



A simulation framework for scenario-based quantification of natural hazard protection provided by mountain forests

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Abstract. Mountain forests often provide important protection against gravitational natural hazards. For this reason, developing management strategies that help maintain resilient forests withstanding climate change impacts is crucial. Existing approaches to quantify the protection against natural hazards provided by forests are often extensions of either forest or natural hazard simulation models. In both cases they tend to suffer from a rather coarse, static representation of their secondary component.

5 Simulation results thus lack the temporally integrated perspective needed when modeling the outcome of interacting, partly stochastic processes. We present a simulation framework that allows for quantitative natural hazard assessment over time as a function of forest management and climate scenarios. By linking a process-based forest landscape model with a mass movement hazard simulation model on an annual basis throughout the simulation period, we integrate the effects of climate change and captures the complex interactions of forest growth, forest disturbances and natural hazards in mountain regions - captured in
10 unprecedented detail. This repeated coupling allows annual changes in forest structure to directly affect rockfall dynamics, while rockfall-induced tree mortality feeds back into subsequent forest development. We tested the framework in a case study area in the Swiss Alps and calculated the expected development of rockfall hazard beneath a currently spruce-dominated forest slope considering different forest management intensities. The residual rockfall hazard varied between 20% and 30% depending on the forest management scenario. Rock size and forest basal area had the strongest influence on protection efficiency. We
15 deem the modeling framework suitable for scenario analysis in quantitative risk assessment, especially after disturbance events, as well as for identifying strategies to increase forest resilience in times of climate change. In conjunction with economic data on forest and infrastructure, the modeling framework even allows for integrated economic cost-benefit analysis of forest and natural hazard management.



1 Introduction

20 Mountain forests provide multiple of ecosystem services (ES), among which protection against natural hazards is a particularly relevant. The latter may include avalanches, rockfall, debris flows and shallow landslides (Brang et al., 2006; Moos et al., 2018a). Previous studies have shown the enormous economic benefits in the form of prevented natural hazard damage based on the analysis of past events (Teich and Bebi, 2009; Grêt-Regamey et al., 2013). Protection forests can thus be seen as an example of nature-based solutions for hazard risk reduction, or so-called “ecosystem-based disaster risk reduction” (Eco-DRR, Estrella
 25 and Saalismaa (2013); Moos et al. (2018a)). Maintaining the protection function by managing them is therefore a priority in hazard-exposed areas (Brang et al., 2006; Bebi et al., 2016).

Research has disentangled a number of factors influencing how well forests protect against natural hazards. Important hazard properties for rockfall are e.g. lithology (Lanfranconi et al., 2020), rock size (Umili et al., 2020) and shape distribution (Ringebach et al., 2023; Lu et al., 2021; Caviezel et al., 2021). After the onset of an event, hazard propagation is influenced
 30 by the slope and forest properties (tree diameter distribution, basal area, age structure, species distribution, crown and ground cover, lying deadwood and gap size) (e.g. Dorren et al., 2004; Bebi et al., 2009; Moos et al., 2017). A comprehensive overview is given by Moos et al. (2018a). As mountain forests are ecosystems strongly characterized by abiotic disturbances, forest properties may vary largely over time. Disturbance legacies and forest resilience are thus two more key factors influencing ES provisioning (Seidl et al., 2014a, b; Maringer et al., 2016; Albrich et al., 2018; Seidl et al., 2019).

35 Many mountainous regions have established forest management systems for hazard control. An example is the Swiss management framework for forests with a protective function: It is based on research, expert knowledge and practical experience and has a strong focus on disturbance resilience. Forest managers can draw on a collection of target forest profiles for a range of hazards and site conditions (“NaiS”, BAFU, 2025; Frehner et al., 2005).

Although protection forests are highly appreciated by the local population, the regulating ES they provide have long been
 40 seen as a by-product of traditional forest management (Schuler, 1995), which has come under economic pressure due to falling timber prices and rising management costs. At the same time, urban expansion and rising property prices have led to an increase of the value exposed to natural hazards (Moos et al., 2018b). In Switzerland, the funding gap for protection forest management has so far been mitigated by public actors such as cantons or municipalities. However, the need to balance multiple ES such as timber production, protection, biodiversity and carbon sequestration makes resource allocation challenging. And the economic
 45 challenges could in the future be exacerbated by climatic changes disrupting the complex interactions between the forest and biotic as well as abiotic disturbance agents, annihilating management efforts and leaving villages unprotected after forest calamities (e.g. Seidl and Rammer, 2017).

In the literature, there is a general consensus that it is beneficial to incorporate forest disturbances and resilience in planning and some studies demonstrate how this can help avoiding economic losses in production forests (Brunette et al., 2015; Breteau-
 50 Amores et al., 2019) or underprovisioning of certain ecosystem services (Albrich et al., 2018; Seidl et al., 2019). Regarding mountain forests with the main purpose of providing protection against gravitational natural hazards, however, some studies question the cost-effectiveness of expensive active management regimes (both pre- and post-disturbance events) in comparison



to passive management (Krumm et al., 2011; Hagge et al., 2019; Dobor et al., 2020; Vanická et al., 2020). The debate even extends to climate adaptation, with some authors advocating proactive adaptation measures (Brang et al., 2013) while others suggest that passive management would be cheaper while equally effective or even superior (Krumm et al., 2011).

Predictive risk assessment tools are needed to evaluate management strategies under climate change.. However, there is no common standard for calculating the economic value of ecosystem-based disaster risk reduction (Dorren and Moos, 2022). And there is a lack of predictive risk assessment tools being able to provide the data for economic cost-benefit analysis with an avoided damage approach as it is advocated by Dorren and Moos (2022): When natural hazard simulation tools are used for quantitative risk assessment they usually assume a fixed forest state and thus neglect forest development over time and in the future (e.g. Berger and Dorren, 2007; Bigot et al., 2009; Dupire et al., 2016; Maringer et al., 2016; Moos et al., 2018b, 2019; Lanfranconi et al., 2020). And when forest models are used to forecast regulative ES, the protection function is usually quantified by indicators using forest structural data (e.g. Jancke et al., 2009; Accastello et al., 2019).

To overcome these limitations, a first attempt has been done by Moos and Lischke (2022), by linking the rockfall model *Rockyfor3D* with the dynamic forest landscape model *TreeMig*. However, this integration does not constitute a fully dynamic coupling, as the rockfall-forest feedback is incorporated via precomputed statistical relationships: Rockfall intensity maps for various forest states were simulated in advance, and local growth hindrance was then derived from these precomputed conditions. While advanced, this approach neglects natural forest evolution. In reality, dead trees increase available light and create forest floor structures that enhance regeneration and growth conditions. Such small-scale changes are inadequately represented in precomputed models.

To address the aforementioned limitations, we have developed a novel simulation framework that dynamically couples a gravitational natural hazard model with a forest landscape model. This integration operates at a real-scale temporal resolution, effectively capturing the natural variability and return periods of rockfall events. By simulating both forest dynamics and rockfall processes within the same temporal framework, we can more accurately assess the interactions and feedback mechanisms between forest development and rockfall activity. This approach allows for a comprehensive evaluation of how different climate change scenarios, disturbance regimes, and forest management strategies influence residual rockfall risk over time. In this article, we first detail the technical aspects of this integrated modeling framework. Subsequently, we present a case study in Davos, Switzerland, demonstrating its application by quantifying the effects of various climate change, disturbance, and forest management scenarios on the residual rockfall hazard.

2 Methods

2.1 Modeling framework and its components

The simulation framework integrates natural hazard – forest growth feedback at a suitable temporal and spatial scale, to capture their dynamic interactions. Rockfall exposure is highly site specific and depends on topography, geology, forest structure and the infrastructure location, requiring fine spatial detail (meter scale). A single-tree representation improves rockfall simula-

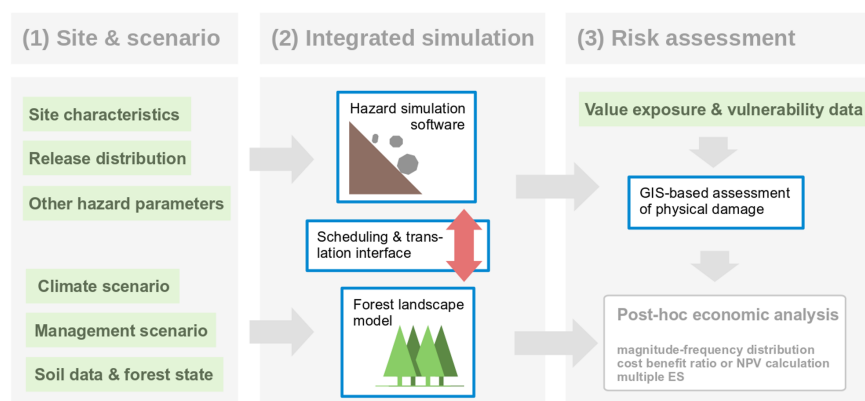


Figure 1. Schematic representation of the simulation framework and its main components. Input data on site, hazard and forest scenario form the input for the integrated simulation. In a third step, outputs are postprocessed and risk assessment is performed. The outputs can be combined with economic data for an economic analysis.

85 tions accuracy (Ringebach et al., 2023) and allows direct integration of hazard induced tree mortality into forest dynamics simulations.

In contrast to conventional rockfall modeling approaches that assume large numbers of rocks starting at each release point, we simulate stochastic event sequences with realistic return periods and rock volumes. This avoids unrealistic overloading of the forest while allowing close-to-nature interaction between rockfall and forest development. Rockfalls are treated as low-
 90 frequency events, reflecting the geological erosion processes of mountain ridges. To account for stochastic variability between single model runs, 200 replications are simulated for each scenario. For meaningful economic analysis of forest management strategies, the simulated area should at least cover whole mountain slopes or forest management units and simulated time spans should be several decades or longer. The need for both fine spatial resolution and a relatively large simulation extent was a determining factor when selecting the components of the modeling framework (Dorren et al., 2006, 2007; Vo, 2015; Moos
 95 et al., 2017).

