several contrasting issues need to be considered. Taking samples for distances between trees over a randomly distributed tree pattern, gives Poisson-like distributions which lowers the mean value over all samples, relative to a regular tree pattern (Stoyan and Stoyan, 1992) which is one of the assumptions in the ADC approach by Gsteiger (1989). A further explanation for shorter ROD_m in the PICUS module is that most boulders in the simulation stop before reaching the maximum distance of 300 m which makes the trajectory relative to the amount of tree hits shorter, and thereby also the ADC. In contrast, with the less realistic formula of Gsteiger the trajectory deterministically ends at 300 m.

In comparing the energy dissipated by the trees within the rockfall module ($Edisp_{PRM}$) and calculations based on Brauner et al. (2005) ($Edisp_{Betal}$) in Experiment 3, the latter increased steadily with increasing stand volume while the former was always lower and increased just slightly over the entire simulation period. Major reason for the deviance between the approaches is, that the PICUS module takes realistically into account only radially directed energy while $Edisp_{Betal}$ assumes full contact with every tree hit. This effect is intensified by the number of tree hits which over the simulation period decrease stronger in PICUS compared to the algorithm of Brauner et al. (2005). The results of Experiments 2 and 3 clearly demonstrate that estimating potentials with regard to rockfall protection effects and employing simplified and highly aggregated approaches might strongly overestimate the protection effect of forests, and that explicit rockfall simulation clearly bears the potential to provide more reliable results.

Before discussing the results of Experiment 4 the issue of integrating understory in the new rockfall module will be addressed. In recent years several rockfall models have been presented (e.g., Dorren et al., 2004; Perret et al., 2004; Brauner et al., 2005). However, most if not all entirely focus on the effect of adult trees on rockfall activity. Nevertheless, understory may play an important part in reducing runout distances of boulders as well as in preventing the start of boulder trajectories. In the current study we attempted to extend the rockfall simulation by explicitly considering understory vegetation. The original approach to model tree regeneration in PICUS was a recruitment model (compare Vanclay, 1994), initializing new saplings at breast height (1.3 m). The new regeneration model in PICUS is a size class model and simulates the development of regeneration through four height classes from establishment of seedlings until the saplings enter the model as individual trees. For this contribution a generalized parameterization based on qualitative information from the literature was used. Simulation experiments aiming at regeneration composition and density along ecological gradients yielded promising results when compared to qualitative data (e.g. Müller, 2003; Ruhm, 2004).

While in general the processes mimicking boulder movement and hits with trees larger 1.3 m height are fairly well established, the effect of the understory on rockfall processes as currently implemented in PICUS has to be seen as a set of hypotheses. Due to the novelty of this approach it was impossible to provide empirical data for the effect of understory on rockfall processes, neither for model development nor for model validation. Clearly, this identifies a knowledge gap and calls for targeted research. Analysis of simulated ROD_m when shifting from a stand development phase consisting exclusively of saplings in height class H4 (80–130 cm) to a stand structure with trees just grown out of H4 showed a reasonably smooth behaviour. While this in general supports the current approach, there are at least three aspects showing potential for improvement: (i) while in the regeneration module competition for light within the four height classes is estimated from cumulated sapling biomass at least as high as the focus height class, the dry mass of the representative individual in the height classes is not affected by competition but can be seen as a broad-scale mean value. Thus, at high regeneration densities the dry mass allometry may overestimate dry mass in the regeneration layer and consequently the dissipated energy; (ii) the aggregation of all conifers (here: *Picea abies*, *Pinus sylvestris*, *Larix decidua*, *Abies alba*) and all broadleaves into two broad species groups might be too simplistic. (iii) Finally, the parameterisation of the fraction work per unit understory biomass which currently is based on data from larger trees surely needs an improved knowledge base. These limitations have to be taken into account when discussing the results of Experiment 4 which addressed the response of the rockfall module to stand management interventions.

The alternative management scenarios, applied to three different mountain forest stands (Experiment 4) indicated that the rockfall module is sensitive to management interventions, and that the relative magnitude of the response appeared realistic. Furthermore, the runs showed the potential of the module to evaluate the protective effect of alternative management interventions and to compare them with the protective effect of stand development without active management. The latter may save cost, but fail in providing protection in a sustainable way. It has to be noted that so far no integrated simulation tool able to realistically mimick heterogeneous silvicultural management and stand structures had been available. Although the protective effect of the regeneration layer may have been overestimated by the current model version, the results indicated the importance of successful regeneration establishment and development in mountain forests. It is important to note that Experiment 4 was not intended to evaluate specific protection forest management concepts but was exclusively aimed at analysing the sensitivity of rockfall activity to realistic silvicultural interventions. Prior to evaluating proposed management concepts for protection forests the knowledge gaps regarding, for instance, the protective effect of understory have to be addressed. To indicate the effect of unsuccessful silvicultural regeneration measures the management scenarios for stand C were simulated twice: one time with abundant and continuous regeneration establishment, a second time without any regeneration success at all. This clearly indicates the potential negative impact of intensive browsing by ungulates and cattle in sustainable mountain forest management and renders the inclusion of browsing as a model feature in specific assessments of silvicultural concepts for mountain forest management a necessity (e.g., Eiberle, 1989).

To further underpin the realism and accuracy of the new rockfall module in simulating rockfall trajectories on

Table A1
Growth and mortality default parameters from the regeneration module in PICUS as used in this study

Regeneration parameters	H_1			H_2			H_3			H_4		
	PA	PS	LD	PA	PS	LD	PA	PS	LD	PA	PS	LD
Height growth potential [cm yr^{-1}]	4	5	10	10	10	12	15	15	25	20	25	30
Mortality rate [fraction]	0.32	0.32	0.32	0.32	0.32	0.32	0.32	0.32	0.32	0.32	0.32	0.32
Min. height growth [cm yr^{-1}]	0.5	1	1	0.5	1	1	1	2	2	1	3	3
Tolerable stress years [yr]	2	1	1	5	3	3	5	3	3	5	3	3

Picea abies (PA), *Pinus sylvestris* (PS) and *Larix decidua* (LD). Height classes: $H_1 = 0$–10 cm, $H_2 = 10$–30 cm, $H_3 = 30$–80 cm, $H_4 = 80$–130 cm.

forested slopes comparison of model results with empirical rockfall data is required. To that end no observational rockfall data was available for model validation. However, as a preliminary test published data from an empirical rockfall experiment by Dorren et al. (2005) was compared with results of the similar setting of stand B in Experiment 4. In their experiment Dorren et al. (2005) report that 34% of 100 boulders released down a forested slope (mean boulder size: 0.49 m^3) surpassed 200 m forested zone. This compares well with the 68% boulders stopped on the first 200 m of stand B in year 2005 in Experiment 4 (compare Fig. 8) and supported the hypothesis that the new rockfall module realistically captures major rockfall processes.

To summarize, we are convinced that the coupling of a rockfall module and a dynamic spatially explicit forest patch model bears huge potential to successfully respond to the need for a quantitative assessment tool in rockfall protection forest management (compare e.g., Wehrli, 2005). The vegetation model PICUS used to project forest development can be applied across a wide ecological range of stand and site conditions (Seidl et al., 2005). As a particular asset PICUS offers the advantage of spatially explicit simulation of rockfall activity and vegetation development, a feature, which drastically improves the realism in simulating mountain forest silvicultural concepts and their effect on rockfall protection effects. Quantitative assessment of the rockfall protection effect of forest management over longer time periods is required to provide specific guidelines for management of mountain protection forests. We are convinced that the presented approach is a promising contribution towards that goal.

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Appendix A

See Table A1.

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8.2 Appendix - Paper II

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Natural Hazards and Earth System Sciences

Evaluation of a 3-D rockfall module within a forest patch model

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Abstract. Many slopes in the Alps are prone to rockfall and forests play a vital role in protecting objects such as (rail) roads and infrastructure against rockfall. Decision support tools are required to assess rockfall processes and to quantify the rockfall protection effect of forest stands. This paper presents results of an iterative sequence of tests and improvements of a coupled rockfall and forest dynamics model with focus on the rockfall module. As evaluation data a real-size rockfall experiment in the French Alps and two 2-D rockfall trajectories from Austria and Switzerland were used. Modification of the rebound algorithm and the inclusion of an algorithm accounting for the sudden halt of falling rocks due to surface roughness greatly improved the correspondence between simulated and observed key rockfall variables like run-out distances, rebound heights and jump lengths for the real-size rockfall experiment. Moreover, the observed jump lengths and run-out distances of the 2-D trajectories were well within the stochastic range of variation yielded by the simulations. Based on evaluation results it is concluded that the rockfall model can be employed to assess the protective effect of forest vegetation.

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1 Introduction

Forests in mountainous regions provide important protection functions for society and particularly the protection against rockfall has attracted considerable attention recently. Reasons are that rockfall is one of the most common natural hazards in mountainous landscapes, and that the protective effect of many European mountain forests may decrease in the future due to abundant old-growth phases with a lack of regeneration (e.g., Ott et al., 1997; BFW, 2004). To study the development of the protective effect as well as the influence of forest management, reliable simulation tools are required which are able to take into account the spatial pattern of rockfall processes on slopes as well as the effect of forest vegetation composition and structure on run-out distances and kinetic energies of falling rocks (Stoffel et al., 2006; Dorren et al., 2005). Due to the long time horizons of regeneration processes in mountain forests, models must be able to cope with time scales of several decades. Of particular importance are trade-off relationships between rockfall protection and other forest services and functions within the framework of multifunctional forest management.

Rockfall is defined here as a fast gravitational movement of rock boulders, rolling, tumbling or sliding down a hillslope (Selby, 1995). Boulders act rather independently and the boulder size considered for trajectory analysis is typically below 5 m^3.

A wide range of rockfall models exists, covering different spatial scales and levels of complexity. Historically, among the earliest approaches are 2-D rockfall models that simulate rock trajectories along a slope profile (e.g. Bozzolo and

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Pamini, 1986; Azzoni et al., 1995; Pfeiffer and Bowenm, 1989; Pfeiffer et al., 1993). Typically, such models have been applied to support the design of technical rockfall protection measures. With the evolution of digital mapping and spatial modeling techniques a new class of 3-D models, simulating individual trajectories based on a digital elevation model, became increasingly popular (e.g. Agliardi and Crosta, 2003; Dorren et al., 2004; Lan et al., 2006). Such models are typically used on local to regional scales.

However, although forests can offer an effective protection against rockfall (e.g. Bigot et al., 2009) only a small number of rockfall models take into account the mitigating effect of trees on forested slopes. These models consider the effect of forest vegetation either implicitely (e.g. Brauner et al., 2005; Wehrli et al., 2006; Berger and Dorren, 2007), using aggregated stand variables like stand density or average diameter at breast height, or spatially explicit (Dorren et al., 2006), simulating individual tree hits along a rocks trajectory. Wehrli et al. (2006) conclude that a spatially explicit representation of forest structure would enhance the simulation approach.

Recently Woltjer et al. (2008) developed a spatially explicit 3-D rockfall model and coupled it with the process oriented 3-D forest patch model PICUS v1.4 (Lexer and Hönninger, 2001; Seidl et al., 2005). In Woltjer et al. (2008) the new rockfall model was tested for parameter sensitivity and for its ability to assess rockfall protection effects in line with static formulations from the literature (Gsteiger, 1993; Brauner et al., 2005). Moreover, the model showed plausible sensitivity to forest management as implemented in the forest model. While the forest model has been evaluated rigorously in several previous studies (e.g., Seidl et al., 2005, 2009), an evaluation of the rockfall module against empirical data is presented in this article.

The objectives of this study are twofold. First, recent model improvements are introduced, and second, the model is evaluated against empirical rockfall data from four test cases from France, Switzerland and Austria. In an iterative manner results from comparisons of model simulations and evaluation data feed back into model enhancement. Finally, conclusions on the applicability of the model are drawn.

2 Methods and materials

2.1 The forest dynamics model

The forest model used in PICUS Rock'n'Roll is the hybrid forest patch model PICUS v1.4, which incorporates elements of a classical patch model as well as a stand level production model based on physiological principles. A detailed description of the hybridization is provided in Seidl et al. (2005). Here, just a brief overview of the core model concept is given.

Basic modelling entity is the individual tree above a threshold of 1cm diameter at breast height. Tree biomass is arranged horizontally on $10\times10\,\mathrm{m}^2$ patches and vertically in 5 m canopy layers. A three-dimensional light model, allowing for the explicit consideration of direct and diffuse radiation within the canopy, is used to model inter- and intra tree species competition. The incorporation of a module that estimates NPP (net primary production) based on the concept of radiation-use efficiency (Landsberg and Waring, 1997) enhanced the robustness in predicting growth along environmental gradients. It also improved the physiological foundation of the model with regard to changing environmental conditions. The model requires input of incoming radiation, temperature, precipitation and vapor pressure deficit in at least monthly resolution.

2.2 The rockfall model

This contribution focuses on the evaluation of the rockfall model Rock'n'Roll as presented in detail in Woltjer et al. (2008). This section presents a brief overview of the model concept. The rockfall model simulates spatially explicit trajectories of spherical rocks of variable size (diameter, mass) on a three-dimensional slope. A rock trajectory consists of a series of rolling and/or jumping motions. The model uses a lumped mass approach for simulating free fall and ground impacts, and a rigid body approach for the simulation of rolling motions and tree impacts. Kinetic energy of a falling boulder is dissipated by (i) rolling friction for rolling motions, (ii) ground impacts for jumping motions, and (iii) tree impacts during rolling and jumping motions.

