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Modeling the effect of rockfall on forest development in a dynamic forest landscape model

Christine Moos[1,2] | **Heike Lischke**[3]

[1]Interdisciplinary Centre for Mountain Research, University of Lausanne, Sion, Switzerland

[2]School for Agricultural, Forest and Food Sciences BFH-HAFL, Bern University of Applied Sciences, Zollikofen, Switzerland

[3]Dynamic Macroecology, Swiss Federal Institute of Forest, Snow and Landscape Research WSL, Birmensdorf, Switzerland

Correspondence
Christine Moos
Email: christine.moos@bfh.ch

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Abstract

Mountain forests below rocky cliffs are regularly impacted by falling blocks. Rockfall thus increases tree mortality and can locally alter the forest structure. At the same time, trees can decelerate or stop falling blocks and play an important role in protecting settlements and infrastructure from rockfall impacts. Furthermore, trees in the upper part of a slope protect trees further downslope. Considering the interaction between forest dynamics and rockfall disturbance in dynamic forest models is necessary to accurately predict the development of rockfall protection forests in the long term. In this study, we integrated the disturbing effect of rockfall on trees in the dynamic forest landscape model TreeMig through a coupling with three-dimensional rockfall simulations and analyzed the rockfall-forest feedback over time. We introduced an additional mortality per cell, based on the probability and severity of rockfall disturbance derived from rockfall simulations. We implemented the potential feedback effect between rockfall disturbance and forest development using a meta-model of the rockfall simulations and analyzed the sensitivity of forest development to varying disturbances for a case study in the Swiss Alps. With increasing disturbance, the total biomass of the forest decreased, whereby differences were relatively small at the scale of the forest complex, but more pronounced at local (cell) scale. Generally, the comparison to light detection and ranging (LiDAR)-derived forest data showed a better agreement between the modeled forest and reality when considering the rockfall disturbing effect. The coupled simulations further revealed a positive feedback effect of rockfall disturbance and forest development. Disturbance probability and severity clearly decreased with advancing forest growth, which, however, lead to an overestimated recolonization of the disturbed areas. Still, the rockfall disturbance module clearly improved the simulations of a rockfall protection forest with TreeMig. Future improvement of the model should include a better representation of soil formation and water availability in the disturbed areas and the consideration of long-term effects of the rockfall disturbances, such as pests and diseases. The consideration of the rockfall disturbance in forest modeling is particularly relevant for small-scale studies requiring a detailed representation of spatial differences in forest cover, as this is the case in protection forest management.

KEYWORDS
disturbance, dynamic forest modeling, meta-model, protection forest, rockfall, rockfall-forest feedback, TreeMig

INTRODUCTION

Mountain forests are substantially influenced by the regular occurrence of natural disturbances (Bebi et al., 2017; Kulakowski et al., 2017). Due to the steep topography, mass movements driven by gravitational forces play an important role as disturbing agent (Zurbriggen et al., 2014). These can be of extensive scale, such as large snow or rock avalanches, destroying entire parts of forest stands, or more punctual impacts, such as rockfall. Falling blocks impact single trees leading to small openings that provide light and space for rejuvenation (Aydin et al., 2012). In parts of higher rockfall activity, constant rock impacts on trees result in a higher tree mortality and forest structure can be altered locally (Moos et al., 2020). Thus, rockfall may increase patchiness and stand heterogeneity (Veblen et al., 1994) and favor uneven-aged forests (Corona et al., 2013).

Falling rocks can uproot, break, decapitate, or harm standing trees (Stokes et al., 2005). Whether or not a tree is killed after an impact depends on the energy of the falling block relative to the energy reduction capacity of the tree. The latter is determined by the diameter of the tree, the height and direction of the impact, and the tree species (Dorren & Berger, 2006; Stokes et al., 2005). In case a tree is only damaged but not killed, growth and survival of the tree are still likely to be affected in the long term, as pests and diseases can affect the tree through the scars (Stoffel & Hitz, 2008; Woltjer et al., 2008).

Generally, single falling blocks constitute a regular, but small-scale disturbance to a forest. The energy of the blocks can be significantly reduced after an impact on a tree and, thus, falling blocks can be decelerated or even stopped (Dupire et al., 2016). Consequently, forests play a very important role as means of protection against rockfall by reducing the risk of people and infrastructure exposed to the falling blocks (Moos et al., 2017). Additionally, trees further downslope are protected from rockfall impacts by the trees above, potentially leading to a positive feedback between the forest and the disturbance in the long term (Rammer et al., 2015). This feedback between forest and rockfall is expected to be influenced by local conditions, such as climate, soil, topography as well as other natural and anthropogenic disturbances. In already extreme environments, where, for example, low temperature or drought hinder growth and increase mortality, the effect of the disturbance is expected to be more pronounced, since rejuvenation takes more time to establish after a disturbing event potentially leading to time lags in forest development. Also, the impact of single falling blocks may become more relevant in combination with other natural disturbances or management (Drever et al., 2006).