The main components of the modeling framework are schematically represented in Figure 1. The framework provides three important new capabilities for forecasting the economic outcomes of different management strategies on a landscape level:

- A temporally integrated analysis of interactions between disturbances, management and forest growth to capture non-linear reactions of the ecosystem (protection gaps, disturbance legacies)
- 100 – A precise quantification of (residual) natural hazard damage
- An estimation of forecasting uncertainties caused by stochastic processes

Besides providing data for predictive cost-benefit analysis of forest management strategies, the simulation framework allows for a range of other applications: It facilitates (1) predictive quantitative hazard risk assessment for specific locations (a house to be built), as well as (2) studying the factors influencing hazards (slope, forest, climate etc.), (3) understanding the influence of



105 disturbances on ES, (4) testing and improving forest management strategies. Finally, it allows for (5) studying different sources of uncertainty (stochastic variation, scenario uncertainty). For the hazards included, we started with rockfall with avalanches being in preparation. The simulation framework is, however, designed in a modular way so that it can easily be extended with additional forest disturbance or natural hazard simulation modules (Sect. 4.3).

2.1.1 Forest model

110 The individual based forest landscape simulator iLand (Seidl et al., 2012a) was used to simulate forest dynamics. iLand operates across scales, representing seedling and sapling as cohorts, and modeling trees individually once a diameter at breast height (dbh) exceeds 8 cm. including assigned x-, y-coordinates on a grid with the finest available spatial resolution of 2 m. Net primary productivity (NPP) is calculated based on light availability and light use efficiency with allocation to individual trees via spatially explicit light competition. This enables effective computation even for large areas. Disturbance modules for wind, 115 bark beetle, and fire complement the growth simulation (Seidl et al., 2014a; Seidl and Rammer, 2017). Climate sensitivity is incorporated using monthly temperature and precipitation data on a 100 m by 100 m grid. With the different disturbance modules, iLand represents all ecologically relevant processes in mountain forests (Seidl et al., 2012a). Key model parameters have been validated for mountain forests in the Alps (e.g. Seidl et al., 2012a; Albrich et al., 2020). In a model comparison, iLand showed high realism for the study region (Petter et al., 2020). The model offers a flexible programming interface for 120 management and external coupling (Rammer and Seidl, 2022a). Its open-source code facilitates custom extensions if required. Forest starting conditions (tree species, diameter distributions, sapling and regeneration cohorts, and the soil inputs nutrient availability, water pools and seedbed properties) are initialized at 100 m resolution, typically using spin-up simulations (Seidl et al., 2012b; Rammer and Seidl, 2022b). Disturbance modules require corresponding input data. Management actions are implemented via the model's JavaScript interface, supporting both fixed schedules and dynamic management strategies depending on forest state (Rammer and Seidl, 2022b). Agent-based decision modeling is also supported (Rammer and Seidl, 125 2015, 2022b).

2.1.2 Hazard model

Process-based simulations of single hazard events are required, with protection forest structure directly influencing rockfall dynamics and receiving feedback from hazard impacts (Dorren and Moos, 2022). Rockfall runout distances and energies were 130 simulated using the 3D model RAMMS::Rockfall (Caviezel et al., 2019), which accounts for impacts on individual trees based on their spatial position and dbh. RAMMS flags trees destroyed by the rock impacts; recent extensions allow inclusion of lying deadwood (Ringebach et al., 2022a). The model requires a fine-scale digital terrain model and soil mechanical parameters per soil type (Caviezel et al., 2019). In future applications, lying deadwood will be included to assess its barrier effect in protection forest management scenarios (e.g. Ringebach et al., 2022b, 2023).



135 2.2 Combined simulation setup

We developed a simulation framework that dynamically couples iLand with gravitational hazard modules via a standardized interface. This novel framework consists of three processing steps (Fig. 1): (i) simulation setup and stochastic hazard scheduling, (ii) simulation execution and model coupling, including data translation between forest and hazard modules, and (iii) postprocessing and analysis of the simulation outputs. The following subsections describe these components in chronological
 140 simulation order. Further details and commented source code are provided in the supplementary materials. While the simulation framework includes a functional avalanche module under development, only the rockfall component was used in the present case study. Avalanche processes were not simulated in this work but are intended for future applications.

2.2.1 Setup and Scenario generation

At every possible release point, the scenario generator initializes each simulation by scheduling stochastic hazard events based
 145 on user-defined scenarios. For each decade, it randomly assigns whether and which rock sizes are released, based on calibrated rock volume–return period distributions. Template setups of iLand and RAMMS are automatically adjusted according to the values specified in a single configuration file. We accounted for variance induced by stochasticity in climate and hazard releases, the scenario-generator offers an option to set up multiple replications of the same scenario. In this case, the hazard scheduling algorithm uses a list of random seeds provided in the configuration file. This feature can even be used to enforce identical hazard
 150 release patterns when comparing different management or climate scenarios. Within this framework, RAMMS::Rockfall needs a volume-return periods-calibrated rock library, where the different rock volumes are already prepared for each return period and a list of all potential rockfall release points. With this setup, it is possible to randomly determine for each year and each release point whether an event occurs and, if so, with what probability.

While forest simulation scales efficiently even for hundreds of hectares, the initialization of trees in RAMMS that needs to
 155 be repeated for every single event is a computational bottleneck when performed for large areas. For this reason, we subdivided the landscape into hazard simulation domains shaped according to rockfall or avalanche runout areas. The initial effort is slightly higher as multiple template setups need to be prepared, but the computational effort is reduced significantly. As each hazard simulation domain is treated separately by the scenario generator, domains can be used to accommodate multiple hazard release areas with differing characteristics (e.g. rock type or release frequency) in a single simulation landscape.

160 2.2.2 iLand natural hazard extension – main simulation

The forest information is translated from the iLand output into the necessary RAMMS::Rockfall input format during each loop. As within iLand, the trees are placed exclusively on the grid points of a 2m-by-2m raster, their position is randomly uniform-distributed within this confinement, in order to prevent rocks traveling unhindered through an alley of trees.

The components involved in the main simulation are represented in Figure 2, red numbers denote the chronological order of
 165 processing steps. A typical simulation run is initiated by starting the iLand simulation and a scheduling process administering the hazard events to be simulated. Forest development including management operations is then simulated until a natural

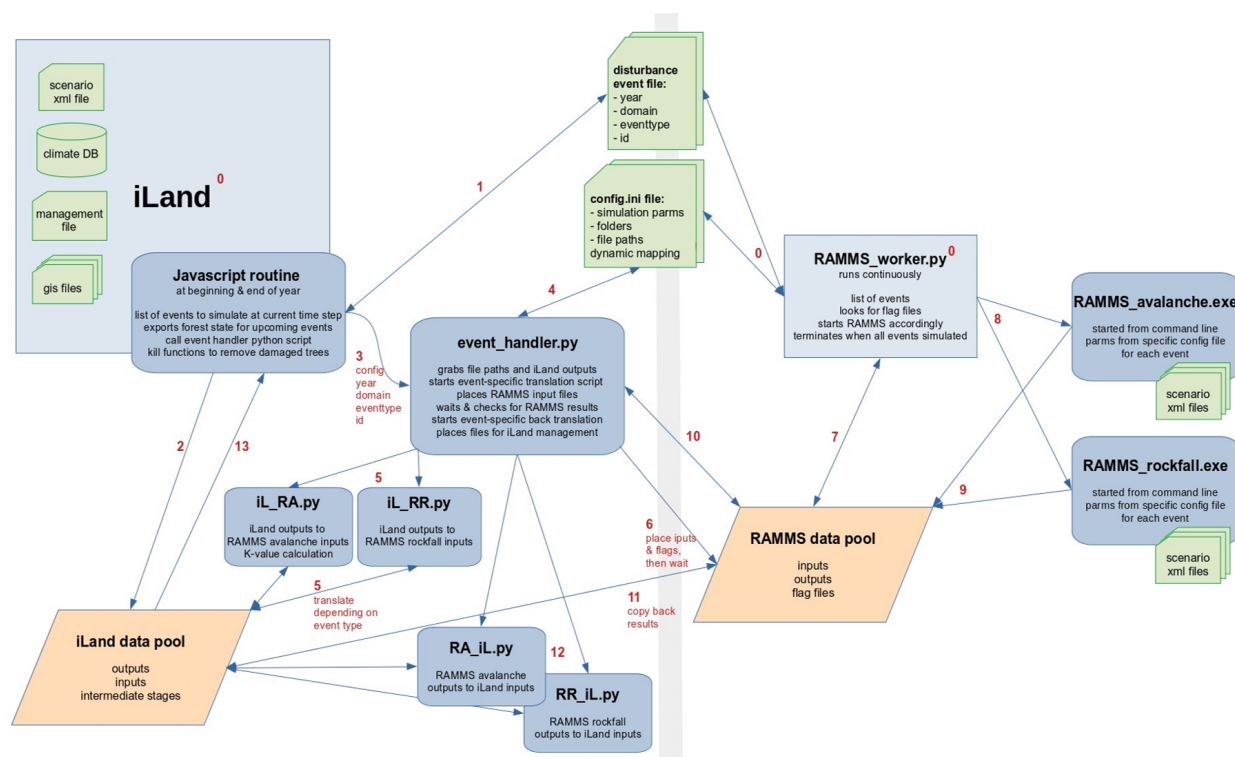


Figure 2. Conceptual representation of the main components of the simulation framework, without setup and postprocessing algorithms. Green boxes represent input data and scenarios, blue boxes represent the core processing parts of the simulation framework, orange boxes represent intermediate data and simulation outputs. Red numbers denote the chronological order of processing steps in case of a hazard release event.

hazard event occurs. In this case, all forest parameters required for the specific event type and release domain are exported. The forest simulation is paused, and the scheduling software calls the suitable script per natural hazard type from the translation library to convert iLand outputs into RAMMS::Rockfall input. These include tree species, dbh and total height translated into the necessary tree-file, from which RAMMS::Rockfall creates three-dimensional cones at the corresponding tree positions (Lu et al., 2021). When all input files are in place, the scheduling software calls the natural hazard simulation executable and waits for results. In RAMMS::Rockfall, rocks are deflected by trees or destroy them trees at impact, depending on energy thresholds as derived by (Dorren et al., 2005) combined with factor (Ringebach et al., 2022a). Once the hazard simulation is completed, the scheduling software triggers the suitable back-translation script and hands back to iLand, which removes destroyed trees via the management interface and subsequently resumes forest simulation until the next hazard event or until the simulation period ends. The framework is capable of handling multiple hazard events during the same year. As hazard simulations are not directly invoked by iLand but by a separate process waiting for input files, forest and hazard simulations can be executed in separate processing environments with dedicated hardware, requiring only a shared storage.