In a simulation rock trajectories start with a predefined initial velocity either from predefined or from randomly selected positions within the simulated area. A rock stops, when its kinetic energy falls to zero.

The slope surface is characterized by coefficients of restitution for jumping mode (i.e. rebound parameters) and by rolling friction coefficients for rolling mode. For the current study the rolling friction coefficient was kept constant at a value of 0.5 which is considered as a sensible default value for various ground types (see Azzoni et al., 1995). Coefficients of restitution describe the ratio of the normal (or tangential) velocity component of the center of mass before and after an impact (e.g. Kharaz et al., 2001). Parameter values for various surface types are retrieved from the literature (e.g., Azzoni et al., 1995; Azzoni and de Freitas, 1995; Chau et al., 2002; Schweigl et al., 2003; Heidenreich, 2004).

The rockfall model includes several stochastic components: (i) the lateral deviation and the jump angle after ground impacts, and (ii) the lateral deviation after tree impacts. Moreover, the coefficients of restitution are subject to uncertainty and may vary within a specified range of variability. Consequently, simulated trajectories may show substantial variability with regard to key variables like jump lengths or rebound heights.

In order to utilize frequently available 2-D trajectories for model validation and calibration a special mode was implemented in the rockfall model. Documented 2-D trajectories from single rockfall events usually report jump lengths and slope angles along the actual trajectory. In a simulation the rockfall model uses the trajectory profile as slope topography and forces the falling boulder along the profile. Within that “2-D mode” all modeled rockfall processes except tree hits are applicable and energy conservation laws are satisfied.

Rock’n’Roll is implemented in the C++ programming language. The rockfall model is integrated with the PICUS forest model and can be invoked every simulated year to assess the effect of vegetation on rockfall activity. The software is optimized for high calculation performance. For instance, the algorithms of rock movement are not based on fixed time steps but rather rely on analytical equations of motion to foster efficient computations.

Based on findings of preliminary model evaluation exercises and conceptual limitations of the modeling approach some components have been revised and extended. In the following sections these model enhancements are introduced.

2.2.1 Representation of surface topography

A major enhancement compared to the model variant in Woltjer et al. (2008) is that in the current version surface topography is modeled as a triangulated irregular network (TIN). A TIN describes a surface as a set of non-overlapping triangles with variable density. Besides raster based digital elevation models, TINs are frequently used for the representation of three dimensional surfaces, and modern GIS software packages usually support the conversion from raster based digital elevation models (DEM) to TINs and vice versa. While the vast majority of all available rockfall models use raster based DEM, we implemented a TIN-based approach. Reasons for the decision to use TINs are, inter alia, that the variable density of triangles allows a memory and time efficient computation of slope regions with more uniform terrain features, and that the flexible spatial resolution of a TIN is easier to couple with the fixed 10×10 m patch size of the forest model.

The spatial distribution of different surface properties, e.g. coefficients of restitution, is incorporated in the model by using a raster based approach. Surface properties are mapped in a GIS environment using arbitrarily shaped polygons which are imported as grids into the coupled rockfall-forest model.

2.2.2 Tree hits

In the original model variant the algorithm for the simulation of tree hits was designed as a set of mechanical and geometrical formulations based on fracture energy experiments in the laboratory. However, in reality a rock impacting a tree triggers far more energy-consuming processes, like deformation of the root-soil system or the swaying of the whole tree. Recently published empirical data on that issue (Dorren and Berger, 2006) and results from a numerical tree impact model (Jonsson, 2007) allow the implicit inclusion of these processes.

Our implementation of the tree hit algorithm is very close to the published model of Dorren et al. (2005; see also Dorren and Berger, 2006). The maximum amount of energy that can be dissipated by a tree during an impact ($E_{\mathrm{diss,max}}$) depends on tree species and is related to the diameter of the tree at breast height via an exponential relationship (Eq. 1).

$$E_{\mathrm{diss,max}} = 38.7\ \mathrm{DBH}^{2.31} \tag{1}$$

$E_{\mathrm{diss,max}}$ = Energy dissipation potential for *Abies alba* trees [kJ]. See Dorren et al. (2005) for coefficients of further tree species. DBH = diameter at breast height [cm].

For impact positions off the central bole axis only a fraction of the dissipation potential is exploited. This is expressed by a sigmoid function relating the consumable fraction of the dissipation potential to the impact position. If the kinetic energy of a rock during a frontal impact is higher than the dissipation potential, the tree breaks.

The horizontal deviation of the rock after the tree hit is modeled by deviation matrices, which define deviation ranges for three different impact types (frontal, lateral and scratch). Within this range a random number determines the realized deviation angle. For situations where the energy of the falling rock is high compared to the energy dissipation potential of the tree an additional upper deviation limit avoids unrealistic deviation angles. This limit is estimated as the hypothetical maximum deviation of the rocks’ trajectory given the energy dissipation potential of the focal tree.

2.3 Data

2.3.1 Real-size rockfall experiments Vaujany

From 2001 to 2003 real-size rockfall experiments have been realized on a forested and an adjoining unforested test slope in the Forêt Communale de Vaujany in France and have been described in detail in several publications (Dorren et al., 2005, 2006; Bourrier et al., 2009). Here we briefly introduce the experimental setup. The test sites are located on a post-glacially developed talus cone, which mainly consists of rock avalanche, snow avalanche and rockfall deposits and is situated on altitudes ranging from 1200 m to 1400 m (a.s.l.) with a mean slope gradient of 38°. A digital elevation model with a resolution of 2.5×2.5 m was available for both sites and surface characteristics (diameters of rocks covering the slope, etc.) were grouped into surface types and mapped throughout the test slopes (see Table 1).

The unforested Site 1 (see Fig. 1 for a profile) has the morphology of a channel for the first 240 m (projected) between the starting point and a crossing forest road. From there Section B extends for 100 m (projected) to another forest road, below which the slope ends in the valley bottom (Section C).

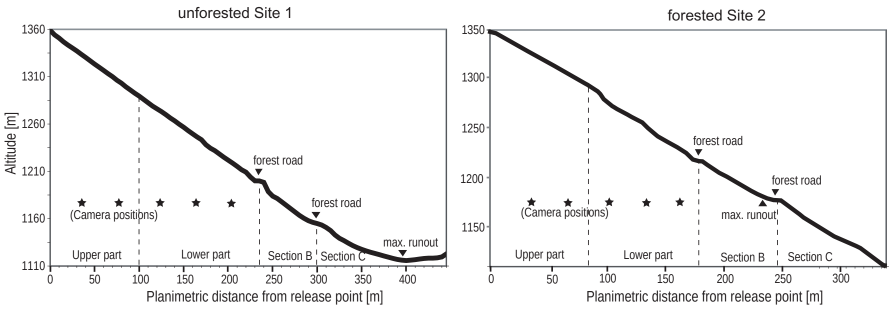

Fig. 1. Profiles of the test sites in Vaujany starting from the release points of the rockfall experiments along the steepest path. Left: unforested Site 1, right: forested Site 2. The camera equipped test sections extend from the top of the slope down to the upper forest road. The observed run-out zones extend further (maxima indicated by triangles).

Table 1. Coefficients of restitution (r_n = normal, r_t = tangential coefficient) used in the simulation series for the Vaujany sites.

Surface type	r_n	r_t
Site 1 (unforested)		
(a) Fine angular debris	0.30	0.75
(b) Coarse debris	0.30	0.65
(c) Fine angular debris and soil	0.30	0.75
(d) Road	0.30	0.85
Site 2 (forested)		
(e) Fine angular debris	0.30	0.75
(f) Soil and small angular debris	0.32	0.75
(g) Forest soil	0.30	0.85
(h) Forest soil with woody debris	0.20	0.85

The first section after release is mainly covered by debris with diameters of 8–10 cm (type (a) in Table 1), Section B is dominated by bigger blocks between 40 and 80 cm (type (b) in Table 1) while Section C is covered by fine debris and soil material (type (c) in Table 1).

The forested Site 2 represents a typical rockfall slope in the European Alps (see Fig. 1). The main tree species with regard to basal area are Silver fir (*Abies alba*, 72%), beech (*Fagus sylvatica* – 14%), Norway spruce (*Picea abies* (L.) *Karst.* – 6%), and Sycamore (*Acer pseudoplatanus* L. – 6%). The stand is characterized by a mean tree diameter at breast height of 31 cm and a stand density of 290 trees per hectare. The coordinates of each tree on Site 2 were mapped. In the upper half of the slope at Site 2 the spatial variability (i.e. patchiness) of the main surface types (e) and (f) (compare Table 1) was considerably higher compared to Site 1.

A total of 218 rocks with a mean diameter of 0.95 m (mean volume=0.49 m^3, S.D.=0.3 m^3) were released individually by an excavator from a forest road. Three-dimensional rock trajectories were captured by combined field measurements and video analysis. Rock velocities and rebound heights were calculated by a frame-per-frame video analysis.

For the model evaluation mean and maximum of rock velocities and rebound heights were available at both sites. The data set further included the distribution of run out distances (ROD) and the jump lengths near the camera positions at both sites (see Fig. 1). For Site 1 the data set was extended by rebound heights and velocities of individual jumps near the cameras, for Site 2 also the distribution of the heights of tree hits on the bole was available.

2.3.2 Single 2-D rockfall trajectories in Steg and Bad Ischl

In addition to the Vaujany data set we used two rockfall trajectories of real rockfall events for model evaluation (Berger et al., 2004). In both cases a 2-D-profile was derived by surveying impact craters of single rockfall events. Additionally, the starting points of the two rockfall trajectories were identified and the size and mass of the rocks were measured. The first trajectory was recorded in Steg, Switzerland, after a rockfall event in March 2003 on a slope with an average inclination of 31°. The rock had a diameter of 1.84 m and a mass of 9100 kg and stopped after 37 ground impacts and 441 m (planimetric) run out distance. The slope is mainly covered by pasture and is crossed by a road and a narrow rock outcrop. The surveyed data includes qualitative characterization of surface properties along the whole trajectory (see Fig. 2 and Table 2). In Bad Ischl, Austria, in summer 2004 a rock with a diameter of 0.96 m and a mass of 1250 kg hit and damaged a rockfall net protecting a parking lot. Here, the slope with an average inclination of 40° is covered by sparse forest. Except the starting zone, a steep and rocky cliff, shallow forest soils covered by woody detritus characterize the slope surface. The trajectory from the assumed starting point to the rockfall net had a length of 250 m (planimetric). Over the entire trajectory nine jumps were recorded (Figs. 2 and 9 and Table 2).

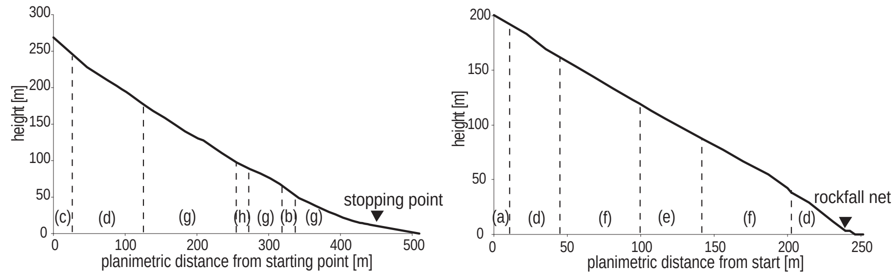

Fig. 2. Slope profiles in Steg (left) and Bad Ischl (right). The lowercase characters denote the surface types presented in Table 2.

2.4 Model validation

2.4.1 Test site Vaujany

The coefficients of restitution for each surface type from the Vaujany test sites were extracted from the literature (e.g., Azzoni et al., 1995; Azzoni and de Freitas, 1995; Chau et al., 2002; Schweigl et al., 2003; Heidenreich, 2004) (Table 1). To mimic the release of the rocks from the shovel of the excavator in the simulations the rocks were started from a height of 1.5 m above ground with a speed of 3 ms^{-1} and an angle of $-30°$ (relative to the horizon).

To account for differences in the shape of the rocks we varied the tangential coefficient of restitution r_t randomly by adding a value from the range [-0.05 to 0.05] assuming a uniform probability distribution. An independent stochastic variation of both coefficients may lead to unrealistic jump angles. Due to lacking information on a possible cross correlation between r_t and r_n we decided to vary only r_t due to its higher relevance for the calculation steps during rock rebounds.

To achieve statistically robust results two different simulation series were run: (i) a total of 10 000 rocks with a diameter of 0.95 m were released from the original starting point, and (ii) to gain insight into the variability of extreme values a series of 100 simulations, each consisting of 100 rocks with a diameter of 0.95 m, were also performed.

For the forested Site 2 we used the measured trees on their mapped positions as well as tree species, diameter and tree height. For the simulation series the dynamic components of the forest model were deactivated. Contrary to the in situ experiment, where the forest structure changed potentially with every released rock, simulated rocks always faced the same trees. For each simulated rockfall trajectory mean, minimum and maximum velocity, rebound heights, jump lengths, tree contacts as well as run out distance were recorded and compared to experimental data.

Table 2. Coefficients of restitution (r_n = normal, r_t = tangential) used in the 2-D simulation series Steg and Bad Ischl.