However, the interaction of rockfall and forest development has little been addressed in research so far. A few studies analyzed differences in forest structure based on field data from rockfall protection forests (Aydin et al., 2012; Moos et al., 2020; Perret et al., 2006). Woltjer et al. (2008) embedded a three-dimensional (3D) rockfall module in the patch-based forest simulator to evaluate the effect of silvicultural interventions, whereas effects of rockfall on stand development were not taken into account (Rammer et al., 2015). Considering rockfall disturbance in dynamic forest models would, however, be necessary to accurately predict the development of rockfall protection forests in the long term.

In this study, we integrated the disturbing effect of rockfall on trees in the dynamic forest landscape model TreeMig (Lischke et al., 2006) through an indirect coupling with 3D rockfall simulations and applied it to a real case study site in Täsch (Valais, Switzerland). We derived a spatially explicit additional mortality, which is based on a rockfall disturbance probability and severity. The forest-rockfall feedback over time was then implemented using a statistical model. The objectives of this study are to

1. integrate the disturbance effect of rockfall as a submodule in the dynamic forest model TreeMig;
2. analyze the effect of the rockfall disturbance on forest development depending on the disturbance probability and severity for a case study site;
3. analyze the long-term effect of rockfall disturbance considering the feedback between forest and rockfall based on a real-case application.

METHODS

Forest model

TreeMig (Lischke et al., 2006) is a dynamic, spatially explicit forest model simulating reproduction including seed dispersal, tree establishment, growth, competition, and mortality of trees in each height class per cell of 25 × 25 m. Processes are controlled by the bioclimatic drivers day-degree sum (sum of mean daily temperatures above 5.5°C), minimum winter temperature, and a drought stress index. The trees in a cell are assumed to be randomly distributed resulting in a Poisson distribution of tree density and light. Light is the only resource trees compete for in the model. Trees in different cells interact spatially through seed dispersal. In addition to environment- and growth-related mortality rates, background mortality can be applied in TreeMig. This mortality is randomly distributed in space and time and can thus only be used to simulate disturbances that are spatially non-explicit. For this reason, a spatially explicit rockfall disturbance mortality was introduced in this study to accurately simulate forest–rockfall interactions (see Rockfall Disturbance Module section). Currently, 30 European species are parameterized for modeling with TreeMig (Appendix S1).

TreeMig, its predecessor model DisCForM, and the follow-up model FORHYCS have proven to provide plausible species compositions, forest dynamics, and migration rates under past, present, and potential future environmental conditions (Feurdean et al., 2013; Löffler & Lischke, 2001; Zurbriggen et al., 2014), including also the study area of Valais (Moos et al., 2021; Scherrer et al., 2020; Speich et al., 2020).

Rockfall disturbance module

Rockfall disturbance was integrated in TreeMig by an indirect coupling of the forest model with a rockfall simulation model (RockyFor3D) (Figure 1). We introduced an additional annual mortality per cell, based on the probability and severity of rockfall disturbance. We focused here on single falling blocks, which occur frequently and can be regarded as a constant but low-intensity disturbance to the forest. Large events, such as rock avalanches, that can destroy entire parts of the forest were not considered in this study, but their potential effect was partially taken into account by analyzing increasing frequencies and intensities of the rockfall disturbance (see Sensitivity Analysis of Disturbance Effect section).

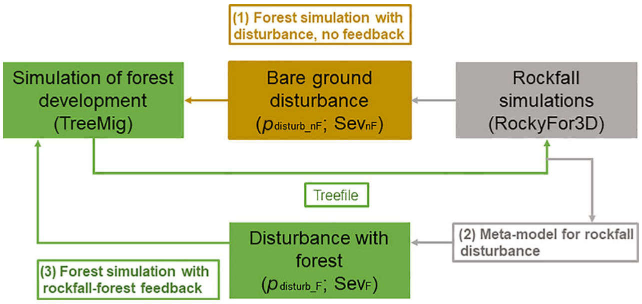

FIGURE 1 Overview of the integration of rockfall disturbance in the forest model TreeMig by an indirect coupling with rockfall simulations. Forest simulations were conducted with a constant rockfall disturbance (1) and with rockfall-forest feedback (3) based on a meta-model for disturbance probability and severity (2)

The probability of a rockfall disturbance (p_{disturb}) in a cell of 25 × 25 m depends on the probability that a block (or several) is released (p_{onset}) and the probability that the block reaches the cell and impacts one or several trees (p_{imp}) (Equation (1) and Figure 2).