2.2.3 Output data postprocessing

180 The simulation framework generates an extensive range of outputs from both forest and hazard modules. An overview of the simulated and post processed outputs is provided in Table A1. Forest-related simulation results are stored in an SQLite-database, and include single tree data, stand or landscape aggregates on forest structure and productivity, disturbance effects, mortality, soil, water and carbon cycle as well as management outcomes. The level of detail is adjustable as described by Seidl et al. (2012a) and the iLand manual (Rammer and Seidl, 2022b). Hazard simulation results, beyond tree destruction,
 185 are stored in RAMMS binary formats. The framework includes scripts for bulk-conversion of RAMMS output files to text or GIS-readable file formats. The resulting hazard intensities can be used for assessing the physical damage done during hazard events or for calculating established hazard risk metrics. To keep case study results comparable to similar studies and avoid variance induced by placement and value of objects at risk, we defined the valley bottom as evaluation area or an uniform object at risk (blue area in Fig. 3). Currently, the simulation framework includes Python and R code for calculating a set of
 190 widely used rockfall risk metrics: First, the Residual Rockfall Hazard (Berger and Dorren, 2007), defined as the ratio between the totally released rocks and those reaching the evaluation area. Second, to get an estimate for the reliability of the protective function achieved by different management strategies, we compared the variances within our envelopes of replications for the different scenarios by calculating the coefficient of variation on the number of rocks reaching the valley during the 20 different replications. Third, the Energy Efficiency Index (EEI, Lanfranconi et al., 2020) quantifying how fast and efficient forest reduces
 195 rock kinetic energy. It is defined as

$$EEI = 1 - \left(\frac{AUC_{\text{forest}}}{AUC_{\text{noforest}}} \right) \quad (1)$$

where AUC is the area under the curve of kinetic energy as a function of distance from the rockfall release point. It approaches 1 if the rock is stopped immediately and 0 if the forest has no energy reduction effect. Fourth, the residual kinetic energy (Dupire et al., 2016) grouped within three rock size / annuity classes when reaching the evaluation area and furthermore,
 200 the Abbreviated Ultimate Characteristic (AUC) of kinetic energy during a rockfall trajectory.

2.3 Extension Modules and Current Implementations

The modular structure of the simulation framework facilitates its extension to additional natural hazards and ecosystem services. To integrate a new natural hazard module, four steps are typically required: (1) preparing a sample simulation setup, (2) adding event and setup generation code to the scenario generator, (3) developing the two-way translation library between
 205 the hazard model and the forest model, and (4) implementing flags and commands to call the module executable in the event handler and daemon.

For avalanches, steps (3) and (4) have already been completed (see Fig. 2). Avalanche pressures are intended to be simulated using `RAMMS::Extended` (e.g. Ortner et al., 2025b), an advanced version of the well-established `RAMMS::Avalanche` model (Christen et al., 2010). This model allows for spatially explicit simulations of avalanche impacts and provides tree



Table 1. Table captions

Component	Output Type	Output Details	Spatial scale	Temporal Scale
iLand	Single trees	Species dbh, height, vol, ba age leaf area compartment masses light response stress	2x2 m	1 y
	Stand aggregates	Tree species distribution tree size distribution regeneration & saplings biomass compartments soil parameters water cycle carbon cycle	100x100 m	1 y
	Landscape aggregates	e.g. Biomass	Whole area	1 y
	disturbances	Barkbeetle damage wind damage fire damage	Whole area	1 y
	mortality	age mortality stress mortality disturbance mortality extraction	100x100 m	1 y
	management	Single trees removed - para-meters & reason for removal extracted timber volume	2x2 m 100x100 m	1 y
RAMMS::Rockfall	Rockfall trajectories	Position velocity & rotation kinetic energy	Exact position	Single event, 0.01 sec
	Tree impact	Killed trees Damaged trees	Exact position	Single event
	Hazard risk indices (postprocessed)	Rockfall release distribution	Hazard domain	simulation period
		Residual rockfall intensity	Hazard domain	simulation period
Var(RRH)		Hazard domain	envelope of reps	
AUC kinetic energy		single event	single event	
Energy Efficiency Index		Hazard domain	simulation period	
	residual kinetic energy	single event	single event	
RAMMS::Avalanche	Avalanche runout grids	Maximum tree pressure	Arbitrary 5x5 m default	Single event
		Maximum momentum		
		Maximum velocity		
		Maximum core pressure		
		Maximum avalanche height		
		Maximum pressure velocity		
		Maximum pressure density		
		Deposition height		
		Density		
		Detrainment		
Height				
Tree impact	Tree destruction	Arbitrary 5x5 m default	Single event	
Hazard risk indices (postprocessed)	-			



210 destruction information at a fine resolution ($5\text{ m} \times 5\text{ m}$ grid), which is directly fed into the forest simulation by flagging destroyed trees. The translation between RAMMS : :Extended and iLand primarily requires the definition of the forest's roughness parameter, the so-called *k-value*, which reflects forest density and structure (Feistl, 2015; Feistl et al., 2015). This parameter accounts for avalanche snow detrainment effects behind trees, thereby capturing the forest's protective function.

2.4 Case study area

215 To demonstrate the capabilities of the simulation framework, we simulated forest development under different management and climate scenarios in the *Dischma valley* case study area and calculated the related rockfall risk metrics for each scenario. This case study is a southeastern side valley of Davos in the Canton of Grison, Switzerland (Fig. 3). The surrounding peaks rise between 2500 and 3150 m whereas the valley bottom sits at about 1600 m a.s.l. Temperatures in the valley range from -10°C in winter to $+20^{\circ}\text{C}$ in summer, annual precipitation is 1023 mm (MeteoSwiss, 2025). Most of the valley has historically been
 220 used for farming activities and trees were cut for firewood, timber and mining activities, which has led to partial deforestation on the slopes of the valley (Bebi et al., 2017). Stricter forest laws and since the 1980s even state subsidies for protection forest management have led to an increase in forest cover and density during the past decades (Sandri et al., 2017). Nowadays, the forest in the valley is dominated by Norway spruce (*Picea abies* (L.) Karst.). On drier sites near treeline the Swiss stone pine *Pinus cembra* occurs. In frequently disturbed avalanche runout zones and towards the treeline the European larch (*Larix*
 225 *decidua*) is common. The main abiotic forest disturbances are avalanches, storms and rockfall, they interact with bark beetle as a major biotic disturbance agent. Avalanches and rockfall are even the main natural hazards threatening buildings and infrastructure in the valley.

2.4.1 Rockfall scenario

Both slopes of the valley are steep and potential release areas for both avalanches and rockfall, yet some cliffs on the southern
 230 slope are the major source of rockfall events. We determined the potential release areas (PRA) according to a simplified slope angle distribution analysis (Ringebach et al., 2022a) based on the a 2 m resolved DEM (swisstopo, 2018) and a 5-by-5 cells focal neighborhood analysis. Grid cells $< 43^{\circ}$ were ignored as potential release areas, inclinations up to 55° were weighted single, and cells $\geq 55^{\circ}$ double. Only PRAs $> 50\text{ m}^2$ were considered (preventing too large fragmentation of the release areas). This process resulted in 365 PRA-polygon comprising more than 10^5 grid cells, of which every 25th cell was picked and used
 235 as one of the 4462 starting points. Based on the topography of the slopes, common runout zones were delineated manually based on a watershed algorithm, separating the study area into 11 simulation domains (Fig. 3).