Surface type	r_n	r_t
(a) Solid rock	0.40	0.90
(b) Weathered rock	0.40	0.85
(c) Fine angular debris	0.30	0.75
(d) Forest soil (with coarse debris)	0.30	0.75
(e) Forest soil (deep)	0.30	0.80
(f) Forest soil (shallow)	0.35	0.80
(g) Pasture	0.35	0.80
(h) Pasture (water influenced)	0.30	0.80

2.4.2 2-D trajectories in Steg and Bad Ischl

For the simulation of the 2-dimensional trajectories, the rockfall model was operated in "2-D"-mode, where the trajectories of the simulated rocks are forced along the slope profile. Also the tree hit module was disengaged because no tree hits occurred along the trajectories.

Quantitative coefficients of restitution were assigned to each mapped surface cover type along the trajectories using information from in situ field tests on representative ground materials from the literature (Azzoni et al., 1995; Azzoni and de Freitas, 1995; Schweigl et al., 2003; Heidenreich, 2004). Due to missing information about the exact starting conditions all trajectories were initiated in rolling mode with a velocity of 1 ms^{-1}.

To account for the stochasticity of the modelled processes 10 000 rocks were simulated for each 2-D site and analyzed for the run out distance of each trajectory as well as the energy at the position of the rockfall net in the Bad Ischl case. Additionally, the profiles were divided into segments of 10 m length along the slope and the mean, minimum and maximum length of jumps that ended in that respective section were recorded.

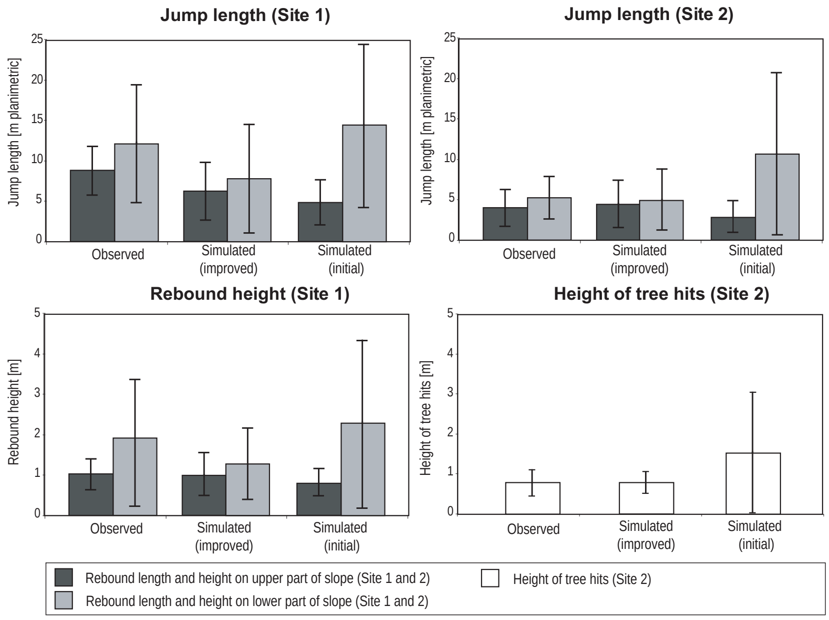

Fig. 3. Comparison of observed and simulated (initial, improved) rockfall parameters from both experimental sites in Vaujany. Jump lengths and rebound heights are taken from the upper and the lower part of the slope near the camera positions, height of tree hits from the entire slope at Site 2. Shown are mean values and standard deviation of 100 simulated rocks with 100 replicates each.

3 Results

3.1 Initial simulation runs in Vaujany

Simulations were run at both sites in Vaujany according to the setup described in Sect. 2.3.1 with the initial model version. A first inspection of simulated and observed rockfall parameters yielded the following results: for both sites in the upper part of the slope (labelled as “upper part” in Fig. 1) the jump lengths were generally too low whereas in the lower parts of the slope jump lengths were clearly overestimated at both sites with regard to both mean values and variability (Fig. 3; upper panel). The deviation between observed and simulated rebound height was smaller (Fig. 3; lower panel), but with a similar tendency to underestimate on the upper slope and overestimate in the lower parts of the slope. That simulated rebound heights were partly overestimated was also confirmed by the simulated heights of tree hits at Site 2 (Fig. 3). Furthermore, the simulated maximum values for rebound heights and rock velocities were found too high (not shown).

In addition, the distribution of the run out distances (ROD) differed substantially from observations at both sites (Fig. 4). Based on these findings the rebound algorithm, one of the central modules of the rockfall model (i.e. the calculation of energy dissipation during a ground contact and the resulting jump angles after ground contact), was re-analysed. The current model version (Woltjer et al., 2008) treats the rebound process as an inelastic point contact based on impulse-momentum law. It is well known that this is a somewhat unrealistic and oversimplifying assumption, nevertheless this approach is frequently used in rockfall models (e.g. Stevens, 1998; Guzzetti et al., 2002; Dorren et al., 2004).

When applying repeatedly the current jump-rebound module on a simplified slope with a constant slope angle and constant coefficients of restitution the rock velocity increases or decreases exponentially (Eq. 2). The actual values of the velocity increment or decrement per jump-impact cycle f_{gain} mainly depends on slope angle and the values of the specific coefficients of restitution.

$$\frac{v_{i+1}}{v_i} = f_{\text{gain}} = \text{const} \tag{2}$$

f_{gain} = relative gain/loss in velocity per jump [$-$], v_i = starting velocity of the ith jump [ms^{-1}].

The velocity reached at the i-th jump is proportional to f_{gain} raised to the power of i (Eq. 3). Maximum rebound height and jump length are proportional to the squared velocity and can therefore be estimated by Eqs. (4) and (5). Jump angles are constant and depend on slope angle and the ratio of the coefficients of restitution. Due to the exponential behavior, trajectories may start with a long series of very short jumps and a slow velocity gain but eventually reach unrealistic velocities and rebound heights if the slope is only long enough.

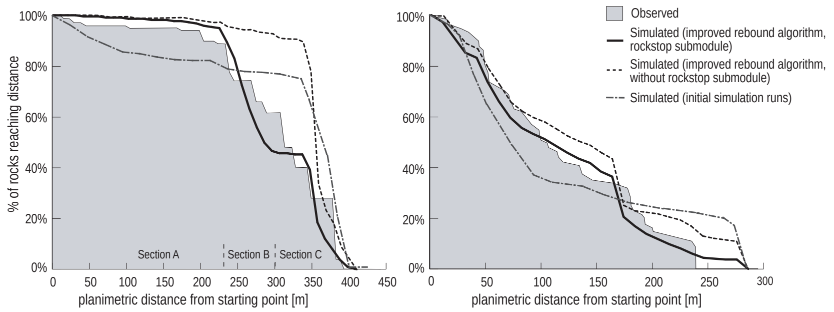

Fig. 4. Percentage of rocks that reach a certain distance at the unforested Site 1 (left) and forested Site 2 (right) in Vaujany. The filled area denotes the observed values, the bold line shows the simulation results (N=10 000 rocks) of the final model version. The dash-dot lines indicates the initial simulation runs, the dashed lines results with improved rebound algorithm but without the rockstop submodule.

$$v_i \sim f_{\text{gain}}^{i} \tag{3}$$

$$H_i \sim f_{\text{gain}}^{2\cdot i} \tag{4}$$

$$D_i \sim f_{\text{gain}}^{2\cdot i} \tag{5}$$

v_i = starting velocity of the i-th jump, f_{gain} = relative velocity gain/loss per jump [−], H_i = rebound height for i-th jump [m], D_i = jump length (planimetric) for i-th jump [m].

However, this is in contrast to empirical evidence about real rockfall trajectories. For instance, on steep sites rocks typically gain energy very quickly and reach maximum velocity after a short distance (e.g. Dorren et al., 2005; Jahn, 1988). Furthermore, reported rebound heights usually do not exceed 2 m to 4 m while simulated rebound heights are much higher (e.g. Dorren and Berger, 2006; Stoffel et al., 2006; see also Fig. 3). Re-inspection of the model formulations focused on the amount of energy that is lost during rebound. Conceptually, the loss depends on the characteristics of the contact process itself and the amount of energy gain during the flight phase, which in turn is strongly influenced by the jump angle after rebound.

The rebound process is characterized as an elasto-plastic contact in many studies (e.g., Pfeiffer and Bowen, 1989), with elastic boulder response and plastic deformation of softer ground material. Johnson (1985) proposed to extend the widely applied point-like contact concept to plastic reaction by reducing the coefficients of restitution with increasing velocity proportional to $v^{(-0.25)}$ to account for deformation work, elastic wave propagation and fracturing during impact (Eq. 6).

$$r = k \cdot v^{-\frac{1}{4}} \tag{6}$$

r = coefficients of restitution (normal and tangential) [−], k = scaling factor [−], v = impact velocity [ms^{-1}].

This relationship is supported by investigations of elasto-plastic contact reaction (Wu et al., 2003, 2005; Hayakawa and Kuninaka, 2003; Heidenreich, 2004). Similar relationships are also found in studies based on field data from rock slopes (Wu, 1985; Pfeiffer and Bowen, 1989; Pfeiffer et al., 1993). The model extension by Johnson (1985) results in increased energy dissipation at high velocities, which is in agreement with field observations (e.g. Dorren et al., 2005; Jahn, 1988). However, rock velocity does not affect the jump angle after impact. Pfeiffer and Bowen (1989) and Pfeiffer et al. (1993) developed separate scaling factors for r_n and r_t from field data causing both coefficients of restitution to decrease with increasing impact velocity. This concept results in both a pronounced energy dissipation and slightly lower jump angles at high impact velocities. This is in accordance with Zinggeler (1989) and Heidenreich (2004) who found for elasto-plastic contacts no strict geometric relationship between impact and jump angles due to various influential factors such as friction or material strength.

3.2 Model improvement

3.2.1 Rebound algorithm

Based on the analysis of the original rebound model as presented above the contact model was extended following the proposal by Johnson (1985) as it refers to velocity as the most influential parameter of the jump-rebound cycle (Eq. 6). Generally, this approach is supported by many studies over various materials and settings (Wu, 1985; Wu et al., 2003, 2005; Hayakawa and Kuninaka, 2003; Heidenreich, 2004).

While still applying the literature values for impact velocities below 10 ms^{-1}, both the normal and the tangential coefficients of restitution were reduced at higher velocities according to Eqs. (7) and (8). This threshold was chosen because values for coefficients of restitution are usually based on rebound field experiments with rock velocities of about

$10\,\mathrm{ms}^{-1}$ or below (Broili, 1973; Azzoni and de Freitas, 1995; Chau et al., 2002).

$$r = \begin{cases} v <= 10\ \mathrm{ms}^{-1} : r_{\mathrm{literature}} \\ v > 10\ \mathrm{ms}^{-1} : k \cdot v^{-\frac{1}{4}} \end{cases} \quad (7)$$

$$k = r_{\mathrm{literature}} \cdot 10^{\frac{1}{4}} \quad (8)$$

$r_{\mathrm{literature}}$ = reported coefficient of restitution in literature (tangential and normal); see Tables 1 and 2 [−], r = resulting coefficient of restitution (tangential and normal) [−], k = linear factor, v=impact velocity [ms^{-1}].

Furthermore, the calculation of jump angles after rebound was modified. The analysis of the jump-rebound cycle already indicated that the geometric approach to calculate the jump angle may not be sufficient to reliably represent the complex processes during actual rebounds. The real-size rockfall experiments from Vaujany provided data on rock velocity after rebound and rebound height for a series of individual jumps on the upper slope of the unforested Site 1. Using this information for each of these jumps the jump angle after rebound was back-calculated. A power function (Eq. 9) was fitted to back-calculated rebound angle and rock velocity data (compare Fig. 5).

The updated rebound model uses this relationship to calculate the jump angles after each rebound. This approach aims at providing realistic jump angles while preserving the ability to consider the dampening characteristics of different surface types via the coefficients of restitution.

$$\alpha_{\mathrm{slope}} = k \cdot v_0^f \quad (9)$$

α_{slope} = jump angle after rebound (relative to slope) [°], v_0 = velocity just after rebound [ms^{-1}], f = empirical exponent [−0.74], k = empirical factor [80].

After implementing these modifications a second set of simulations were run. Simulated velocities and rebound heights, as well as the distribution of jump lengths were much closer to observed values. However, the simulated distribution of run-out distances deviated still substantially from observations (Fig. 4). Particularly the high frequency of stops in the middle section of the unforested Site 1 in Vaujany (Section B in Fig. 1) was still not satisfactorily captured by the improved model. This section, where almost one third of the rocks stopped despite high rock velocities, is characterized by the presence of debris large enough to act as obstacles. We concluded that rocks are stopped randomly by obstacles on the surface, a process which is not accounted for by the standard rebound algorithm.

3.2.2 Stopping algorithm

The hypothesis in improving model behavior was that the probability for rock stops at high velocities depends on the relation of (i) the size and distribution of obstacles on the surface of a given surface type and (ii) the size of the falling

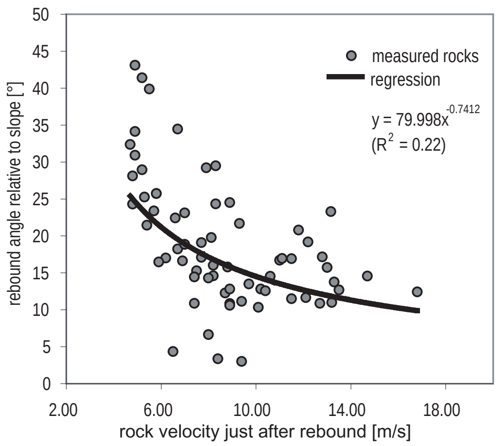

Fig. 5. Relationship of rebound angle and velocity just after rebound for 63 recorded rebounds on the unforested Site 1 in Vaujany.

rock. To establish such relationships we developed a separate software module external to the PICUS model and ran a large number of simulations of boulder impacts on virtual surfaces of block deposits. The virtual surface of block deposits is generated by imitating a natural deposition process where added blocks tend to accumulate at already present deposits. The characteristic sizes of the deposited blocks are either pre-defined or drawn randomly from observed rock size distributions. This process roughly resembles a rockfall-related talus generation. After reaching a defined degree of surface coverage the process is stopped (see Fig. 6 for an example).