$$p_{\mathrm{disturb}} = p_{\mathrm{onset}} \times p_{\mathrm{imp}}. \tag{1}$$

p_{onset} is determined based on the number of released blocks per year. We quantified it using a power-law-based magnitude–frequency relationship, which we derived from rockfall deposits, in combination with an assessment of tree damages below the release area (Moya et al., 2010; Trappmann & Stoffel, 2013), whereby extensive data from dendrogeomorphological analyses were available from previous studies (Moos et al., 2018; Stoffel et al., 2005). We considered a minimum block volume of 0.05 m^3, as it can be assumed that the damages of smaller blocks have a rather negligible effect.

We then calculated p_{imp} based on 3D rockfall simulations with the rockfall model RockyFor3D (see Simulation Set-Up section).

We therefore registered the number of simulated block impacts per tree and block volume class for a given forest coverr. In case the impact energy of the block is higher than the energy that can be dissipated by the tree, it is registered as "fatal impact." p_{imp} per single tree is the proportion of the number of hits per tree (fatal and non-fatal) and the total number of simulated blocks (n_{sim}). The proportion of the number of fatal tree hits (n_{fatal}) and the total number of simulated blocks is the probability that a tree is actually killed ($p_{\mathrm{kill}} = n_{\mathrm{fatal}}/n_{\mathrm{sim}}$). We first calculated p_{disturb} of an individual tree by adding up the product of p_{imp} and p_{onset} of each block volume class i. p_{disturb} of the cell was then calculated as the maximum p_{disturb} of the individual trees (i.e., a cell is disturbed if at least one tree is impacted by a block).

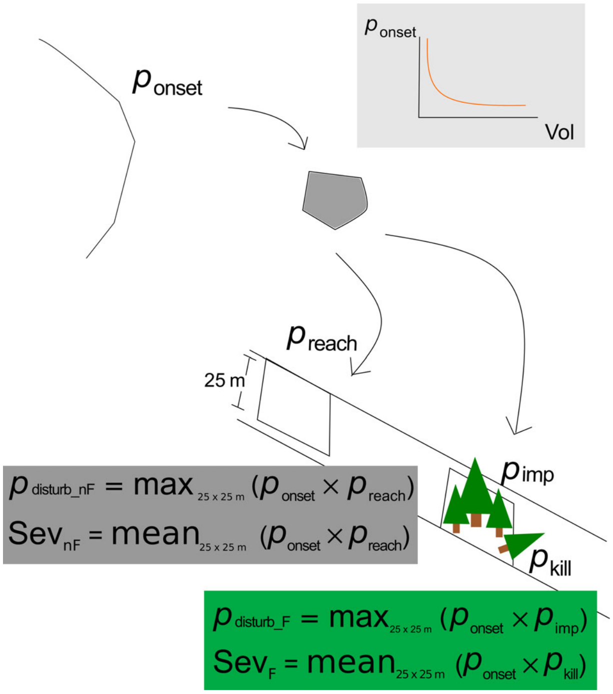

FIGURE 2 Schematic illustration of the definition of the disturbance probability ($p_{disturb}$) and severity (Sev) for the forested situation and without forest cover

We then rasterized $p_{disturb}$ with a resolution of 25 m (resolution of forest simulations) based on the maximum $p_{disturb}$ per cell (Equation (2) and Figure 1).

$$p_{disturb\_F} = \max_{25\times25\,m}\left(\sum\nolimits_{i=1}^{V} p_{onset,i} \times p_{imp,i}\right). \qquad (2)$$

For the unforested slope (initial bare ground situation), p_{imp} was approximated as the probability that a cell is reached by a block given that it has been released from the cliff (p_{reach}). It is calculated as the proportion of the number of blocks passing a cell and the total number of simulated blocks. We derived p_{reach} as raster for the unforested slope based on simulations for the median block volume class of 0.5 m^3. We calculated $p_{disturb}$ for each 2 × 2-m cell (resolution of rockfall simulations) as the product of p_{reach} and p_{onset}, and resampled it based on the maximum $p_{disturb}$ per 25 × 25-m cell (Equation (3) and Figure 1).

$$p_{disturb\_nF} = \max_{25\times25\,m}\left(p_{onset,0.5\,m^3} \times p_{reach,0.5\,m^3}\right). \qquad (3)$$

The disturbance severity (Sev) is the proportion of an impacted cell that is actually fatally affected by the impact. It was determined as the product of p_{kill} per tree and p_{onset} and then averaged over the cell ("mean yearly probability of trees of being killed"; Equation (4) and Figure 2).