We determined the used block size distribution based on a measuring campaign of 310 deposited rockfall blocks – so-called silent witnesses – of three representative transects as well as the size of 5 specific large blocks in the valley (blue marks in Fig. 3). Based on these measurements, we estimated the rock volumes 0.4 m^3 , 0.9 m^3 , 1.6 m^3 , 2.1 m^3 and 4.2 m^3 for the return
 240 periods 1y, 10y, 30y, 100, 300y and fitted a truncated power law, as proposed by Kleinn et al. (2024, 2026). With this approach, we assigned a specific rockfall volume for every return period between 1 and 1000 years. However, Rockfall events with annuities < 10 were excluded from simulations. Mainly due to computational limitations, but also with the strong conviction

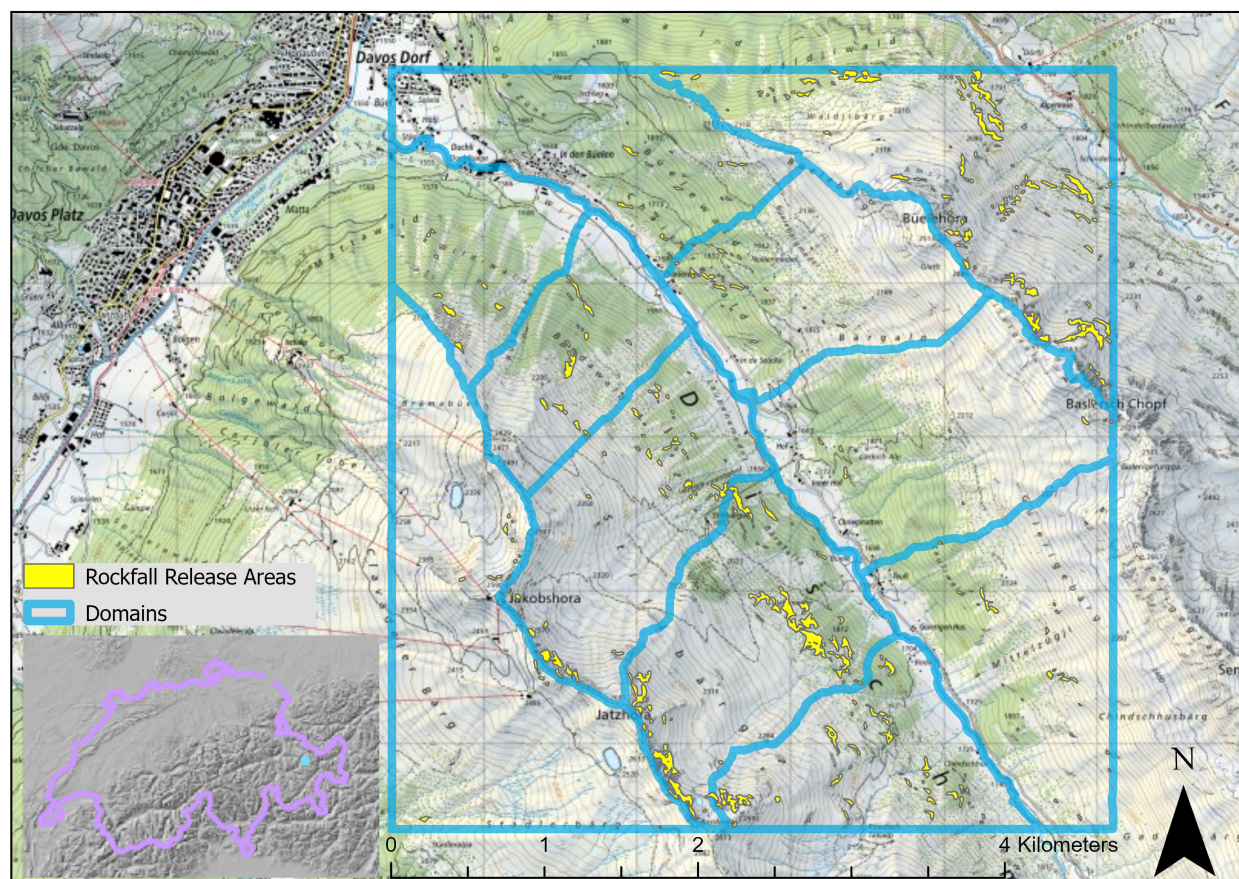


Figure 3. Location of the Dischma Valley case study area near Davos, Switzerland, showing the simulation domains (blue lines) and mapped rockfall release areas (in yellow, source of the topographical map: Federal Office of Topography).

that frequent events are better integrated into the spatial behavior pattern of people and therefore there is less endangered infrastructure is expected. Additionally, these volumes are minor resulting in lower kinetic energies. Very large rocks (annuity > 1000, size > 41 m³) were also excluded and they might bias the results due to their rare occurrence. We used solely symmetrical cubic rock shapes, known from certification tests of rockfall nets (European Organisation for Technical Approvals (EOTA), 2013), rockfall experiments (Caviezel et al., 2021; Ringenbach et al., 2023) and rockfall simulations (Ringenbach et al., 2022a; Caviezel et al., 2019). Such equant rocks are known to have a long run out distances (Caviezel et al., 2018) but feature a low lateral dispersion (Caviezel et al., 2021). We focused here solely on one shape, as the rock shapes introduces an additional stochastic dimension. Albeit the inclusion of this dimension is highly recommended for hazard assessments (Caviezel et al., 2021; Ringenbach et al., 2023), we refrain from it, primarily to reduce the number of the necessary repetition. Based on the rockfall experiments in forests (Ringenbach et al., 2023), we know additionally, that we covered the worst-case scenario.



2.4.2 Forest development and management

For the forest simulation, we used the same input data and starting conditions as Petter et al. (2020), which covered an area of 923 ha, while we focussed on a sub-area of 282 ha. Roughly half of these 282 ha are forested, the rest being pastures in the valley bottom or areas above tree line and rock faces. The forest state at simulation start is based on 910-year spin-up runs assuming unmanaged forest development disturbed by avalanches with a frequency and size distribution as observed between 1960 and 2010. Historic climate data were generated by extrapolating weather station data using topography data and the DAYMET algorithm (Thornton et al., 1997) as cited by Petter et al. (2020). Climate change scenarios were calculated by applying the delta change method to the historic data with anomalies derived from the HadGEM2-Es general circulation model (Van Vuuren et al. 2011 as cited by Petter et al. (2020)). For limiting the number of scenarios in this case study, we only used the historic dataset and the RCP8.5 scenario generated by Petter et al. (2020). To best demonstrate the capabilities of our hazard assessment framework and the possible influence of forest management, we chose the following four simulation scenarios described in Table 2.

- As a reference scenario (Scenario 1), we first simulated all rockfall events without any protection forest. This is important as even without the forest’s protective function, a certain ratio of rocks naturally stops on the slope without doing any damage.
- The second scenario is closest to the historic status quo in all regards: historic climate, bark beetle and historic frequency of abiotic disturbances as well as unmanaged forest. On the southern side of the valley, which is most relevant for rockfall events, there has in fact been almost no forest management during the past decades.
- The third scenario reflects a strong yet realistic climate change scenario combined with a management strategy focused on timber production that exceed the current regulations for forests with a protective function in Switzerland. With RCP8.5, annual mean temperatures increase around 6°C in the study area while precipitation slightly decreases (Petter et al., 2020). The probability for abiotic disturbances is set to two times the historically observed level. Forest management in this scenario assumes that timber production, not protection, is the primary management goal and that no legal constraints for management interventions apply. Proactive climate adaptation is not intended either. The imaginary forest owners try to maximize their economic output by planting even-aged spruce stands, thinning twice at stand age 50 and 80 and harvesting (clearcut) at age 150.
- The fourth scenario assumes the same climate change (RCP8.5) and disturbance scenario (two times historical level) as scenario three. However, the forest is not managed whatsoever so that this can be considered a minimum effort strategy counting on natural succession instead of proactive climate adaptation.

To enable changes in forest structure to take effect, we simulated forest development and rockfall for 200 years from 2001 throughout the year 2200. To account for the influence of stochasticity in spatial distribution and timing of rockfall release events, we simulated 20 replications.



Table 2. Simulation scenarios

	Climate	Disturbances	Forest Management
Scenario 1	-	-	no trees
Scenario 2	historic climate	bark beetle and historic disturbances	no forest management
Scenario 3	RCP 8.5	bark beetle and strong abiotic disturbances	logging and spruce replant
Scenario 4	RCP 8.5	bark beetle and strong abiotic disturbances	no forest management

285 3 Results

3.1 Forest simulation results

The baseline scenario 2 simulation realistically reproduced the current real-world distributions of species composition and standing volume along the altitudinal gradient in the valley (Fig. 4.a compared to Petter et al., 2020). Standing volume peaked at 700 m³ ha⁻¹ in the Norway spruce dominated forest at 1500 m.a.s.l. and decreases towards the treeline at around 2300
 290 m.a.s.l., with European larch and Swiss stone pine becoming more common at higher altitudes. Simulation results are very consistent between the 20 different replications.

In scenario 4, more frequent bark beetle disturbances lead to a slightly decreased standing volume of Norway spruce in the lower parts of the case study and a slightly increased proportion of European larch and Swiss stone pine. These changes were consistently observed throughout the replications. In scenario 3, the logging leads to a lower standing volume especially in
 295 the lower parts of the slope. The planting of Norway spruce on non-stocked areas leads to an upwards shift of the treeline with spruce regeneration constituting the dominating tree species in this altitude. Variance between the simulation runs is very moderate even in this scenario. However, the total Biomass is lower due to the logging and the mean tree DBH is lower as its corresponding value in Scenario 4 and as in Scenario 2.

3.2 Residual Rockfall Hazard

300 The simulated rock trajectories are plausible and well aligned with real-world observations. The difference becomes apparent when mapping a set of identical rockfall release events and comparing the trajectories on a slope with and without forest (Fig. 5). The median number of rockfall events of relevant size occurring during one simulation replication of 200 years was 21, with a minimum of 11 and a maximum of 27. Summed up over 20 replications, a total of 1612 rockfall events were simulated, 403 for each scenario. On a non forested slope (scenario 1), 75.7% of the rocks reached the valley bottom (Fig. 6). All three
 305 forested scenarios have lower rockfall reach probabilities of the evaluation area: While in scenario 2 (19.4 %) and scenario 4 (19.6 %) roughly one out of five rocks reaches the Valley bottom, the protection effect of scenario 3 is slightly lower, with one out of four rocks (26.8 %) reaching the evaluation area. The residual rockfall hazard differed significantly between scenarios (χ^2 p < 2.2e-16), even when excluding the scenario without any forest (χ^2 p = 0.015).