Starting with randomly distributed angles between 10° and 20° relative to the surface, i.e. a realistic range of impact angles for real rockfall events, rocks are thrown from random positions above the surface. A rock is considered "stopped" if an obstacle at the surface is centrally hit. This is the case when the angle between the hit point and the direction vector of the falling rock is below 25° (Fig. 7). If no obstacle is hit a simplified rebound is simulated assuming equality between incoming and outgoing angle. Finally, the "stopping probability" for a certain combination of surface type and falling rock size is defined as the ratio of stopped to total number of events (Eq. 10).

$$p_{\mathrm{stop}} = \frac{N_{\mathrm{stopped}}}{N_{\mathrm{total}}} \quad (10)$$

p_{stop} = probability that a rock is stopped during ground contact, N_{stopped} = number of rocks that were stopped, N_{total} = total number of rocks thrown onto surface.

During trajectory calculations within the Rock'n'Roll rockfall model Eq. (10) is used to calculate p_{stop} for each ground impact. If the kinetic energy of a falling boulder exceeds zero, a uniform random number R_{rs} [0–1] decides whether a falling rock comes to a halt (a boulder is stopped

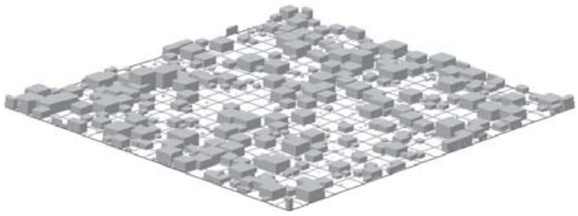

Fig. 6. Visualization of a geerated virtual surface used to calculate stopping probabilities (Screenshot). Cover percentage of deposited blocks = 30%.

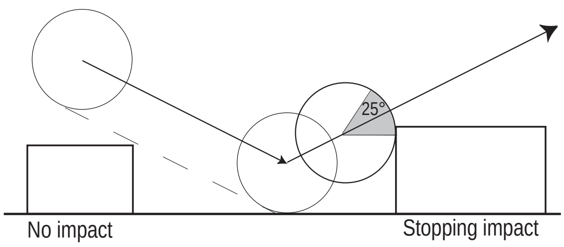

Fig. 7. 2-D-scheme for calculating the stopping probability of a rock (indicated by circles) during a single ground contact. The gray arc indicates the sensitive 25° region for considering a collision as a stop.

if $p_{\text{stop}} > R_{rs}$). To that end the macro-roughness of the generated virtual surface types was visually compared to surface types observed in the field by mapping personnel. First tests yielded promising results and should be corroborated by an extended quantitative comparison of simulated and observed surface roughness in the future.

3.2.3 Vaujany

After implementing the new model algorithms the complete set of simulations was repeated. For 3-D simulations – especially when the forest is considered explicitly – run-out distances are of particular interest. Regarding the simulated distribution of run-out distances the improved model was able to reproduce the observed pattern well (Fig. 4). Especially for the unforested Site 1 the effect of the rockstop submodule is notable for the region between 225 m and 300 m (Section B in Fig. 1). In this section the slope inclination is about 38°, comparable to the section above, but the surface is covered with bigger blocks resulting in a higher probability of stopping impacts.

Table 3 shows that mean and maximum velocities as well as the average number of tree hits as simulated by PICUS Rock'n'Roll match the observations well. While the model only slightly underestimates the average rebound heights, the simulated maximum rebound heights deviate still substantially from observed values, especially on the forested Site 2.

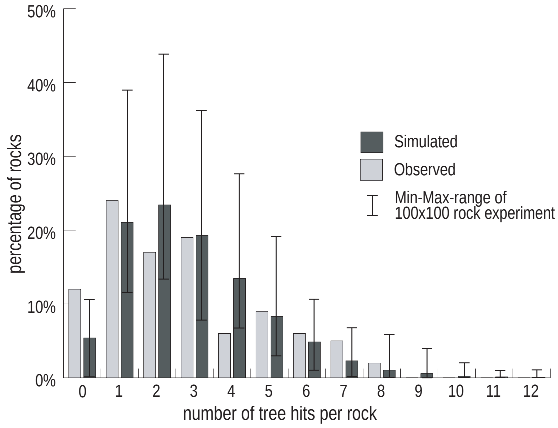

Fig. 8. Observed and simulated frequency of rocks in categories for "number of tree hits per rock" for the forested Site 2 in Vaujany. The simulated tree hits are represented by the mean value of 10 000 simulated rocks, the error bars indicate the minimum/maximum range of 100 simulated rocks with 100 replicates each.

The average of the maximum rebound heights from 100 repetitions of a simulation series with 100 rocks overestimates the maximum rebound height by factor three. However, in the majority of simulations, the maximum rebound heights are substantially lower (see average value and value of the 90th percentile) and extremely high jumps were simulated only on few specific spots along the slope. The general plausibility of simulated rebound heights is also indicated by the good match of the height at which trees were hit on Site 2 (Fig. 3, bottom left corner).

Figure 8 shows the distribution of the number of tree hits per rock on the forested Site 2. The error bars indicate the extreme values for 100 simulation series with 100 rocks each. The simulated number of rocks that hit only one tree or no tree at all is lower than the observed value, while the number of rocks that hit two to four trees is overestimated by the model. A possible explanation for this deviation is that during the Vaujany field experiment the forest especially near the starting point was thinned out by previously released rocks, thus reducing the likelihood of early tree hits.

The match of simulated mean and standard deviation of jump lengths for the upper and lower part of the slopes improved considerably with the revised model (Fig. 3). Compared to results of the original model version the simulated jumps of the updated model in the upper part of the slope are now longer while the jump lengths in the downslope sections are shorter and exhibit less variation (Fig. 3).

3.3 2-D trajectories in Steg and Bad Ischl

The 2-D trajectories are single events which are compared to the range of outcomes from a stochastic model. The simulated run out distance in Steg with 453 m±9 m (standard

Table 3. Summary of observed and simulated (with improved rebound algorithm) rockfall parameters for both sites in Vaujany. The columns denoted with $N = 100 \times 100$ present the mean and standard deviation of 100 simulation series with 100 rocks each.

Parameter	Unit	Site 1 (unforested) Observed N=100	Site 1 (unforested) Simulated N=10 000	Site 1 (unforested) Simulated N=100×100	Site 2 (forested) Observed N=100	Site 2 (forested) Simulated N=10 000	Site 2 (forested) Simulated N=100×100
average of maximum trajectory velocities	ms^{-1}	15.4	17.3	17.2±0.57	11.7	12.9	12.8±0.34
90th percentile of max. trajectory velocities	ms^{-1}	–	25.5	25.1±0.84	–	17.1	17.1±0.81
maximum velocity	ms^{-1}	30.6	32.7	29.5±1.24	24.2	29.5	23.1±1.95
mean velocity	ms^{-1}	11	9.4	9.6±1.5	8	6.8	6.7±1.2
mean number of tree hits per falling rock	–	–	–	–	2.8	2.8	2.9±0.19
maximum rebound height	m	8	13.8	10.33±1.27	2	7.9	5.8±1.05
90th percentile of max. rebound heights	m	–	6.4	6.5±0.6	–	2.2	2.1±0.4
mean rebound height	m	1.5	1.2	1.1±0.2	1	0.8	0.8±0.2

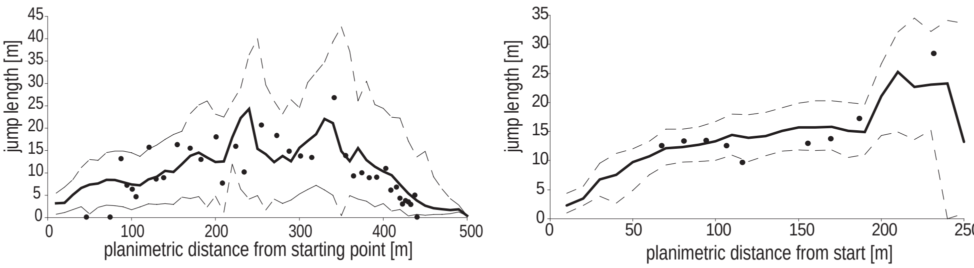

Fig. 9. Simulated and observed jump lengths for the profiles in Steg (left) and Bad Ischl (right). Dots denote observed jump lengths. The bold line indicates mean jump length and the dashed line the minimum and maximum jump length of 10 000 simulations.

deviation) is in agreement with the observed value of 441 m. In Bad Ischl more than 99.9% of the simulated rocks reach the rockfall net with an average kinetic energy of 349 kJ±132 kJ (90th percentile=570 kJ). Keeping in mind the stochastic nature of observed jump lengths resulting from a singular rockfall event, the observed jump lengths fit well within the distribution of simulated jump lengths (see Fig. 9).

4 Discussion

In this paper a comprehensive model validation experiment with a 3-D rockfall and forest model was presented. Focus of the validation was on the rockfall model. The study features an iterative cycle of testing and improving the model (e.g. Vanclay and Skovsgaard, 1997). A first set of simulation runs at the sites in Vaujany indicated major deficiencies of the initial model version with regard to simulated rock velocities, rebound heights and run-out distances. Attempts to improve the match of simulated and observed data through calibration of the coefficients of restitution were not successful. Based on the re-analysis of the rebound algorithm two major changes in the rebound algorithm were implemented: (i) an increased damping during ground impacts with increasing rock velocity based on Johnson (1985), and (ii) a new approach to calculate jump angles after rebound based on empirical jump data. The effect of increased damping for ground contacts at higher rock velocities due to a larger effect of plastic deformation is not only suggested by literature but has been successfully implemented in existing rockfall models (e.g. Pfeiffer and Bowen, 1989). While the complex impact process is still not fully understood, the magnitude of plastic deformation is assumed to depend on ground material characteristics (mainly strength) and impact characteristics such as impact angle and contact pressure. However, in the current study the relationship of velocity and the coefficients of restitution is the same for all surface types.

Additionally, an empirical relationship to estimate jump angles after rebound was derived. This modification resulted in a more realistic model behavior but also in a weakened physical foundation of the rebound algorithm. We used specific data from one of the Vaujany experimental sites itself, thus rendering the Vaujany data no longer an entirely independent data set for model evaluation. However, detailed empirical data on rockfall processes is sparse, and excluding the Vaujany data from model development deemed unduly restrictive. We are aware that the empirical relationship of velocity and jump angle based on limited data from one specific site is not a generally valid relationship. However, the modified model variant combining Johnson's approach with the empirical relationship worked well for both sites in Vaujany as well as for the two trajectories in Steg and Bad Ischl. Considering the quite diverse conditions represented by these four sites we conclude that the chosen approach has some potential which should be further explored. More empirical data on individual jumps from different surface types are required to test the generality of the approach and to provide insight into the sensitivity of simulated trajectories to variation in the rebound algorithm. In general, the necessity to calibrate rockfall models for each individual site and application may severely hamper model applicability. For instance, for assessments at larger scales such calibration procedures are very likely not feasible due to missing calibration data, thus calling for generalizable approaches.

A major model improvement was the implementation of a probabilistic stopping algorithm for falling rocks. Based on a conceptual model of the interaction of a falling rocks with boulder obstacles on the ground virtual data were generated with an external software module to derive a general meta model of the process. The advantage of the presented approach is that the virtual surface types used to establish stopping probabilities for falling boulders of specific size can be compared to surface types used for site mapping activities. Thus, a direct link can be established between input parameters used in generating the virtual surface types and observable data (e.g., block cover percentage, size distribution of deposited blocks).

Generally, the updated model showed good agreement with observed rockfall parameters, particularly with regard to rock velocities, jump length and run-out distances. Worthwhile to note is the persistent overestimation of maximum rebound heights for the Vaujany simulations despite the relatively small range of additionally applied variability in the tangential coefficient of restitution r_t. However, especially on the forested Site 2 large rebound heights occurred on only few spots along the slope. A possible reason is that Rock'n'Roll calculates jump angles relative to the slope angle at the impact point. Large rebound heights can thus arise from an overestimated variability of the inclinations along the slope as a result from artifacts of the digital elevation model (Agliardi and Crosta, 2003) or the transformation to a TIN. A possible further model extension would be the consideration of soft impact with penetration of the boulder into the ground on loose soils and scree deposits. This feature could be implemented by smoothing the point inclinations along an estimated contact zone.

Both single event 2-D trajectories were contained within the range of simulated stochastic outcomes. Compared to comprehensive 3-D data sets as available in Vaujany, 2-D profiles from post-hoc analysis of individual rockfall trajectories provide less opportunity to explore and validate model behavior. However, they proved to be a readily available and efficient complementary element in our model evaluation.