TABLE 1 Variation of disturbance probability and severity to analyze the effect of rockfall disturbance on forest development

Metric	Variation
Disturbance probability	prob_0 = without disturbance prob_1 = $p_{disturb}$ for initial bare ground situation prob_2 = 2 × $p_{disturb}$ prob_3 = 3 × $p_{disturb}$
Disturbance severity	sev_0 = without disturbance sev_1 = Sev for initial bare ground situation sev_5 = 5 × Sev

$$Sev_F = \text{mean}_{25\times25\,m}\sum\nolimits_{i=1}^{V}\left(p_{onset,i} \times p_{kill,i}\right). \qquad (4)$$

We only accounted for a direct mortality through tree hits, and not for a potential increased mortality of impacted trees due to a higher risk of pests and diseases. Such a gradual mortality is difficult to determine since hardly any quantitative knowledge on mortality rates after tree impacts exist. For the initial bare ground situation, we approximated Sev based on the mean p_{reach} per 25 × 25-m cell.

$$Sev_{nF} = \text{mean}_{25\times25\,m}\left(p_{onset,0.5\,m^3} \times p_{reach,0.5\,m^3}\right). \qquad (5)$$

The rockfall disturbance affects the tree density of a cell at each time step of the simulations (=each year). Based on the disturbance probability ($p_{disturb}$) of a cell, it is determined whether the cell is affected by rockfall. The disturbance severity (Sev) then determines the proportion of trees dying.

Sensitivity analysis of disturbance effect

We conducted forest simulations for different rockfall disturbance probabilities and severities to study the effect of disturbance probability and severity on forest development and to detect potential thresholds leading to transitions in forest structure. As basic disturbance probability and severity, we used $p_{disturb}$ and Sev without forest cover. We then increased $p_{disturb}$ by a factor of two and three and Sev by a factor of five (Table 1). The situation without disturbance served as a reference. The disturbance effect was analyzed regarding tree diameters, tree density, basal area (bA), and species distribution on local (only disturbed area) and stand scale.

Rockfall-forest feedback

Since standing trees can stop or decelerate falling blocks, trees in the upper part of the slope are assumed to protect those more downslope. Therefore, the disturbing effect of rockfall is not expected to be constant over time but to decrease with increasing forest cover resulting in a positive feedback between forest cover and rockfall disturbance. We implemented this feedback in TreeMig based on a statistical model of p_{disturb} and Sev depending on the forest cover, which is a meta-model of the rockfall simulations (Figure 1). To this aim, we designed generalized linear models (GLM) predicting p_{disturb} and Sev as a function of the disturbance probability and severity without forest cover ($p_{\mathrm{disturb\_nF}}$; $\mathrm{Sev}_{\mathrm{nF}}$), the cumulative basal area (bA_cum), as well as the mean tree diameter and mean tree density per cell. Thereby, bA_cum is the sum of the bA from the release area to a specific cell along the "flow path" (determined by topography and calculated based on the digital height model). The explanatory variables were selected from a wide range of terrain and forest factors (e.g., diameter at breast height [dbh], tree density, mean slope, etc.), resulting in the highest explanatory power. The models were designed for $p_{\mathrm{disturb\_F}}$ and $\mathrm{Sev}_{\mathrm{F}}$ calculated based on rockfall simulations at our case study site Täsch for four different forest states, after 10, 50, 200, and 350 years of simulated forest development. They were fitted for a sample of 80% of all cells with a bA greater than 5 m^2/ha. The full models can be found in Appendix S2. In case the bA of the actual forest cover is lower than 5 m^2/ha, as well as if the mean diameter of the trees is <10 cm, we assumed p_{disturb} and Sev to correspond to $p_{\mathrm{disturb\_nF}}$ and $\mathrm{Sev}_{\mathrm{nF}}$. The latter is significantly higher than p_{disturb} and Sev with forest cover, since it is only considered whether a cell is reached and not whether tree stems are hit. This, however, accounts for the difficult conditions for vegetation to establish on active rockfall slopes, where the soil material is unstable (including the re-mobilization of blocks) and hardly any mineral soil is available. The thresholds of 5 m^2/ha and 10 cm are an assumption based on the analysis of the results. Furthermore, we accounted for the aggravated establishment conditions by a lowering of the bucket size of the soil (see Simulation Set-Up section) by 3 cm in the highly active rockfall zones ($p_{\mathrm{disturb\_nF}} \geq 0.5$).

We tested and validated the statistical models based on rockfall simulation data of another site in the canton of Valais (Nax; see Simulation Set-Up section), which has substantially differing rockfall and forest characteristics. We directly calculated $p_{\mathrm{disturb\_F}}$ and $\mathrm{Sev}_{\mathrm{\_F}}$ for different forest states (10, 50, 200, and 350 simulated years) and compared them to the values predicted with the models for the case study site Täsch.