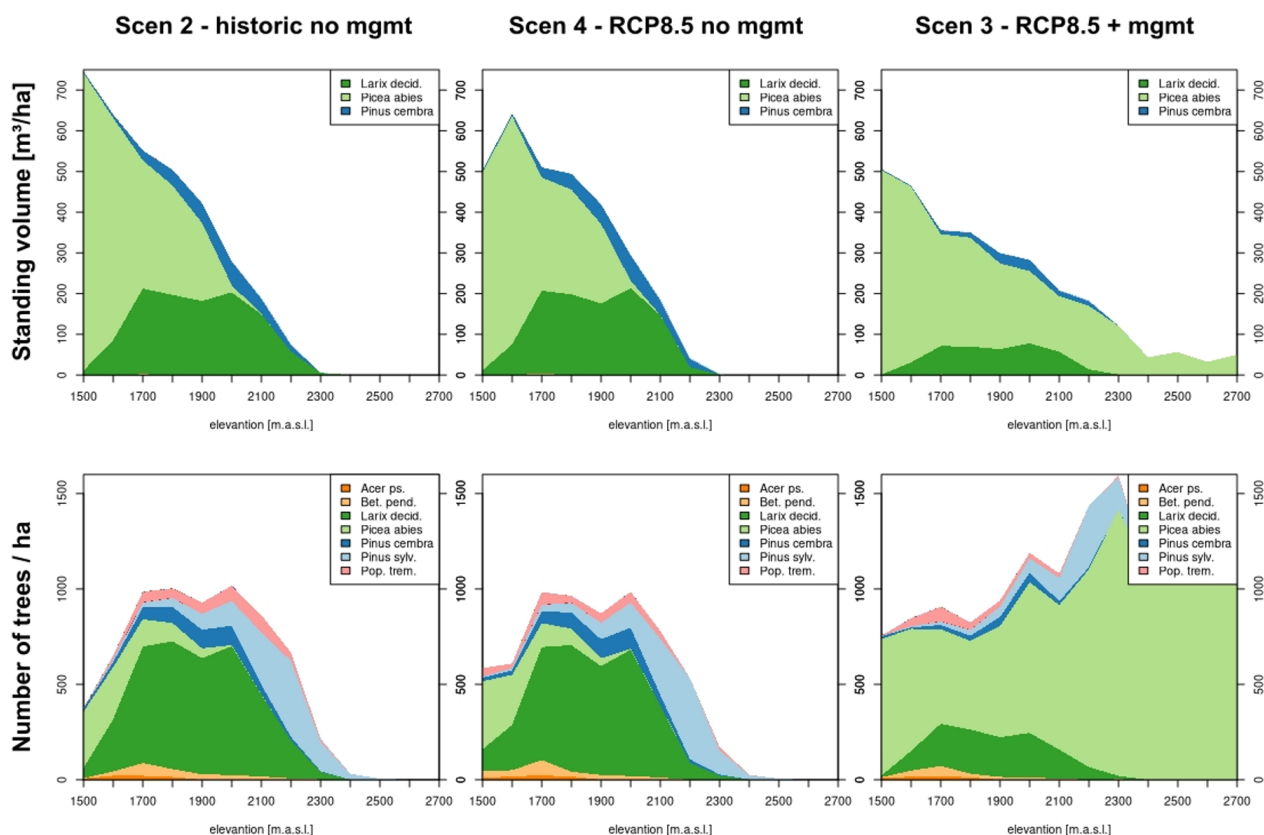


Figure 4. Simulation results for a single, representative replication: standing volume (top row) and tree count (bottom row) per hectare along a height gradient. Left column: Scenario 2 with historic climate and disturbances, no management. Middle column: Scenario 4 with future climate and disturbances, no management. Right column: Scenario 3 with future climate and disturbances, timber logging and spruce replanting.

The forest reduced the residual rockfall hazard (RRH) most effectively for smaller rocks whereas the protective function diminished with increasing rock size (Fig. 6). Climate and management scenarios had a significant effect on residual rockfall hazard resulting from smaller and medium size rocks, whereas the differences between scenarios were negligible for very large rocks.

To assess the reliability of such a directly linked simulation setup, we analyzed the variance of the number of rocks reaching the evaluation area in between the 20 replications (Fig. 7). Generally, the dispersal within the envelope of replications of each scenario is larger than the difference in median rock number between scenarios. Although the variance within the envelope of replications is much larger in scenario 1 than in the other scenarios, the coefficient of variation is actually smaller than in the other scenarios due to the larger median of the distribution. Variance is 12.1, 4.0, 5.1 and 3.3 in scenarios 1 through 4. The respective coefficients of variation are 0.23, 0.51, 0.42 and 0.46.

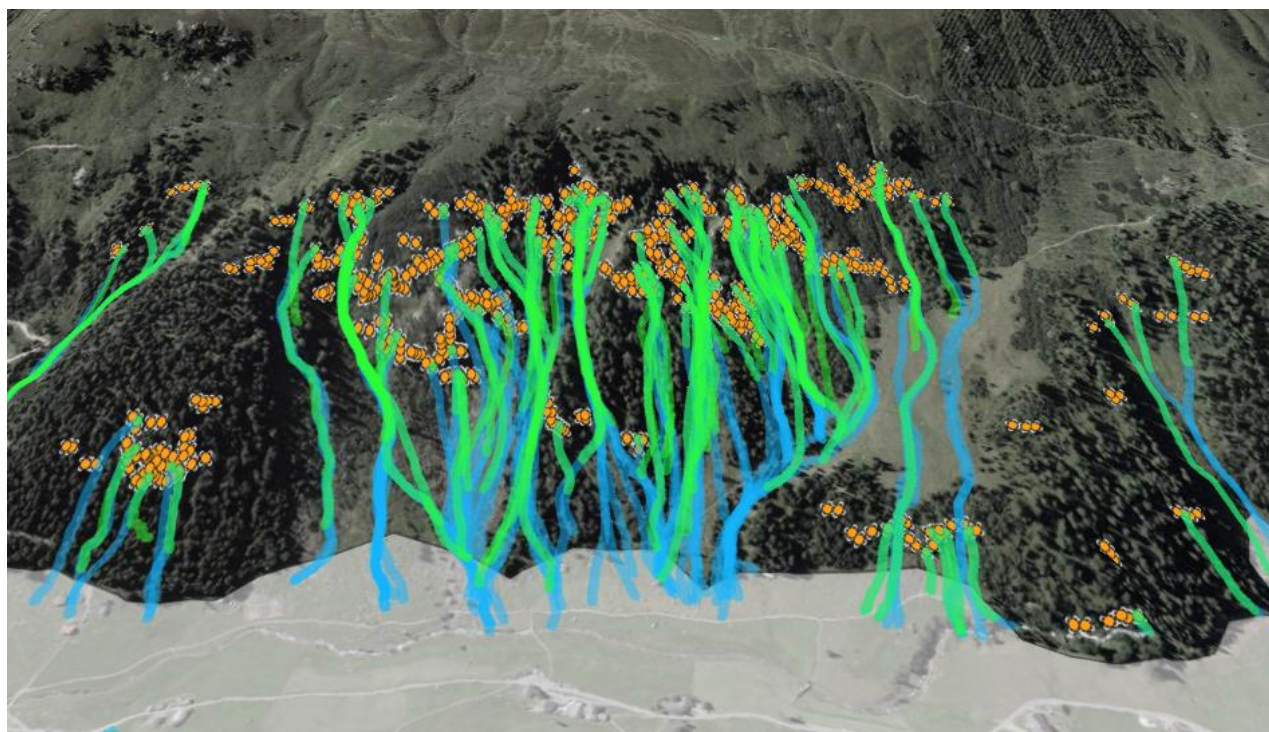


Figure 5. Three-dimensional representation of a sample decade in the Dischma Valley, including the assessment area (grey, at the bottom of the valley), all potential release points (PRP, in orange) and the modeled rockfall trajectories, without forest (in blue) and with unmanaged forest under historical climate conditions (in green; Orthophoto: Bing maps).

3.3 Kinetic Energy

320 The overwhelming majority of all rockfall trajectories stopped earlier on forested slopes, than their corresponding release without forested, indicated by a positive y-axis position in Figure 8. In rare cases rocks that would otherwise have stopped in depressions are deflected by trees so that they travel a longer distance. In such cases, EEI was negative. For rock masses $\leq 1.4 \text{ m}^3$ the EEI values feature a uniform distribution (values between 0-1), for larger rock volumes, the distribution is rather bipolar distributed, rather close to 0 or 1, but missing values between 0.5 and 0.9.

325 Figure 8 shows the EEI for all 403 simulated rockfall events in the three forest scenarios. In all scenarios, smaller rocks were slowed down more effectively than larger rocks, yet the protective efficiency was generally lowest in the managed forest. Differences between forest scenarios were largest in the small and medium rock size compartment but negligible for large rocks. In all scenarios, some rocks were stopped immediately after release, some were completely unaffected and a few traveled longer than they would have on an unforested slope. Smaller rocks reaching the valley bottom were still slowed down in many cases
 330 whereas larger rocks reaching the valley bottom tend to be unaffected by the forest. This could be rocks traversing clearings or patches of young forest resulting from disturbance or management. In young stands, smaller rocks are still slowed down while