In the presented validation experiments the forest dynamics model was deactivated as the rockfall processes featured in the evaluation data took place within one time step of the forest model. As already outlined in Woltjer et al. (2008) a fully coupled forest and rockfall model with feedback of rock hits on the vitality and subsequently stability and mortality risk of trees is conceptually possible within this framework. Based on data of the Austrian National Forest Inventory Vospernik (2002), for instance, showed that Norway spruce trees with rockfall wounds had an increased probability of death. However, rock fall frequency as a prerequisite for such an approach cannot be readily inferred from standard data sources, limiting a fully coupled simulation approach.

5 Conclusions

The current model version produces reliable results over a wide array of conditions for rockfall processes as well as for forest dynamics (e.g. Seidl et al., 2008, 2005). It can thus be applied to analyze protective effect of forest vegetation over time periods of several decades under natural forest development or different forest management regimes. The rockfall model itself is designed for high computing performance and is able to calculate approx. 1000 trajectories per second (using standard hardware from 2007) which allows to efficiently extend the spatial scale of application. The coupled rockfall and forest model can simulate an area of about 40 hectares which is sufficient for most protection forest management projects. The evaluation results presented in this contribution generally support the approach and increase the credibility of the rockfall module. Hence, we are confident that the presented model can be used for operational assessments of the protective function of forests against rockfall.

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8.3 *Appendix - Paper III*

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RESEARCH ARTICLE

Evaluating the effects of forest management on rockfall protection and timber production at slope scale

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We used the coupled forest and rockfall model PICUS Rock'n'Roll, linking a hybrid forest patch model and a 3D rockfall model, to assess the effects of four management scenarios (BAU: business as usual age class shelterwood approach; PFM1 and PFM2: rockfall protection management scenarios with slit-shaped gaps; NOM: no management scenario without any active silvicultural intervention) on rockfall protection and timber production on a 38 ha slope over 100 years. Compared to PFM1 and PFM2, we found slightly more harvested timber for the BAU scenario (BAU: 6.7 $m^3ha^{-1}yr^{-1}$, PFM: 5.7–5.9 $m^3ha^{-1}yr^{-1}$), but lower contribution margins (BAU: 55 €$ha^{-1}yr^{-1}$, PFM: 113–115 €$ha^{-1}yr^{-1}$). Overall, depending on rock size and forest state, 30–70% of the simulated rocks that would otherwise hit the road at the foot of the slope were stopped by the forest. While the PFM scenarios maintained a high rockfall protection level over 100 years (PE between 45–64%) the BAU showed periods of reduced protection (PE between 26–65%). The NOM scenario maintained favorable conditions in the beginning, but declining protection efficiency in the last decades of the century (PE 49–63%). We conclude that rockfall protection management can outperform BAU with regard to both timber production and rockfall protection.

Keywords: rockfall; mountain forests; simulation modeling; PICUS

Introduction

In the Alps, many forests play an important role in protecting infrastructure like roads or buildings against rockfall. Major factors influencing the protective effect are tree density and size structure of the tree population, tree species composition, but also how these attributes vary along a slope (Dorren et al. 2005). Since forest structure evolves dynamically and is strongly influenced by forest management, the knowledge about long-term effects of management decisions on rockfall protection is highly relevant. The importance is amplified by high management costs in mountain forests due to difficult terrain conditions and by competing goals in multi-functional mountain forest management (e.g. timber production vs rockfall protection).

Available indicator-based schemes for rockfall protection management define forest states that are desirable with regard to the protective effect. Typical indicators are gap size, tree density, and mean tree dimensions (Ott et al. 1997; Frehner et al. 2005). They, however, are implicitly static and focus exclusively on the protective function, neglecting other ecosystem service demands. In addition, such schemes apply at stand level and include the spatial dimension with regard to scale and resolution only implicitly, e.g. by considering maximum gap sizes. The relevant spatial scale for rockfall processes and related protective effect of forest vegetation, however, typically reaches beyond the stand level. Therefore, a tool for projecting mid- to long-term rockfall protection efficiency (PE) in unmanaged and managed forests needs to extend the analysis by incorporating future stand development and by considering both spatial resolution (i.e. addressing rockfall processes at the level of individual trees) and scale explicitly (i.e. expanding the spatial scale from stand to slope level). Simulation modeling has been used extensively for projecting forest development (Pretzsch et al. 2008) and also for the assessment of rockfall processes (Volkwein et al. 2011). Forest models addressing the slope scale are rare: typical stand level forest simulation models are often unable to simulate multiple hectares explicitly, while models aiming at larger scales usually lack the required resolution for dealing with structurally diverse mountain forests. Moreover, only few models are able to cope with mountain forest management practices like spatially explicit gap creation along cable yarding tracks and similar small scale harvesting interventions (Maroschek et al. 2014).

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Various tools for assessing rockfall processes, on the other hand, are available, reaching from landscape level tools to models that simulate detailed trajectories of single rocks (see Volkwein et al. 2011). Recent developments increasingly focus on three-dimensional (3D) models allowing for the simulation of single rock trajectories on a high-resolution 3D slope (Agliardi & Crosta 2003; Dorren et al. 2006; Rammer et al. 2010).

Acknowledging the importance of forests for rockfall protection (Dorren et al. 2005), several attempts were made to combine forest and rockfall simulation. Some of the studies concentrated on applying trajectory models to either current forest states as reported by stand inventories or yield table based extrapolations (Stoffel et al. 2006; Wehrli et al. 2006; Bigot et al. 2009). Others focused on projecting future forest development and assessed rockfall protection with simplified indicator-based approaches (Wehrli et al. 2006; Cordonnier et al. 2008).

A step toward a full dynamic integration of forest and rockfall modeling is the coupling of the process-oriented forest patch model PICUS (Lexer & Hönninger 2001) with the spatially explicit 3D rockfall simulation model Rock'n'Roll (Woltjer et al. 2008). Rammer et al. (2010) performed a thorough validation of the rockfall module using data from real-size rockfall experiments and empirical rockfall trajectories across the Alps. They conclude that combining the rockfall module with the well-tested forest model (e.g. Seidl et al. 2005, 2010) provides a well-suited tool for assessing the long-term implications of forest management on rockfall protection and the interdependencies with other ecosystem services. Highly efficient silvicultural systems for timber production often feature shelterwood approaches and stripwise clearcuts, which may compromise the protective effect. Finding a suitable balance with regard to grain and extent of cutting pattern has attracted substantial interest by forest managers. Another frequent approach in mountain forest management is refraining from active management at all, either due to low productivity or lack of road infrastructure, accepting the potential negative long-term effects on rockfall protection (Woltjer et al. 2008).

In this paper, the integrated model PICUS Rock'n'-Roll (hereafter called in short PICUS) is applied to analyze effects of different silvicultural systems on rockfall protection and timber production for a case study slope in the Austrian Alps. The slope covers about 40 hectares and is characterized by small scale ownership structure. Specific objectives of the study are (1) t o quantify the effects of different silvicultural strategies on management objectives and (2) to assess the trade-off relationship between rockfall protection and timber production at slope scale.

Materials and methods

Simulation models

The forest model Picus 1.41

The forest model used in this study is the hybrid forest patch model PICUS v1.41 (Seidl et al. 2005), which incorporates elements of a classical patch model (PICUS v1.2, Lexer & Hönninger 2001) as well as a stand level production model based on physiological principles (3-PG, Landsberg & Waring 1997). A detailed description of the model is provided in Seidl et al. (2005). Here, just a brief overview on the core model concept is given.

PICUS simulates individual trees on a regular grid of 10 × 10 m² patches. The leaf biomass of trees is arranged in crown cells with a vertical resolution of 5 m. A 3D light model, allowing for the explicit consideration of direct and diffuse radiation within the canopy, is used to model inter and intra tree species competition. Stand level productivity is estimated by means of a simplified model of radiation interception and light use efficiency (Landsberg & Waring 1997), which depends on temperature, precipitation, radiation, vapor pressure deficit, soil water, and nutrient supply. Redistribution of assimilates to individual trees, assuming fixed respiration rates (Landsberg & Waring 1997), is accomplished according to the relative competitive success of the individuals within the patch model environment (see Lexer & Hönninger 2001). The tree regeneration layer dynamics are modeled within five height classes (Woltjer et al. 2008). PICUS contains a flexible management module based on a scripting language allowing for spatially explicit harvesting interventions as well as planting operations at the level of the 100 m^2 patches. The basic time-step of the simulation is monthly with annual integration of the tree population dynamics processes. The model requires information about the soil water storage capacity, the pH value of the mineral soil as well as plant-available nitrogen as a proxy for nutrient supply and is driven by monthly values of temperature, precipitation, solar radiation, and vapor pressure deficit of the atmosphere. PICUS is initialized with stand level tree lists or aggregated species-specific DBH distributions where trees are drawn from the distribution and assigned to the simulated patches. When PICUS is run in combination with the rockfall module, trees are additionally assigned specific coordinates within their patch using minimum distances between neighboring trees.

PICUS has been tested extensively (Seidl et al. 2005). Recent applications of the model to study mountain forest management include Seidl et al. (2011a, 2011b), Lexer and Seidl (2009), and Maroschek et al. (2014).

The rockfall model Rock'n'Roll

PICUS Rock'n'Roll is a rockfall model that simulates individual spatially explicit rockfall trajectories on a 3D slope (Rammer et al. 2010; Woltjer et al. 2008).

The trajectory of a spherical rock with variable size consists of a series of rolling and/or jumping motions. The model uses a lumped mass approach for simulating free fall and ground impacts and a rigid body approach for the simulation of rolling motions and tree impacts. Kinetic energy of a falling rock is dissipated by (1) rolling friction for rolling motions, (2) ground impacts for jumping motions, and (3) tree impacts during rolling and jumping motions. In a simulation rock trajectories start with a predefined initial velocity either from predefined or from randomly selected positions within the simulated area. A rock stops, when its kinetic energy falls to zero.

The slope surface is characterized by coefficients of restitution for jumping mode (i.e. rebound parameters) and by rolling friction coefficients for rolling mode. Coefficients of restitution describe the ratio of the normal (or tangential) velocity component of the center of mass before and after an impact (e.g. Kharaz et al. 2001). Parameter values for various surface types have been retrieved from the literature (Azzoni et al. 1995; Schweigl et al. 2003; Heidenreich 2004).

Within PICUS Rock'n'Roll, trees are specified by location, species, diameter at breast height, and tree height and act as spatially explicit obstacles for rocks. The tree hit algorithm closely follows the model described by Dorren et al. (2005) and Dorren and Berger (2006). If a tree is hit by a rock, kinetic energy is dissipated up to a maximum dissipation potential, which depends on tree species and diameter. If the total kinetic energy of the rock is consumed by the impact, the rock stops. Otherwise the direction of the rock may be deviated and the rock trajectory is continued. Tree level output of individually simulated forest stands (i.e. tree position, species, and dimensions) is used to populate the stand polygons on the slope that is then subsequently used in the assessment of rockfall protection.

The rockfall model was evaluated successfully with data from real-world rockfall experiments in France and with two ex-post 2D trajectories from single rockfall events in Switzerland and Austria (Rammer et al. 2010). The model was able to predict key rockfall characteristics like run out distances and rock velocities well, being parameterized with standard values for coefficients of restitution from the literature.

Study area

The study area is located in the valley of the Ziller, a tributary to the river Inn in the province of Tyrol in Austria (lon: 47.16°/ lat: 11.16°). The forest used for demonstration in this study has an area of 38 ha and is located on a south-facing slope, which extends from

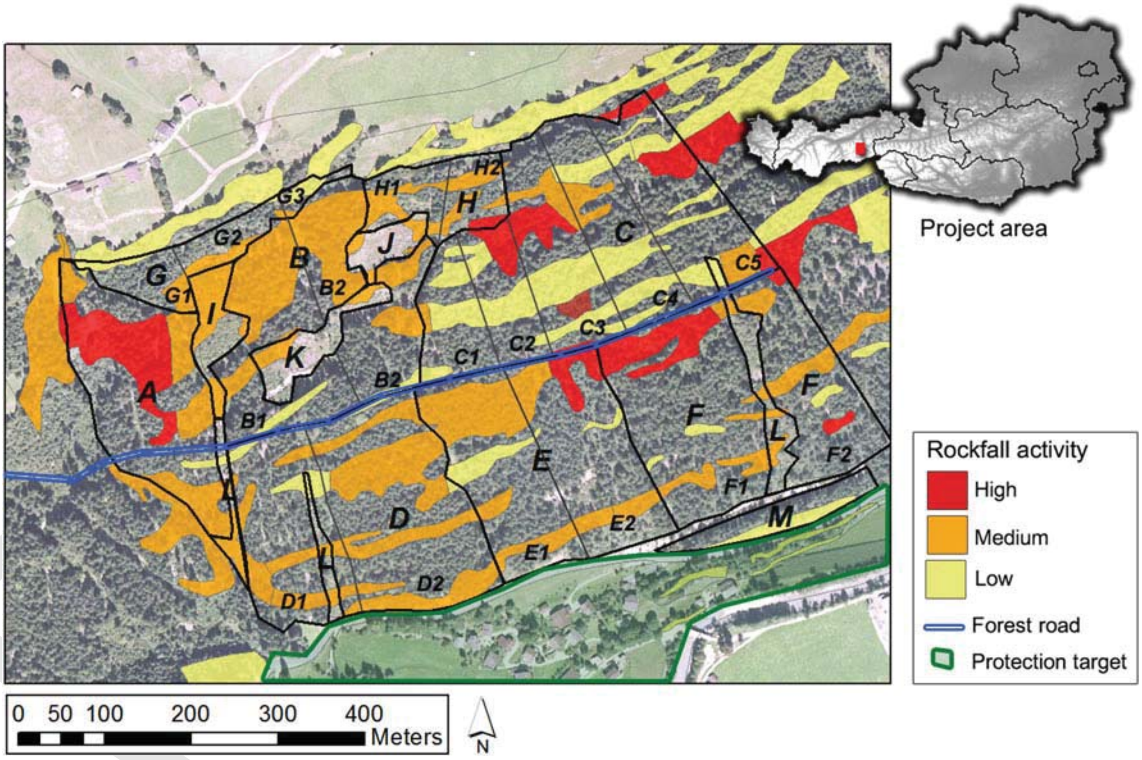

Figure 1. The 38 ha slope in the Eastern Alps in Austria. The stand polygons are drawn in black and indicated with capital letters A to M. Some larger stands are divided into management areas (gray lines, letter-digit combinations B1 to F2). Access to the slope is provided by a forest road (blue) in the middle of the slope. The protection objects are the road and the settlement at the foot of the slope (green). Rockfall source areas in three activity classes (high, medium, low) are overlain.