The forest simulation with feedback was conducted for a time period of 220 years. We started from bare ground with $p_{\mathrm{disturb\_nF}}$ and $\mathrm{Sev}_{\mathrm{nF}}$ as initial disturbance probability and severity. We then simulated the forest in time steps of 20 years. After each time step, the new p_{disturb} and Sev of every cell were calculated based on the statistical models.

Study site

The integration of rockfall disturbance in the forest model was elaborated and tested for a case study site in the village Täsch in the Swiss Alps (Figure 3). It is a very active rockfall zone with a considerable release area, ranging from 2000 to 3100 m above sea level (asl). The current forest is mainly dominated by *Larix decidua* trees, with a small abundance of *Picea abies* and some occurrences of *Pinus sylvestris*.

The climate of the study site is continental with a mean winter temperature of the whole slope of currently about −6°C (period between 1930 and 2016) and a minimum winter temperature of −15°C. The mean day degree sum is 852°C and the minimum day degree sum is 245°C. The site experiences moderate drought stress (Figure 3).

The statistical meta-model for the rockfall disturbances was tested for a second site in Nax (canton of Valais, Switzerland). The site is at lower elevation (600–1200 m asl) and with a dryer and warmer climate. The forest is mainly composed of *P. sylvestris* and *Betula pendula*.

Simulation set-up

Forest development was simulated in a forest mask based on the existing forest cover derived from land cover data (Swisstopo, 2020b) but including areas where trees had apparently been removed due to the impact of rockfall. We checked this on the basis of orthophotos (Swisstopo, 2020a). Simulations were conducted from bare ground for a time span of 400 years with constant rockfall disturbance probabilities and severities (see Sensitivity Analysis of Disturbance Effect section) and 200 years, respectively, with disturbance feedback (see Rockfall-Forest Feedback section). Climate data were taken from measurements from 1930 to 2016 with randomly sampled values for the years before. For the simulations with disturbance feedback, we kept the climate constant (based on climate data from 1980 to 2010) to avoid confounding effects.

Soil water holding capacity ("bucket size") for the entire transect was estimated between 6.2 in the main part of the slope and 11.6 cm in the southern part based