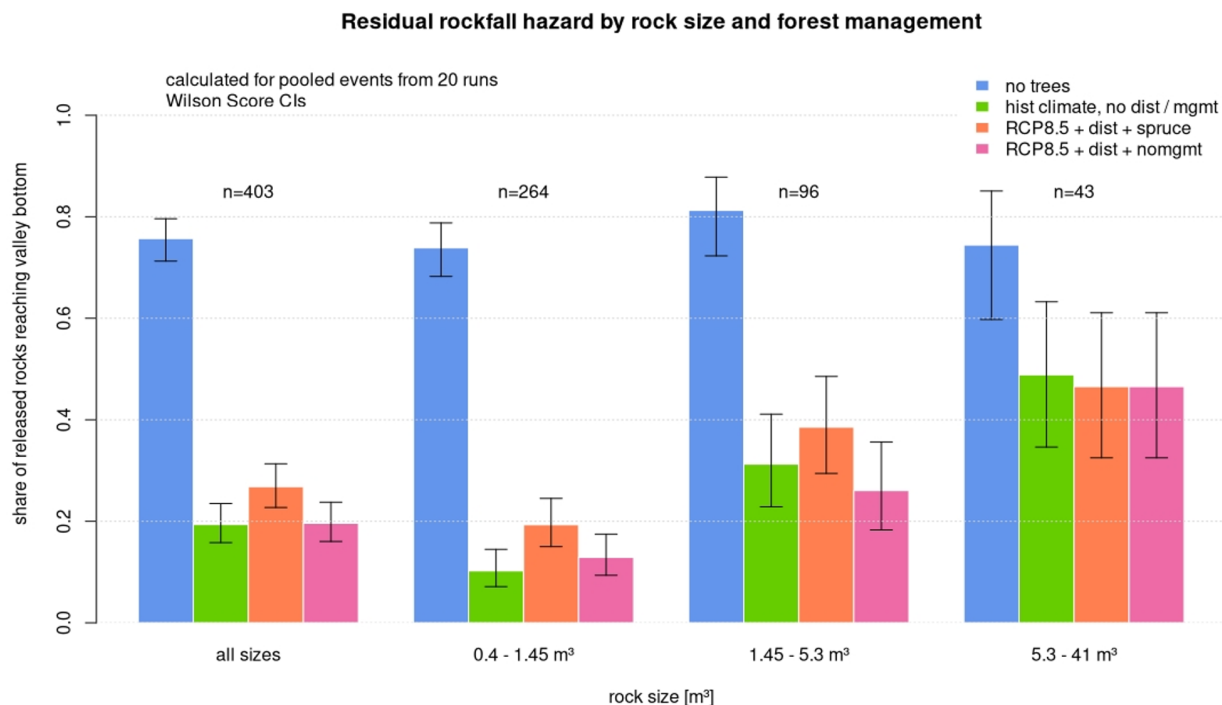


Figure 6. Residual rockfall hazard by rock size and climate / forest management scenario. All rockfall events from 20 replications for each scenario were pooled. Bar colors indicate the different simulation scenarios (same color code as introduced in Fig. 5, the subfigures shows residual hazard for different rock size classess, corresponding to return periods of 10-1000 years, 10-30 years, 31-100 years and 101-1000 years (from left to right).

larger rocks are hardly affected. Mean EEI increased over time in all forest scenarios, with scenario 3 starting on a lower level (Fig. 9).

By comparing the residual kinetic energy of identical rocks upon reaching the boundary of the evaluation area at the valley
 335 bottom across different forest scenarios (i.e. same rock shape and size, same release position, same simulation year but varying
 forest scenarios), we can assess the effectiveness of the forest managements against the rock size classes. Figure 10 illustrates
 the residual kinetic energy of rocks in scenarios 2 through 4 (y-axis, subfigures a-c) compared to the same rock on a treeless
 slope (x-axis). Both axes are log-scaled. Each encircled area represents a rock, with the circle size proportional to its volume.
 The diagonal blue line indicates parity with the treeless scenario: rocks below the line had reduced kinetic energy, while
 340 rocks above the line had an increased kinetic energy compared to their treeless counterparts. Rocks that did not reach the
 valley bottom were assigned a kinetic energy of 0 kJ. The plot shows that all forest scenarios stopped a substantial number
 of rocks entirely (i.e. with a residual kinetic energy $y = 0$). These were predominantly small to medium-sized rocks, while
 large rocks were often unaffected by the forest conditions. Among the small and medium-sized rocks that did reach the valley,
 many experienced reduced kinetic energy in scenarios 2 (historic climate, no management) and 4 (RCP8.5, no management)
 345 compared to the treeless slope. In contrast, scenario 3 (RCP8.5, harvest and spruce replant) produced more variable results:

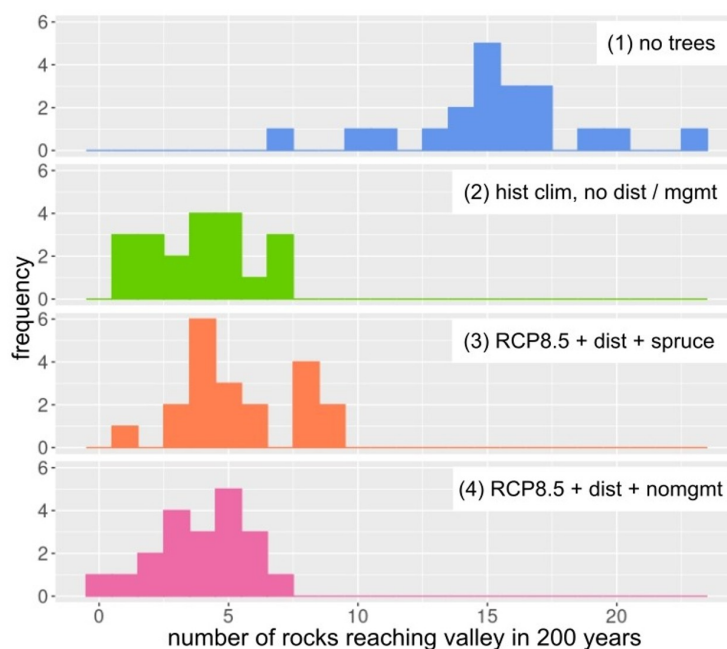


Figure 7. Reliability of rockfall protection provided, represented by histograms of the number of rocks reaching the valley during one simulation run. Histograms based on the outcomes of 20 replications of 200 simulation years per scenario: (a) no trees (scenario 1), (b) historical climate without disturbances or management (Scenario 2), (c) RCP 8.5 Climate including disturbances and forest management (Scenario 3) and (d) RCP 8.5 including natural disturbances, but no management.

several smaller and medium-sized rocks showed increased kinetic energy, suggesting possible acceleration through the altered forest structure.. Across all scenarios, only two out of 403 rocks reached the valley, that would have been stopped on a treeless slope.

4 Discussion

350 Economic development, land use change, and climate change increasingly challenge long-term management of mountain forests. To ensure these forests continue to provide effective protection against natural hazards, it is essential to understand the future ecological and economic outcomes of different management strategies. However, current tools are limited in their ability to quantify and predict avoided damage from gravitational natural hazards - key risks in mountain regions. To adress this gap, we introduce a modeling framework that enables dynamic, temporally explicit interactions between forest dynamics
 355 and natural hazard processes. Compared to existing models (Berger and Dorren, 2007; Grêt-Regamey et al., 2008; Moos et al., 2017; Lanfranconi et al., 2020), our framework uniquely incorporates the disturbance feedbacks from hazard events and captures non-linear interactions between different forest disturbances and their combined effect on protective capacity.

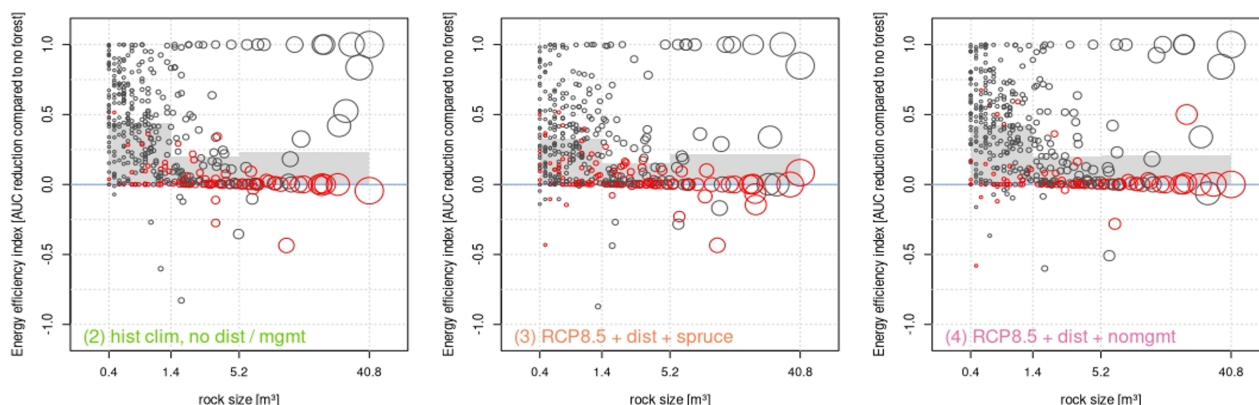


Figure 8. Energy Efficiency Index (Lanfranconi et al. 2020) quantifying kinetic energy absorption in the forest in different forest development scenarios. Y-values of 0 (blue line) correspond to no forest influence, values close to 1 shows very efficient protection with rocks coming to halt almost immediately whereas negative values belong to rocks that were deflected in such way that they made a longer trajectory than they would have on a treeless slope. Rocks are ordered by annuity along the logarithmized x-axis, the symbol area corresponds to rock volume. Rocks reaching the valley bottom are highlighted in red. The grey bars visualize mean EEI values for three annuity / rock size bins. Subfigures from left to right: (2a) historic climate, unmanaged forest. (3b) future climate, logging and spruce replant. (4) future climate, no management.

influence the protective capacity of the forest. We tested this framework by simulating rockfall risk under various management and climate scenarios in a case study near to Davos, Switzerland.

360 4.1 Plausibility of case study results

The modeling framework integrating the iLand forest simulator with the RAMMS rockfall module performed well in our test scenario. Computation times were acceptable with a replication of 200 forest growth years, 20 rockfall events and up to 144 hectares of forest within the rockfall domain taking a few hours on a standard personal computer. As expected, the main computational bottleneck was the tree initialization in RAMMS::Rockfall. This step involved converting between 75000 and 135000 trees to polyhedrons for each rockfall simulation. We strongly recommend minimizing the size of hazard simulation domains reduce the number of trees initialized before each rockfall simulation (see chapter 2.2.1).