650 m to 1100 m a.s.l and has length of approximately 500 m (projected) (Figure 1).

The bedrock layers consist mainly of schist and show typical inclinations between 35° and 40°. Large parts of the slope are covered by scree and bigger blocks. Several steep and heavily weathered cliffs cut horizontally through the slope serving as the primary sources of rockfall. Access to the forest area is provided by a road at midslope position and another road at the foot of the slope. Due to the steep and rocky terrain, timber extraction relies on skyline-based cable yarding systems.

The natural vegetation type is Norway spruce (*Picea abies (L.)* H Karst.*)* with Larch (*Larix decidua* Mill) and some admixed Silver fir (*Abies alba* Mill). The current forest vegetation consists of mainly mature timber stands dominated by spruce (98.68% of the standing volume) with small shares of Silver fir (0.95%), Larch (0.27%), and other species (0.01%).

The forest under study is managed by an agricultural community and considered by the owners as a source for timber and income generation. The rockfall activity along the slope sets the regional road and a settlement situated below the forest at the valley bottom at risk (Figure 1). Thus, priority of public interest is on the protective effect of the forest.

Climate data

For the simulation of forest development, a 100-year time series of monthly mean temperature, precipitation, global radiation, and vapor pressure deficit was constructed from a de-trended observed weather record from 1961–2003, which had been interpolated to the study area from nearby weather stations. Within the study area an altitudinal temperature gradient of −0.6°C/100 m was assumed in preparing adjusted climate data-sets for each forest stand. The mean annual temperature at 900 m is 6.6°C with moderately cold winters (−3°C average temperature for January) and the mean annual precipitation is 1040 mm.

Forest and soil data

In a previous management plan, the slope area had been structured into 13 stand polygons (Figure 1). Current forest and soil conditions were sampled on a fixed 100 × 100 m^2 grid that was further condensed to ensure at least four sample points per stand polygon. For trees above a DBH threshold of 4 cm an angle count measurement with basal area factor 4 was taken. Drill cores were extracted from selected individuals for stand age determination. At each sample plot forest regeneration was mapped in five height classes on concentric circles with class dependent radius between 1 m and 2 m. At each sample point soil type and stoniness were recorded from a 30 cm deep soil pit and soil depth determined with a soil corer. The gathered data were used to generate initial stand conditions for the model simulations. Water holding capacity and plant-available nitrogen were estimated for each forest stand by relating the surveyed soil data to the soil database for Austrian forests from Seidl et al. (2009). See Table 1 for an overview of stand and site characteristics.

Surface properties

A digital elevation model of the area at a resolution of 1 × 1 m was available from the Austrian Service for Torrent and Avalanche Control. From a generic rock size distribution representing the entire slope, which was fitted to 240 surveyed rockfall blocks, three rock sizes were derived for the simulations (1 m, 0.5 m, 0.3 m), representing the mean (0.3 m), the maximum (1 m), and the 90th percentile (0.5 m) of the expected rockfall blocks. In addition, a ground survey was conducted to generate maps of the required parameters for the rockfall model (Table 2). To classify the rock source areas, four

Table 1. Initial stand conditions and site properties used in the simulations.

Stand	Area (ha)	WHC (mm)	Available nitrogen (kg ha^{-1} $year^{-1}$)	Stems (stems ha^{-1})	Standing volume (m^3 ha^{-1})	Share of Picea abies (% volume)
A	3.4	95	50	514	448	100
B	4.2	162	60	559	880	98
C	8.0	77	80	632	709	99
D	5.9	95	55	584	543	99
E	5.0	72	45	564	516	97
F	5.4	95	50	821	633	100
G	1.2	182	110	3841	294	99
H	1.2	162	110	3016	301	96
I	0.6	101	60	558	30	48
J	0.4	95	60	0	0	–
K	0.6	152	60	528	0	0
L	1.0	–	–	12807	–	–
M	0.7	77	70	1120	535	95

Note: Two smaller areas covered by shrubs were combined to stand L (1.0 ha), which was not actively simulated.
WHC, water holding capacity.

Table 2. Attributes used to map areas with homogeneous surface properties and related model input parameter for the simulations.

Surveyed attributes	Description	Model input parameter
Surface type	Solid rock, scree, shallow soils with fine debris, forest soils, pasture, road	Rebound parameters R_n, R_t
Scree cover percentage	Percentage of the area covered with scree (0%, 25%, 50%, 75%, and 100%)	Stopping probabilities
Block size	Block size (height) of the block representing the 90th percentile of deposited blocks	Stopping probabilities

rock release activity classes were mapped in the field. Likewise, seven surface types were used to assign rebound parameters from the literature (Azzoni & de Freitas 1995; Azzoni et al. 1995; Chau et al. 2002, see Table 3). The input to infer one of 20 obstacle types consisted of scree cover percentage and an estimate of the largest block size. Assuming that this block represented the 90th percentile of the underlying rock size distribution, the surface characteristics for each obstacle type were generated from the generic rock size distribution and the cover percentage. The obstacle types are linked to a stopping probability algorithm for falling blocks (see Rammer et al. 2010).

Experimental design

Silvicultural alternatives

The focus of the study was to compare current management with alternative silvicultural concepts. The spatially explicit structure of PICUS allowed a realistic design of fine grained mountain forest silviculture (Ott et al. 1997; Dorren et al. 2004). The management scenarios included the "business-as-usual" scenario (BAU), two rockfall protection management regimes (PFM1 and PFM2), and a "no-management" scenario (NOM). Any timber harvesting operation in the project relied on skyline cable yarding systems operated downslope in the upper part of the slope and upslope in the lower part (compare Figure 1). In rockfall terrain skyline tracks are positioned diagonally across the slope to prevent rockfall along the skyline track. The skyline corridor in which removals can take place is defined via the maximum lateral yarding distance that in cut-to-length systems is 25–30 m (Stampfer et al. 2006).

The BAU management resembles a shelterwood approach aiming at natural regeneration after a seeding cut and a subsequent removal of the overstorey after 20 years. In the pole stage phase two thinnings reduce stem numbers and improve stand stability. This approach is applied in zones of 1–3 skyline corridors at a time and represents a frequent approach in Austrian mountain forestry with emphasis on efficient timber harvests.

PFM1 is based on Frehner et al. (2005) and Ott et al. (1997) and aims at sustainable PE and stand stability. Overall silvicultural goal is the transformation of current stands to an uneven-aged forest structure that is initiated by transversal slit cuts of 20–30 m length and 6–10 m width. About three of such slits per 100 m skyline length are initiated (10–15% of stand area in a corridor) and enlarged either along the contour line or downslope as regeneration in the initial slits has been established. Additionally, individual trees are also removed between the slits, particularly in later phases. Structural thinnings increase vertical stand heterogeneity in young pole stands.

PFM2 follows a similar approach and was derived from a "trial marking" in the field with local foresters. Compared to PFM1, the slits extend across the entire skyline corridor along the contour lines; slit width is 7–10 m. Every 20 years the slits are enlarged in downslope direction. No trees outside the slits are harvested. Only

Table 3. Numerical values for coefficients of restitution in normal (R_n) and tangential (R_t) direction as used for different surface types (see Table 2) in the rockfall simulation.

Surface type	R_n	R_t	Description
Solid rock	0.4	0.9	Rock face, outcrops, large individual blocks
Scree	0.35	0.7	Area fully covered by scree
Shallow soils with fine debris	0.3	0.75	Fine scree and debris, partly with soil
Forest soils	0.2	0.75	Soils with humus layer, ground vegetation
Pasture	0.35	0.8	Pastures, agricultural use
Roads, compacted soil	0.25	0.9	Roads and forest roads

after three entries with a total regenerated area of about 60% the residual canopy is sequentially removed.

For all scenarios it was assumed that seed supply is determined by current species composition and that regeneration success is not limited by browsing.

Harvesting costs were calculated based on Stampfer et al. (2006) and included fixed and variable cost components depending on skyline length, logging direction (up-slope, down-slope), mean harvested tree volume, and total logged volume. Timber revenues were based on regional prices for an average assortment mix.

Based on these silvicultural regimes, operational management plans were derived for the entire slope area. The devised management schedules in each of the three actively managed scenarios (BAU, PFM1, PFM2) aimed at efficient rockfall protection by splitting up larger stands in smaller management areas (see Figure 1) and scheduling the management operations in such a way as to avoid the formation of large adjacent and insufficiently stocked areas. An example for a spatio-temporal coordinated management schedule for the BAU scenario is given in Table 4. The NOM scenario represents natural forest development without any silvicultural intervention, which is a widespread “management option” in the case study region.

Simulation setup

The forest model was run for each stand and management scenario using the site and initial stand properties (Table 1) as well as the management schedule that was derived from the slope level management plan. In order to perform rockfall simulations at slope scale, forest state information (dimension, species, and position of individual trees) every 20 simulated years was retrieved from the model and stored in a database. All forest simulations were run for a representative stand area of one hectare.

Table 4. Example of a management schedule for three adjacent forest stands (C, E, F) in the BAU management (compare Figure 1).

	C					E		F	
Year	C1	C2	C3	C4	C5	E1	E2	F1	F2
2000	S		S		S		S		
2010								S	
2020	F	S	F	S	F	S	F		S
2030								F	
2040		F		F		F			F
2050									
2060									
2070	T1		T1		T1		T1	T1	
2080									T1
2090	T2	T1	T2	T1	T2	T1	T2		
2100								T2	

C1–C5, E1–E2, and F1–F2 are management areas. Capital letters indicate management operations: S, seeding cut; F, final cut; T1, first thinning; T2, second thinning.

The simulated forest state data were used to populate the stand polygons of the slope for the rockfall simulations. The simulated 1 ha stands were clipped to the stand polygons and, when necessary, used repeatedly. The slope scale rockfall simulations were conducted for each of the six forest states. For each of the selected rock sizes (0.3 m, 0.5 m, 1 m) 1000 rockfall trajectories per hectare were simulated. The rocks started from randomly selected locations within the source areas. Statistics on trajectory variables were collected for each trajectory and additionally for each 10 × 10 m patch traversed by falling rocks. A total of 0.6 million trajectories per management scenario were simulated.

For this study, effects of rockfall on stand development – e.g. an increased mortality risk for trees due to wounds after rock impacts – were neglected.

Indicators

Indicators for rockfall protection. The main protection target in the study area was the road at the foot of the slope. Rockfall PE for this study was defined as the number of rocks reaching the road given any specific forest state on the slope compared to a hypothesized slope devoid of vegetation. PE was calculated for each combination of rock size, source type, management scenario, and time as:

$$PE = 1 - \frac{N_{s,r,m,t}}{M_{s,r}} \quad (1)$$

with PE the protection efficiency (0–1), $N_{s,r,m,t}$ the number of rocks of size s that reach the road and originate from source type r for management scenario m at year t, and $M_{s,r}$ the number of rocks of size s from source type r that reach the road when the hypothetical case without protecting vegetation is simulated. Thus, high values for PE indicate a high share of rocks that are stopped due to forest vegetation structure.

Mean values of rock velocity, total rock energy (kinetic plus rotational energy), and rebound height at the forest – road transition were calculated. Additionally, average values for maximum rock velocity, maximum rebound height, and run out distance for all simulated trajectories were used to characterize the rockfall processes on the slope.

Indicators for timber production. Several indicators were defined to measure the performance of the management scenarios regarding timber production. Specifically, the indicators were (1) standing tree volume (m^3 merchantable timber over bark ha^{-1}), (2) harvested volume ($m^3 ha^{-1} yr^{-1}$), and (3) the contribution margin 1 (CM1,

€ha^{-1}). CM1 was calculated by subtracting harvesting costs from revenues per harvested m^3 of timber.

Results

Timber production

Figure 2 shows the average stem density and standing volume for the entire project area. The actively managed scenarios showed an increase in stem numbers due to the on-set of regeneration after initial harvests. NOM lacked regeneration, but showed the highest standing volume over the simulation period.