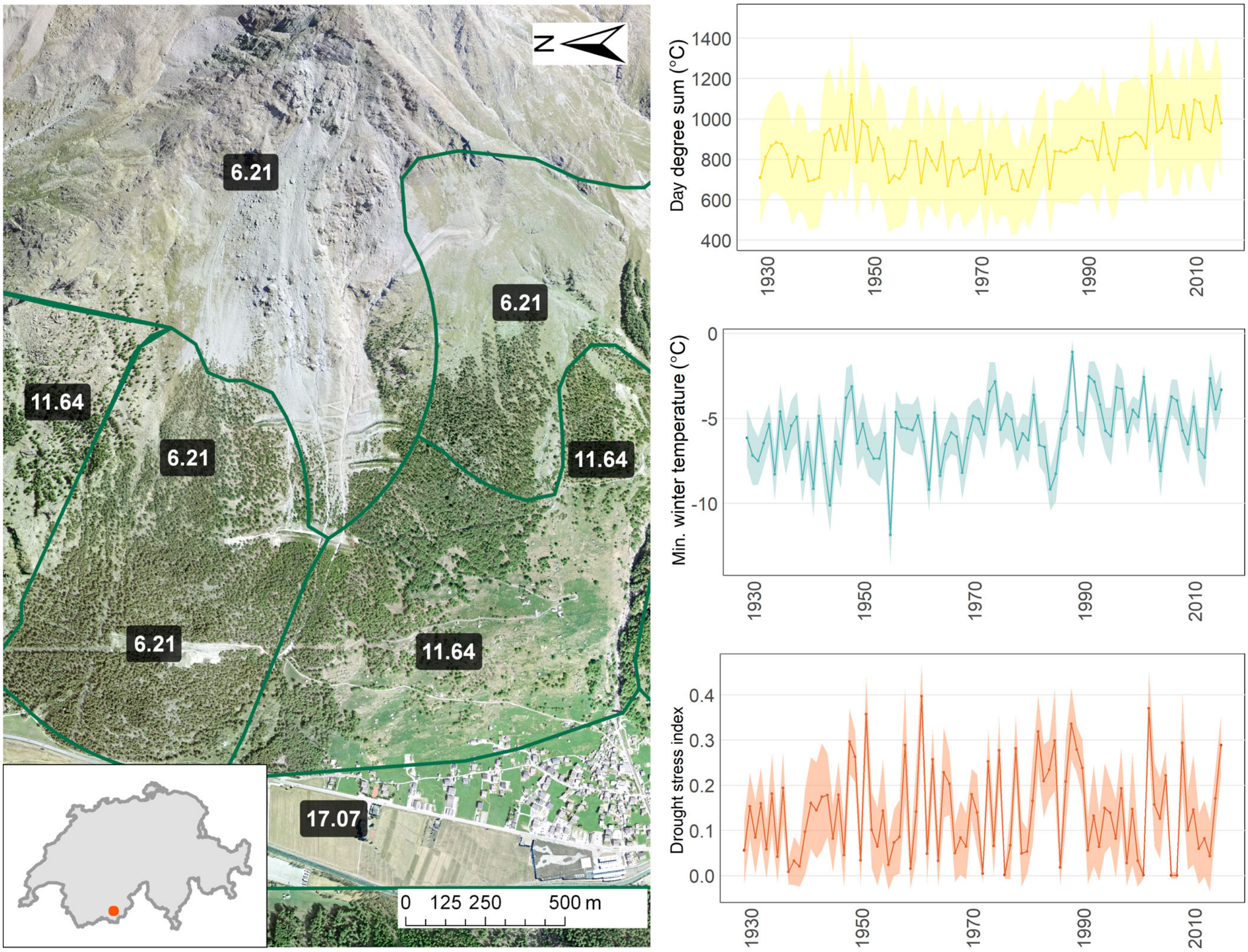

FIGURE 3 Study site in Täsch with "bucket size" (in cm; left) calculated based on water-retention potential and soil wetness data (see Simulation Set-Up section), and day degree sum (right top), mean minimum winter temperature (right center) and drought stress index (right bottom; based on the initial bucket size) between 1930 and 2016

on water-retention potential and soil wetness data from the Swiss soil suitability map (BFS, 2000; Löffler & Lischke, 2001; Figure 3). In the upper part (above ~1900 m asl), the calculated bucket size (~33 cm) was rated as too high since the soil consists mainly of rocky debris. We thus adapted based on the bucket size in the main part (bucket size = 6.2 cm) of the slope where the soil is comparable.

The simulation results were validated with data on species, diameter, and tree density data from 15 sample plots of 20 × 20 m (Moos et al., 2020). We further compared tree densities and bA to light detection and ranging (LiDAR)-derived canopy data available from the Canton of Valais (VS, 2019).

We conducted rockfall simulations with the rockfall module RockyFor3D (Dorren, 2016) for eight-block volume classes, which were derived from the fitted power-law-based magnitude–frequency relationship (see Rockfall

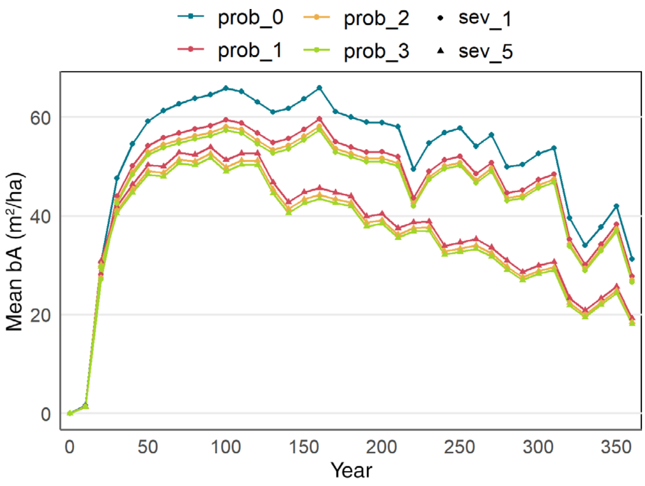

FIGURE 4 Evolution of mean basal area (bA) per hectare of the total stand over time for different disturbance probabilities and severity. The mean basal area of the current stand is 30.0 m^2/ha (SD = 20.9 m^2/ha) based on 15 sample plots across the slope