Both components of our combined simulation framework delivered plausible results. The forest simulation results are well in line with real world observations and simulation results produced by Petter et al. (2020). Disturbances, climate change and management have a measurable effect on forest structure (Fig. 4). Climate-induced disturbances (scenario 2 vs. scenario 4) reduce standing volume mostly in older stands at lower altitudes, which is a plausible result due to warmer temperatures favoring bark beetle larval development (Baier et al., 2007; Seidl et al., 2007; Košťál et al., 2011) and taller trees being more susceptible to windthrow (Hale et al., 2012; Gardiner, 2021). Even scenario 3 with logging and spruce replant delivers realistic results at medium altitudes up to 2400 m.a.s.l. Spruce growth in this altitude is likely enabled by the competitive advantage

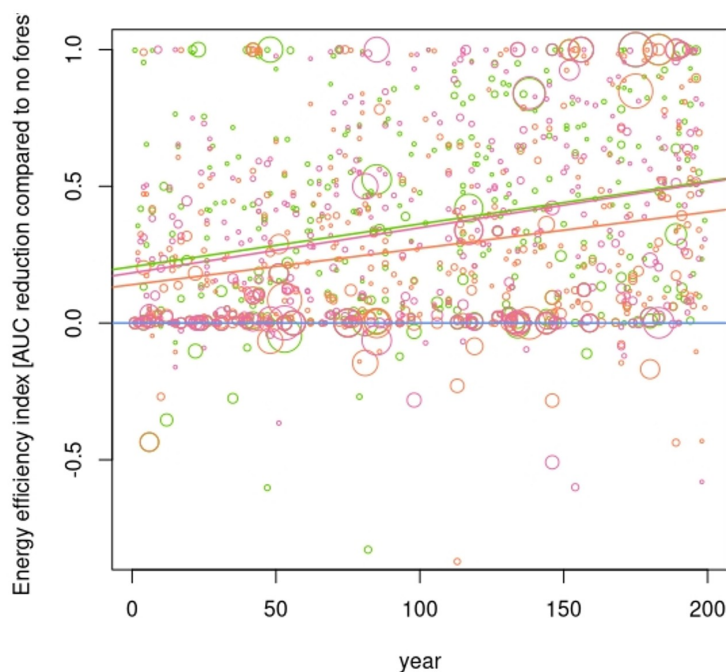


Figure 9. Temporal development of Energy Efficiency Index (Lanfranconi et al. 2020) which quantifies kinetic energy absorption in the forest. Green: scenario 2 with historic climate and disturbances, no management. Purple: Scenario 4 with future climate and disturbances, no management. Orange: Scenario 3 with future climate and disturbances, timber logging and spruce replanting. Symbol area represents rock volume. Trendlines show a simple linear model of EEI year.

through planting compared to the slower natural dispersal of other species and very warm climate scenario. At higher altitudes, unnaturally high numbers of young spruce appear to cause a treeline shift. However, natural mortality of spruce saplings in this altitude is usually high due to snow mold (*Herpotrichia juniperi*, Brang, 1998; Cunningham et al., 2006). Therefore, this simulation result must be considered an artifact of the simple forest management implementation in scenario 3 with spruce replant performed indifferently at all altitudes. The simulated rockfall trajectories aligned well with historic rockfall runout areas and deposition zones mapped in the field. Observed differences in runout distance between forested and unforested slopes were consistent with field data. Our results regarding general rockfall protection efficiency even match well with the results of Lanfranconi et al. (2020) who found a rock-size-dependent protection efficiency with average EEI values of 0.95 for small 0.52 m³ blocks and EEI values between 0.2 and 0.8 for larger 1 m³ blocks on similar slopes. Even our results for residual rockfall risk are well in line with results obtained from other simulation software (RockyFor3D as used by Moos et al. (2017)) and field experiments (Dorren et al., 2006). We tested a broader range of rock sizes and return periods (0.4-40 m³, 10-1000 years) than most previous studies (Lanfranconi et al., 2020: 0.5 and 1 m³, Moos et al., 2017: 0.05 – 2 m³). This range revealed that the forest management has the greatest effect on medium sized rocks (0.5-5 m³), which are large enough to cause damage, but still influenced by forest structure. In contrast, small rocks pose low risk and are effectively mitigated across all scenarios,

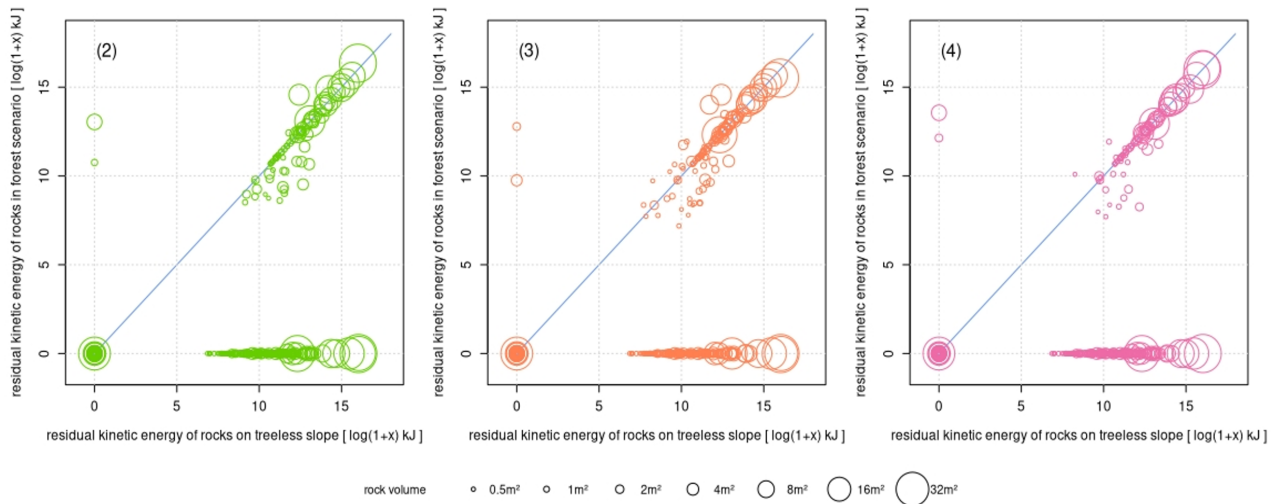


Figure 10. Residual kinetic energy of rocks in the valley bottom after rolling through forest (y-axis) compared to their identical counterparts rolling down a treeless slope (x-axis). Rocks not reaching the valley were assigned an energy of 0 kJ. Logarithmized axes. The surface area of the circles is proportional to rock volume. Subfigures from left to right: (2) historic climate, unmanaged forest. (3) future climate, logging and spruce replant. (4) future climate, no management. The blue line corresponds to an identical outcome, i.e. no energy reduction by the forest. Circles below the blue line: residual energy reduced by the forest. Circles above the blue line: residual energy increased by the forest

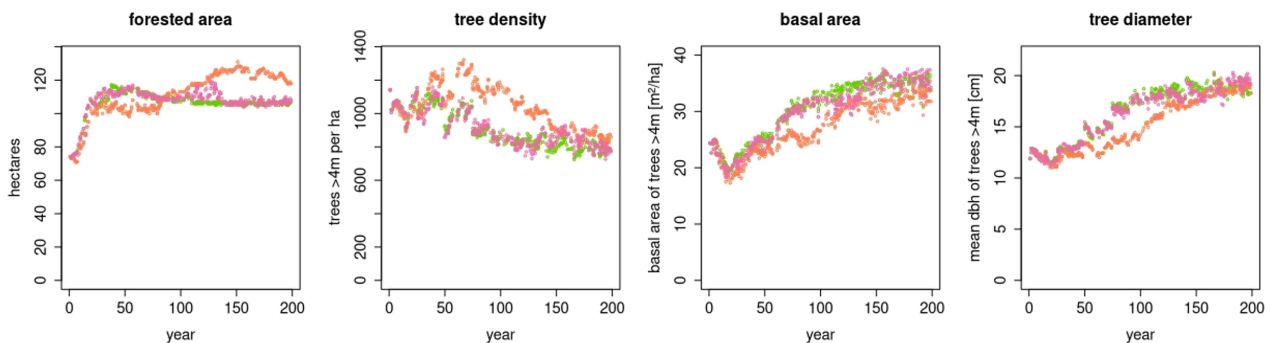


Figure 11. Temporal development of forest characteristics in three different climate, disturbance and forest management scenarios in the rockfall simulation domain (not the whole case study area). Data points based on 10 replications per scenario, forest characteristics extracted before randomly distributed rockfall events. Green: scenario 2 with historic climate and disturbances, no management. Purple: Scenario 4 with future climate and disturbances, no management. Orange: Scenario 3 with future climate and disturbances, timber logging and spruce replanting.

while forests offer limited resistance to very large boulders. These findings align with expert assessments placing the upper limit of a significant forest effect at around 5m^3 or $10'000\text{ kg}$. (Rickli et al. (2004) as cited by Dorren et al. (2007)).



390 The increment in EEI over time across all scenarios (Fig. 9) is likely driven by rising basal area per hectare (i.e. cumulative cross section area of all trees at breast height, measure for how densely a stand is stocked) and DBH over the simulation period (Fig. 11). Both parameters - proxies for stand density and tree sizes - are known to influence rockfall protection efficiency (Dorren et al., 2007; Moos et al., 2017). All four indicators - residual rockfall hazard, number of rocks reaching the valley bottom, EEI and residual kinetic energy – showed clear differences between forested and treeless slopes. In contrast, differences
 395 among the forest scenarios themselves were relatively small. We attribute this to three main factors:

1. limited management impact in the release area due to starting conditions and management rules
2. Offsetting effects of climate change: increased disturbances in scenarios 3 and 4 was partly balanced by enhanced growing conditions
3. Treeline expansion in scenario 3 had minimal effect, as most rockfall release points lie at or below the historical treeline.