The economic performance of the three evaluated active management regimes is presented in Table 5. While the contribution margin (CM1) is a key indicator for profitability of timber harvests, the mean periodic removals indicate the flow of timber over time. The negative contribution margins during the second half of the simulation period under BAU management resulted from cost-intensive tending of the mostly juvenile stands and low revenues due to small timber dimensions. On the other hand, the protection management scenarios PFM1 and PFM2 were able to achieve positive CM1 values over the entire 100 year period by avoiding the creation of larger-scale young stand development phases and the resulting need for costly stand tending measures. The mean harvested timber was highest for BAU with 6.7 m^{3}ha^{-1}yr^{-1} and lower for PFM1 (5.7 m^{3}ha^{-1}yr^{-1}) and PFM2 (5.9 m^{3}ha^{-1}yr^{-1}). The higher productivity of BAU is due to the quick transformation of the overly mature initial stands, which are way beyond the culmination of periodic increment, into productive young stands.

Table 5. Mean harvested volume [m^3 ha^{-1} yr^{-1}] and contribution margin CM1 [€ ha^{-1} yr^{-1}] in five 20-year periods and for the full simulation period.

	BAU		PFM1		PFM2	
Period	Harvest	CM1	Harvest	CM1	Harvest	CM1
2000–2019	12.6	209	6.5	136	8.0	168
2020–2039	11.4	94	6.7	147	6.4	121
2040–2059	1.1	−9	6.3	122	4.9	101
2060–2079	3.6	−25	3.3	68	5.3	105
2080–2099	5.0	−2	5.9	108	4.9	75
2000–2099	6.7	53	5.7	116	5.9	114

BAU, business as usual shelterwood system; PFM1 and PFM2, rockfall protection management.

Rockfall protection efficiency

The upper panel of Figure 3 compares PE for different rock sizes over time. Under BAU management PE decreases for all rock sizes during regeneration stages, with low density of mature trees in several stands or no such trees at all after removal of the residual shelter. The PFM scenarios performed comparably well; however, the higher density of smaller trees in PFM2 corresponded with higher protection efficiency for smaller rocks and slightly reduced protective effect against larger rocks from 2020–2040. The NOM alternative showed a declining tendency in PE for all rock sizes, but in relative terms performed better for larger rock sizes.

Simulated rock velocities and run out distances (Figure 3) showed a similar pattern. The mean maximum velocity of all trajectories was highest for periods with high share of stands in the regeneration stage with low standing volume (BAU) but also under PFM2 as long as regeneration has not been established in the created gaps.

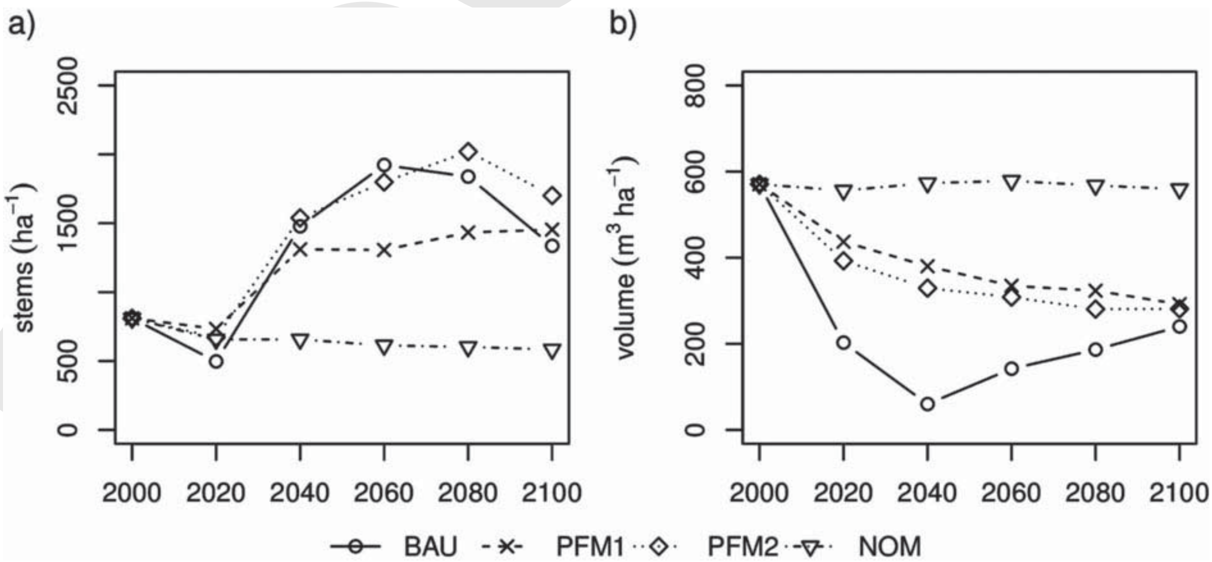

Figure 2. Mean tree density (stems >1.3m height) (a) and standing volume (b) on the study slope over time. BAU = business as usual shelterwood management, PFM1 and PFM2 = protection forest management, NOM = no management.

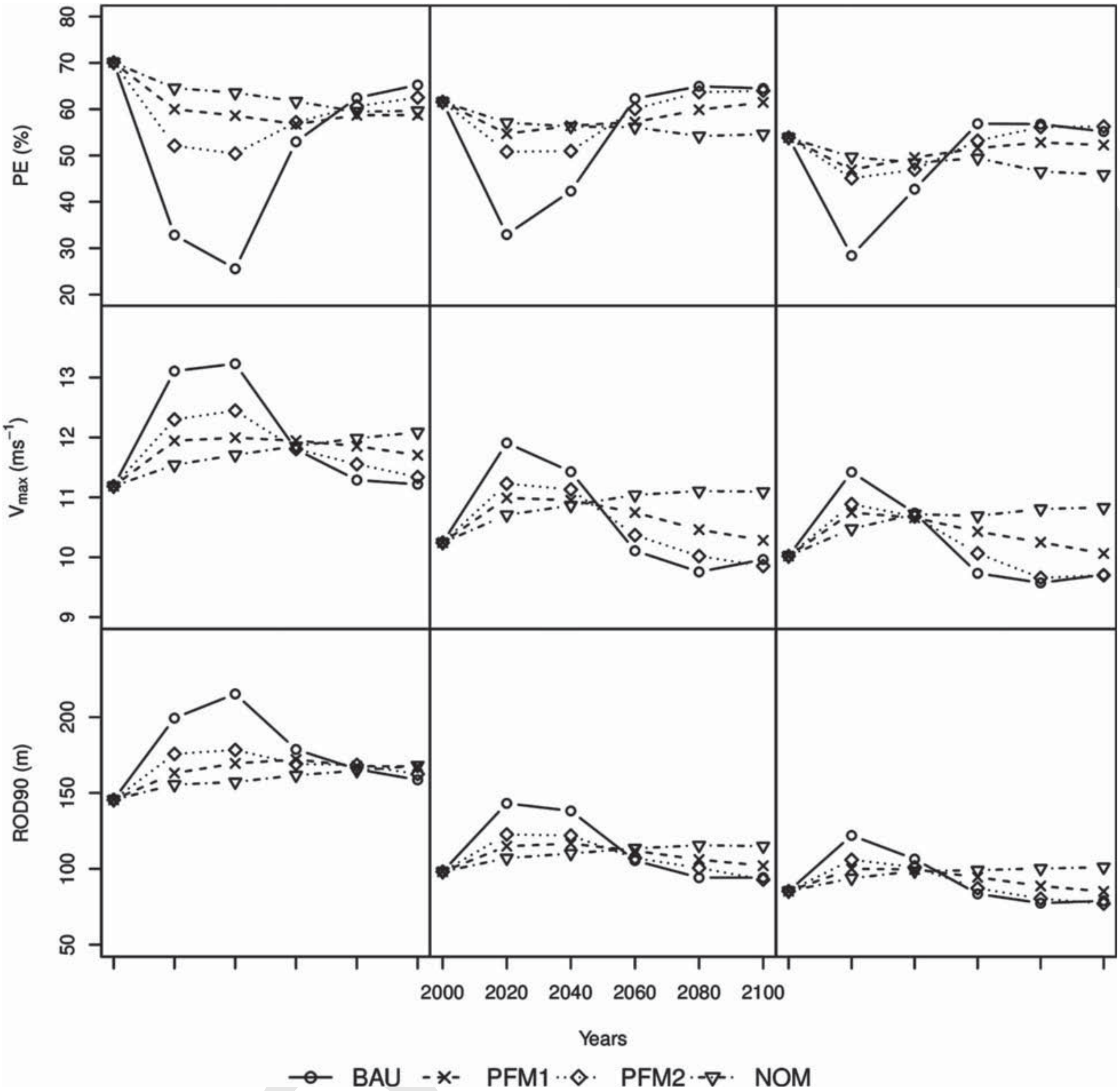

Figure 3. Upper panel: protection efficiency (PE = the number of rocks stopped by the forest compared to the situation without tree vegetation). Central panel: mean maximum velocity [V_{max}]. Lower panel: 90th percentile of the projected run out distances (ROD90). Data are shown for three rock diameters (left column: 1 m, middle: 0.5 m, right: 0.3 m) and four management scenarios (BAU = business as usual shelterwood, PFM1 and PFM2 = rockfall protection management, NOM = no management).

The 90th percentile of the run out distances (ROD90) was distinctly higher for larger rock sizes. Under BAU management there was an increase in ROD90 until 2040 with a subsequent decreasing trend for all analyzed rock dimensions.

Trade-offs in ecosystem services

A combined view on the relationship between profitability of timber harvests and the related rockfall protection efficiency is provided in Figure 4. CM1 and PE for the protection management scenarios (PFM1, PFM2) showed relatively little variation. The periodic CM1 values ranged from 68 to 168 €$ha^{-1}yr^{-1}$, while the PE for the protection management scenarios varied between 45% and 64%. In contrast, the BAU management showed a large variation for both CM1 and PE indicators: CM1 ranged from −25 to 209 €$ha^{-1}yr^{-1}$ and PE from 26% to 65%. Under the NOM scenario no revenues were generated, and the PE was between 49% and 63%. Figure 4 reveals also a distinct trade-off relationship between timber production and rockfall

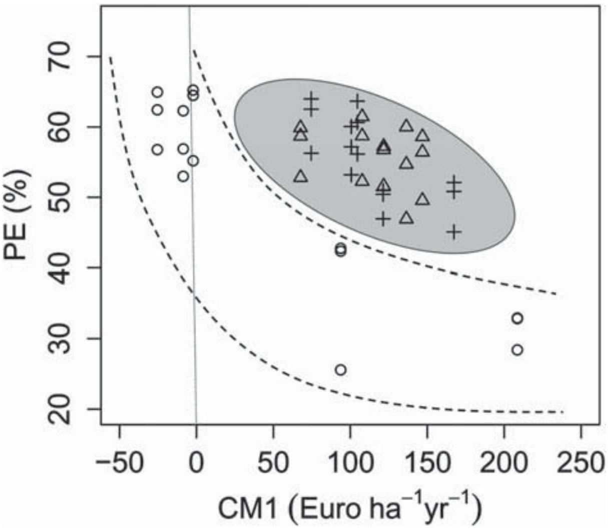

Figure 4. Trade-off relationship between protection efficiency (PE) and contribution margin (CM1) for the four management scenarios BAU (open dots), PFM1 (triangles), PFM2 (+-signs), and NOM (x-signs) for 20 year periods and three rock diameter classes. In BAU high economic returns come with low protection efficiency and vice versa (dashed corridor). Under the NOM scenario, no revenues are generated. Under protection forest management PFM1 and PFM positive contribution margins and protection can be sustained over the entire simulation period (gray-shaded ellipsoid).

protection in the BAU scenario for the 20-year periods: economic success is achieved at the cost of low protection efficiency and vice versa.

The aggregated average of PE (mean over full simulation period of 100 years and three rock sizes) for the BAU management was 50%, while the other three management scenarios had PE values between 55% and 56%. Similarly, the average CM1 over the full simulation period was 55 €$ha^{-1}yr^{-1}$ for BAU and between 113 and 115 €$ha^{-1}yr^{-1}$ for the protection management scenarios.

Detailed analyses of mechanisms

Additional details on the effect of forest structure on rockfall protection are provided by comparing four contrasting forest states (Table 6). The simulated average rebound heights as well as the velocity of rocks when reaching the road at the foot of the slope showed a pattern similar to the one in Figure 3. The protection efficiency for rocks starting within 50 m (projected) distance from the road ($PE_{<50m}$) was below 24% for all four cases and for all rock sizes. For the forest state after intensive silvicultural interventions (BAU-2020) the $PE_{<50m}$ was even lower (2.7% to 6.9%).

Table 6. Stand characteristics and rockfall indicators for three rock sizes (0.3 m, 0.5 m, 1.0 m) and four contrasting forest states from the BAU shelterwood scenario (BAU2000 = mainly mature stands, BAU2020 = regeneration phase, BAU2100 = mainly pole stage) and one protection forest management scenario (PFM12060 = protection management with regeneration ins slit-shaped gaps).