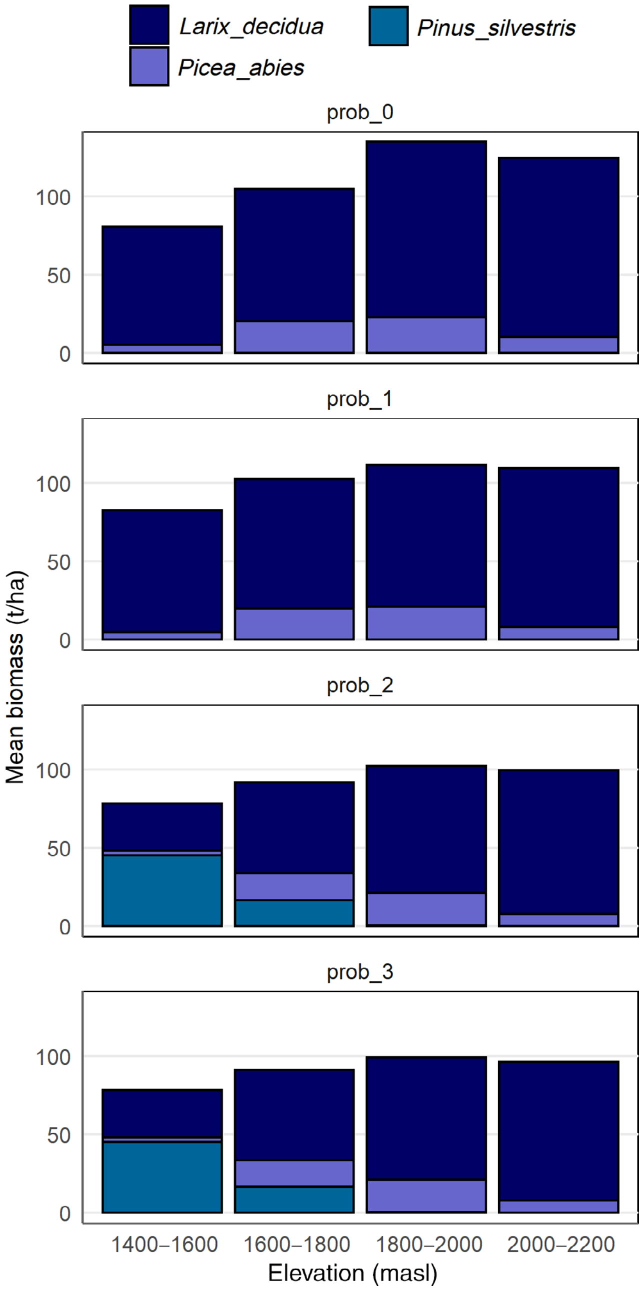

FIGURE 5 Mean biomass at the end of the simulation per elevation level and tree species and increasing rockfall disturbance probability (disturbance severity = sev_1)

Disturbance Module section). The maximum considered block volume was 20 m^3, and the estimated overall onset probability for blocks >0.05 m^3 was 103 blocks per year for the considered release area. RockyFor3D (Dorren, 2016) is a "probabilistic process-based" rockfall model that simulates flying, bouncing, and rolling blocks in three dimensions depending on the terrain and standing trees. The latter are considered spatially explicitly, and the energy reduction of a block is calculated after each tree impact depending on its diameter, the block volume, the impact height, and direction as well as the tree species (Dorren & Berger, 2006). We simulated each block volume