400 We expect that more substantial structural changes—such as those caused by large-scale disturbances—would lead to greater differences in protective function if included in the simulations.

4.2 Model functionality and current applications

Swiss protection forest management guidelines (Schwitter, 2020) emphasise the integration of hazard potential, damage potential and forest protective capacity - while accounting for past and future development. Our modeling framework addresses
 405 all these elements by coupling a process-based forest landscape model with a natural hazard simulation software for quantitative hazard assessment. The framework incorporates site conditions, climate effects, disturbances and ecological interactions. It quantifies rockfall hazard intensities and rockfall protection efficiency using common metrics including and magnitude-frequency-distributions. Together with iLand's versatile forest outputs (Seidl et al., 2012a; Rammer and Seidl, 2022b), these results support cost-benefit analyses and help identify high-impact forest management strategies. To our knowledge, this is
 410 the first simulation model to dynamically couple forest development and with hazard impact, feeding hazard-induced damage back into forest dynamics. This feedback enables spatially and temporally explicit scenario analysis and supports adaptive management. it allows forest managers to explore the pathways from a current to desired forest states, plan post-disturbance recovery, evaluate climate adaption strategies, and assess trade offs between multiple ecosystem services from a resilience perspective. Based on the plausibility of the case study results, the presented simulation framework closes key research gaps by
 415 (a) integrating forest and hazard dynamics over time, (b) providing quantitative hazard metrics, and (c) capturing uncertainty through replication envelopes.

4.3 Potential future extensions

The modular design of our simulation framework allows for a broad range of future extensions, both in terms of additional hazard processes and expanded socio-economic analysis. Below, we outline key areas currently under development or planned.



- 420 1. **Avalanche Simulation Module:** Initial integration of avalanche processes is underway. While the framework currently focuses on rockfall, a coupling with RAMMS : :Extended has been partially implemented. For RAMMS : :Avalanche simulations, input data include avalanche release areas and snow height. Forest structure influences model parameters such as surface roughness and snow detrainment, which are calculated from stand characteristics including tree count, diameter at breast height (DBH), canopy cover, average tree height, and ground vegetation (Christen et al., 2010; Feistl, 425 2015). Tree destruction is then assessed using thresholds established by Feistl (2015).
- Avalanche events are simulated prior to rockfall if both occur in the same simulation year, reflecting their typical seasonal timing—mid-winter for avalanches and spring/autumn for rockfall (Pielmeier et al., 2013; Schneuwly and Stoffel, 2008; Pratt et al., 2019).
- Despite these developments, avalanche simulation is not yet operational in this version of the framework. A major 430 challenge is generating realistic snow volumes. While Gumbel-based snow depth estimates have proven effective in traditional applications (Bühler et al., 2022), they result in overestimated runouts in RAMMS : :Extended, which accounts for snow entrainment. To address this, Ortner et al. (2025b, a) proposed a revised workflow for estimating snow inputs. Full integration of this approach into our framework is ongoing.
2. **Additional Hazard Modules:** The framework architecture supports future additions of other gravitational hazards such as Shallow landslides, Debris flows, snow creep or -gliding events. Each hazard type can be integrated by defining event 435 scheduling, translation libraries, and coupling mechanisms similar to those used for rockfall and avalanche.
3. **Ecosystem Service Integration** Beyond hazard mitigation, the framework can evaluate additional ecosystem services (ES) using iLand's outputs. This includes carbon sequestration, biodiversity, and water regulation (Seidl et al., 2012b; Albrich et al., 2018; Seidl et al., 2019). If appropriate valuation functions are available, these ES can be included in 440 trade-off analyses to support multi-objective forest management strategies (e.g. Blatter et al., 2017).
4. A refinement of the forest-rockfall-interface adding lying deadwood and ground vegetation dynamics could enable more detailed studies of forest management options after disturbances such as windthrow or possible synergies and trade-offs between different forest ecosystem services beyond hazard protection. Work on this extension is already ongoing and will build on research by Ringenbach et al. (2022b)
- 445 5. **Economic Risk Assessment:** The framework could be extended to support integrated economic evaluation. According to Moos et al. (2018a), the risk to an element at risk e is calculated as:

$$Re = \sum (P_{\text{onset}} \times P_{\text{prop}} \times P_{\text{presence}} \times \text{Vulnerability} \times \text{Value}) \quad (2)$$

Our simulation quantifies the hazard-related components of this equation, namely the probabilities of onset, propagation, and impact, in a new and more precise way than conventional scenario-based approaches that rely on selected return



periods. To complete the analysis, spatially resolved data on object values and vulnerability functions are required. These can be derived from external NatCat platforms like CLIMADA (Aznar-Siguan and Bresch, 2019) or EconoMe, the swiss tool to analyze the cost-benefit ratio of subsidies of technical mitigation measures. Simulation outputs can then be aggregated to evaluate: Avoided damage under different management strategies, Net present value of protective function over time or Feasibility of PES (Payment for Ecosystem Services) schemes (Grêt-Regamey et al., 2008; Wunder, 2005; Engel et al., 2008; Baumgärtner and Strunz, 2014).

6. Risk maps for different climate scenarios can be generated by running simulations with a larger spatial extent. They could help refine existing hazard maps by predicting future temporal and spatial shifts in different natural hazards risk, test disturbance resilience and climate adaptation strategies

These planned extensions will further enhance the utility of the framework for adaptive protection forest planning and long-term ecosystem service optimization under changing climate and disturbance regimes.

4.4 Limitations and uncertainty

The modeling framework has obviously limitations. Most notably, simulation results are subject to both scenario uncertainty and model uncertainty. Petter et al. (2020) found that the choice of forest model largely influences simulation results of future forest development. The iLand model we use performed best in their comparison, yet a certain degree of model uncertainty is inevitable. When simulating far into the future, the climate scenario and the down-scaling uncertainties propagate. However, data availability for both rockfall and forest simulations can be considered exceptionally good in the case study area and might be a limitation in other areas. Further, we want to emphasize that stochastic processes affecting the place and time of rockfall release, tree growth and forest disturbances induce lots of variance in simulation results. To compare different scenarios, we used 20 replications and thus simulated 4000 years of each scenario. Still, the envelope of outcomes is broad and overlaps between scenarios (Fig. 7). Forests act like a filter changing the magnitude-frequency-distribution of a hazard, and changes in forest management usually take a long time to show effects (Fig. 9 and Fig. 11 and Moos et al. (2018a)). In these two aspects, forest largely differ from technical rockfall barriers. Our modeling framework does not directly provide monetary values for protection ES yet. This step of analysis can be accomplished with NatCat (natural catastrophe) modeling software like e.g. CLIMADA (Aznar-Siguan and Bresch, 2019) by using rockfall trajectories to calculate NatCat damage in a certain scenario and comparing it to a baseline scenario (no forest or no management). As the goods at risk (e.g. buildings and infrastructure) vary in spatial distribution, size, value and vulnerability, this conversion from physical simulation outputs to economic outcomes will likely add further variance to the results.

5 Conclusions

This article presents a modeling framework that allows for a temporally integrated analysis of interactions between disturbances, management and forest growth. It combines the process-based forest landscape model iLand with the process-based



hazard simulation software RAMMS and is therefore capable of forecasting the outcome of climate and management scenarios while capturing non-linear reactions of the ecosystem. Hazard simulation outputs are post-processed and converted to a set of metrics commonly used in quantitative risk analysis. By comparing multiple replications of the same scenario, forecasting uncertainties caused by stochastic processes can be quantified. We conclude that our modeling framework contributes to the closure of the identified research gaps: precise quantification of hazard over time, temporally integrated analysis of system interactions, quantification of uncertainties and stochasticity. These capabilities makes it a powerful tool for identifying protection gaps and supporting adaptive forest management in hazard-prone mountain areas.

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Code and data availability. The used code is available upon request.

Video supplement. None

Competing interests. None

Disclaimer. None

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Appendix A: Appendix A



Component	Output Type	Output Details	Spatial scale	Temporal Scale
iLand	Single trees	Species dbh, height, vol, ba age leaf area compartment masses light response stress	2x2 m	1 y
	Stand aggregates	Tree species distribution tree size distribution. regeneration & saplings biomass compartments soil parameters water cycle carbon cycle	100x100 m	1 y
	Landscape aggregates	e.g. Biomass	Whole area	1 y
	disturbances	Barkbeetle damage wind damage fire damage	Whole area	1 y
	mortality	age mortality stress mortality disturbance mortality extraction	100x100 m	1 y
	management	Single trees removed – parameters & reason for removal. extracted timber volume	2x2 m 100x100 m	1 y
RAMMS rockfall	Rockfall trajectories	Position velocity & rotation kinetic energy	Exact position	Single event, 0.01 sec
	Tree impact	Killed trees Damaged trees	Exact position	Single event
	Hazard risk indices (postprocessed)	Rockfall release distribution Residual rockfall intensity Var (RRH) AUC kinetic energy Energy Efficiency Index residual kinetic energy	Hazard domain Hazard domain Hazard domain single event Hazard domain single event	simulation period simulation period envelope of reps single event simulation period single event
RAMMS avalanche	Avalanche runout grids	Maximum tree pressure Maximum momentum Maximum velocity Maximum core pressure Maximum avalanche height Maximum pressure velocity Maximum pressure density Deposition height Density Detrainment Height	Arbitrary 5x5 m default	Single event
	Tree impact	Tree destruction	Arbitrary 5x5 m default	Single event
	Hazard risk indices (postprocessed)	-		

Figure A1. Overview of possible outputs of the simulation framework



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