Rock size	Management year	BAU 2000	BAU 2020	BAU 2100	PFM1 2060
	Stems per ha	760	497	1335	1306
	Standing volume [m^3ha^{-1}]	476	202	240	335
	Low volume area[a] (%)	3	50	7	0
0.3 m	v_{mean} [ms^{-1}][b]	10.5	11.4	9.7	10.4
	h_{mean} [m][b]	1.5	1.8	1.3	1.5
	v_{target} [ms^{-1}][c]	9.3	10.2	9.0	9.2
	$PE_{<50m}$ [%][d]	18.9	5.8	22.9	19.6
	$PE_{\geq 50m}$ [%][d]	76.3	44.1	84.9	77.8
	$PE_{\geq 300m}$ [%][d]	94.7	65.9	84.9	99.5
0.5 m	v_{mean} [ms^{-1}][b]	10.7	11.9	10.0	10.7
	h_{mean} [m][b]	1.7	2.0	1.5	1.7
	v_{target} [ms^{-1}][c]	9.6	10.7	8.9	9.3
	$PE_{<50m}$ [%][d]	18.6	6.9	23.9	21.6
	$PE_{\geq 50m}$ [%][d]	73.5	44.9	86.5	74.9
	$PE_{\geq 300m}$ [%][d]	96.2	66.4	98.6	95.2
1 m	v_{mean} [ms^{-1}][b]	11.7	13.1	11.2	11.9
	h_{mean} [m][b]	2.3	2.7	2.2	2.3
	v_{target} [ms^{-1}][c]	10.0	11.4	9.7	10.1
	$PE_{<50m}$ [%][d]	15.0	2.7	19.7	13.4
	$PE_{\geq 50m}$ [%][d]	68.7	38.6	73.2	64.3
	$PE_{\geq 300m}$ [%][d]	89.9	53.0	86.7	82.9

[a]Share of slope area with standing volume < 10 m^3 ha^{-1}.
[b]Average values for the full trajectory.
[c]Mean velocity at the road over all trajectories that reach the road.
[d]Protection efficiency for rocks that started (1) less than 50 m, (2) more than 50 m, and (3) more than 300 m (projected) above the road.

For well-stocked forests (BAU-2000, BAU-2100, PFM1-2060), usually more than 2/3 of the rocks that started more than 50 m upslope the road were effectively stopped by the forest ($PE_{\geq 50\mathrm{m}}$). The $PE_{\geq 300m}$ for rocks starting more than 300 m upslope the road was between 82% and 99% for well-stocked forests and between 52% and 67% for BAU-2020. However, only few rocks from those distant sources reached the valley bottom at all, either due to the geomorphology itself or due to obstacles on the slope. This is also illustrated by Figure 5, visualizing the number of traversing trajectories per 10 × 10 m pixel that subsequently reach the road at the foot of the slope. Generally, larger rocks reached the road also from larger distances, with increased frequency if standing timber stock was reduced by shelterwood cuts in the BAU scenario. A dense forest cover (BAU-2100) effectively protected against small rocks from larger distances.

Discussion

A new combination of simulation tools was used to assess the long-term implications of different forest management regimes on timber production and rockfall protection at slope scale. Before the simulated indicators for these two key ecosystem services in mountain forests are discussed, the assessment approach as such needs to be carefully scrutinized.

Modeling approach

In this contribution the application of PICUS Rock'n'-Roll, a recently developed coupled rockfall and forest modeling framework (Woltjer et al. 2008; Rammer et al.

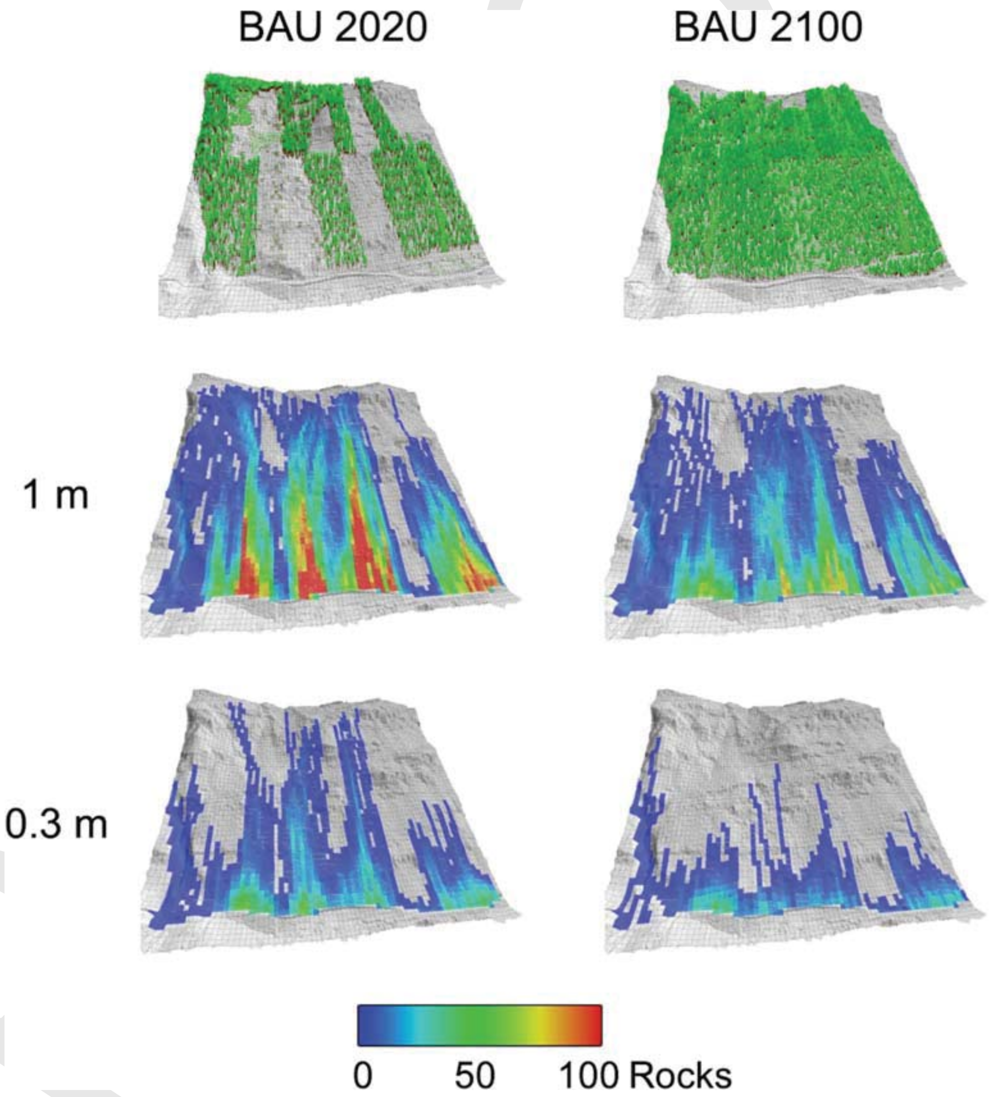

Figure 5. Effect of vegetation state (top panel) and rock size on rockfall protection efficiency (central and bottom panel). Colors indicate the number of rocks crossing a pixel (10 × 10 m) that subsequently reach the road at the valley bottom (out of N = 33977 simulated rock trajectories) for rock sizes of 1.0 m (central) and 0.3 m (lower panel). Vegetation states are taken from the BAU scenario (BAU2020 = regeneration stage, BAU2100 = dense pole and small timber stages).

2010) to a case study in the Austrian Alps, has been demonstrated. The coupled model approach extended the utility of the individual models for scenario analysis in several ways. First, the spatial scale of the combined assessment was extended beyond the stand scale that is used by the forest model. Second, the rockfall assessment was run repeatedly against changing forest vegetation over time, thus allowing to extend the assessment of rockfall protection efficiency from a single point in time to a full rotation period. And third, the implementation of different spatially explicit management regimes enabled to study the effects of silvicultural regimes on the trade-off relationship of rockfall protection and timber production.

The model coupling approach has, however, also a number of limitations. Forest simulations were still based on individual forest stands that are simulated sequentially and thus do not permit interactions between stands. The approach can therefore only be applied as long as landscape processes such as species migration or disturbance regimes operating at larger scales can be neglected. Furthermore, a dynamic feedback from the rockfall model to the forest model has not been considered. This limitation may hamper the applicability in areas with high rockfall frequencies and thus frequently damaged trees. However, as long as no robust estimations of real rockfall frequencies in a study area are available, generalized rockfall analyses as performed in the current study are justified.

Data requirements and alternative analysis approaches

Applying coupled rockfall and forest simulation on slope scale requires detailed input data for both the rockfall and the forest model. For this study, a high-resolution digital elevation model as derived from airborne laser scanning data and a field survey were employed to map rockfall source areas and surface properties, which in turn were then used to infer rockfall parameters from the literature. In addition, standwise forest inventory and detailed slope-scale management planning was necessary to provide the input data for the forest model. The applicability of the simulation approach may therefore be hampered in practice by high efforts for data collection, especially when the spatial extent of the project area is large. This problem could be tackled in different ways: one option is to include a first, large-scale "scanning" phase to select areas with high rockfall intensity or relevant protection objects and concentrate subsequently on those slope sections for further data collection and analysis. Such areas could be determined by simulations based on digital elevation models without considering forest vegetation. This approach could reduce the efforts and costs of fieldwork considerably.

A second option is to utilize approaches that rely more on (increasingly available) remote sensing data and less on (expensive) field-based data collection. Remote sensing data could be used to (partially) substitute and enhance terrestrial forest inventories (Van Leeuwen & Nieuwenhuis 2010), e.g. to generate spatially explicit realistic forest structures for large areas. If the technical know-how or the data requirements regarding rockfall processes limit the application of the proposed simulation approach, indicator-based protection forest assessment schemes (Frehner et al. 2005) are a possible fall-back option. However, such approaches miss the explicit spatial dimension in assessing the protection effect of forests and are thus of limited value at scales beyond the stand level.

Assessment results

The results of the current study demonstrated that silvicultural regimes, specifically designed for protection forest management, can outperform the business as usual strategy with regard to both timber production and rockfall protection when also mid- to long-term implications are considered. The protection forest management regimes succeeded in maintaining a high level of rockfall protection over the full simulation period of 100 years while enhancing the resilience of the forest by initiating a continuous regeneration process. By concentrating the timber removals in slit-shaped gaps, efficient logging is possible and harvesting costs are kept at acceptable levels. In contrast, BAU showed phases with significantly reduced rockfall protection efficiency and negative contribution margins. This aligns well with results from Cordonnier et al. (2008) who found that management regimes that aim at creating a shifting mosaic of small patches of different development stages provide long-term stand stability, resilience, and sufficient rockfall protection. However, the BAU approach performed better than PFM1 and PFM2 with regard to overall timber production (on average 17% and 14% more volume ($m^3ha^{-1}yr^{-1}$) than PFM1 and PFM2, respectively) mainly due to an earlier transformation to younger and more productive stands, but also due to a decreased standing stock. However, BAU performed poorer economically, because tending operations in earlier stand development stages – which are required to increase and maintain tree and stand stability – yielded very small or even negative contribution margins. Thus, moving from age class shelterwood systems to small scale interventions in steep terrain can be economically viable, even if installation times of cable yarding systems are a significant cost factor in mountain forest management (Stampfer et al. 2006).

The studied forest consists of mostly mature to overly mature forest stands, which is a widespread situation in Alpine protection forests due to a lack of forest road infrastructure and low productivity. In BAU this imbalance resulted in parallel stand regeneration cuts at relatively large shares of the study area. Given that management can be coordinated among owners, the spatiotemporal pattern of stand regeneration cuts could be further optimized. The benefits of coordinating management interventions in small scale ownership structures is also supported by the finding that for a reasonable high probability to stop a falling rock a forested slope of up to 300 m may be required (compare Table 6). Also, the mix of management strategies has potential to improve protection efficiency and cost effectiveness. However, in small scale ownership structures this requires benefit sharing approaches.

Given the initial age structure and stand conditions, the NOM scenario maintained reasonable protection efficiency for several decades. However, the long-term consequences of missing targeted management interventions are decreasing rockfall protection efficiency and the build-up of a "regeneration debt," which negatively affects the functional resilience of the system.

It should also be noted that the simulations did not consider browsing by ungulates or disturbances such as bark beetle infestations. Given the high browsing pressure at present, regeneration success might be overestimated in all scenarios (compare Didion et al. 2009). Considering bark beetle related mortality would likely lower the rockfall protection efficiency, particularly for the NOM scenario. While current disturbance intensity is relatively low this may change under warmer conditions of climate change (Seidl et al. 2011a, 2014; Pasztor et al. 2014).

The study provides also more general insights into the effects of forest structure on rockfall protection. Specifically, we found a strong effect of forest management on the simulated run out distances and consequently on the amount of rocks that reached the protection objects. Effects on rock velocities, rebound heights, and accumulated energies were consistent but less pronounced, as the geomorphology of the slope allowed rocks to regain high speeds quickly. We were also able to confirm the effect of rock size on rockfall protection efficiency: smaller rocks are more effectively stopped by dense forests while trees with high biomass are more effective in stopping large rocks (Figure 3, see also Dorren et al. 2007). Generally, rockfall protection management regimes that avoid large gaps and maintain a sufficiently large number of stable trees per ha (*sensu* Frehner et al. 2005) were successful in regenerating the forest while continuously providing a high degree of rockfall protection.

From the operational perspective it is important to note that concentrating the removals of trees within slit-shaped gaps reduces damages to residual trees and advance regeneration and positively affects the productivity of harvesting operations compared to more dispersed removal pattern. Management measures to increase the roughness of the slope, e.g. to leave cut tree trunks or high stumps on site (Dorren et al. 2005; Frehner et al 2005) were not implemented in this study, but can temporally further improve the protective effect.

While it is important to note that care must be taken in directly transferring the results as initial forest structures affect the timing of silvicultural interventions and related protective effects, the study revealed valuable insights to the interdependencies of management interventions, timber production, and rockfall protection in mountain forests.

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