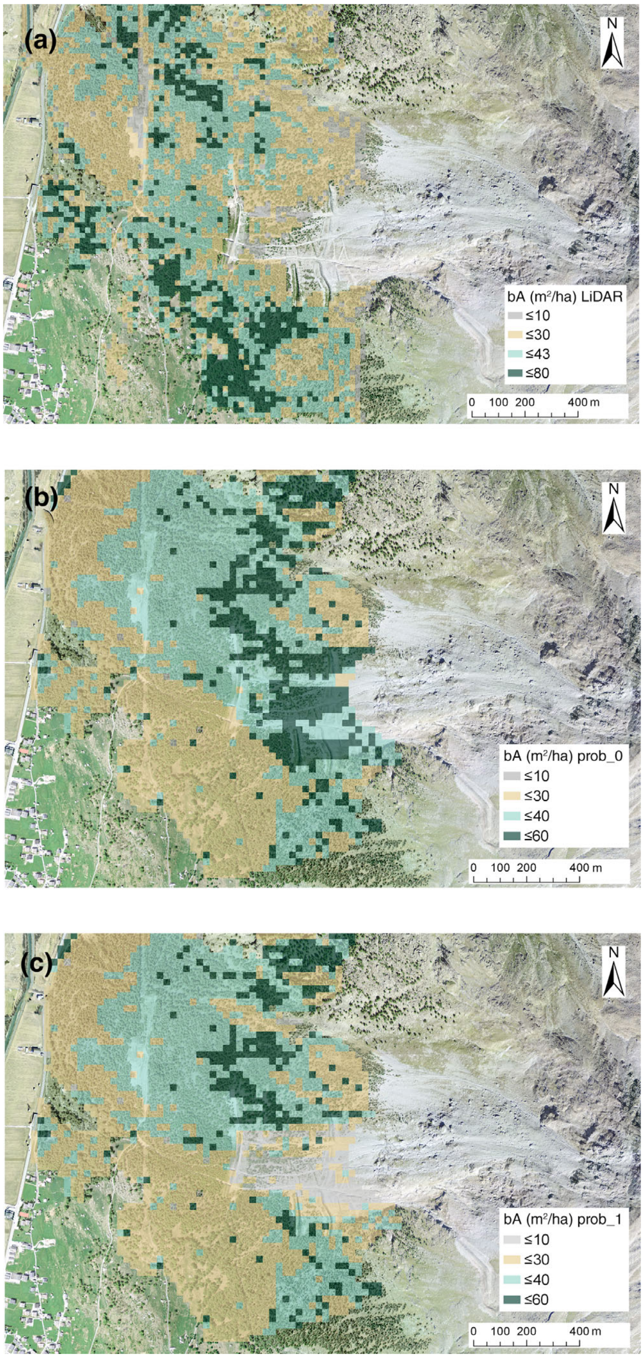

FIGURE 6 Basal area (bA) derived from a LiDAR-based canopy height model (limited up to 2000 masl) (a), and TreeMig simulations (simulated end state) without (b) and with (c) rockfall disturbance

class 100 times per start cell with uniformly sampling the block volume from the respective volume class for each simulation (total number of simulations of ~75,000). The release area and slope characteristics (soil types and soil roughness) were determined based on the digital terrain model, orthophotos, and field surveys. We used a digital terrain model with a resolution of 2 m for the simulations. Block deposits measured in sample plots across the slope (see also Moos et al., 2020) and inventory data from cantonal authorities served for validation of the simulated rockfall runout zones, which were judged as plausible.

RESULTS

Forest development in dependence of varying disturbance probability and severity

The simulations with rockfall disturbance (prob_1) resulted in a *L. decidua* dominated forest with *P. abies* trees mainly in the southern part. The mean bA varies between 30 and 45 m^2/ha and decreases to <10 m^2/ha in the highly active rockfall zones. The tree density ranges between 400 and 1000 stems/ha with up to 1500 stems/ha at lower elevation in the northern part, and the mean diameter (dbh) of *L. decidua* is between 15 and 30 cm and of *P. abies* between 13 and 17 cm. The simulated forest is thus slightly denser and has smaller dbh than the current forest, but with a comparable bA (Figure 4). The current forest has a tree density between 300 and 400 stems/ha and a dbh varying between 15 cm in the zones with high rockfall activity and 35 cm in the

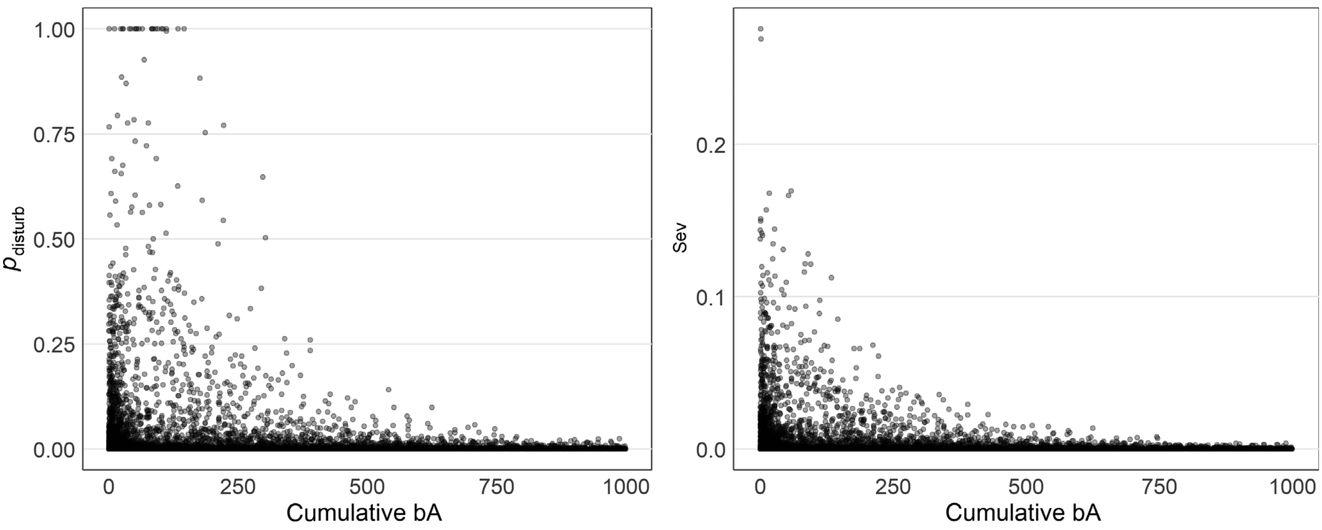

FIGURE 7 Disturbance probability (left) and severity (right) (*y*-axis) versus the cumulative basal area (*x*-axis) of the forest

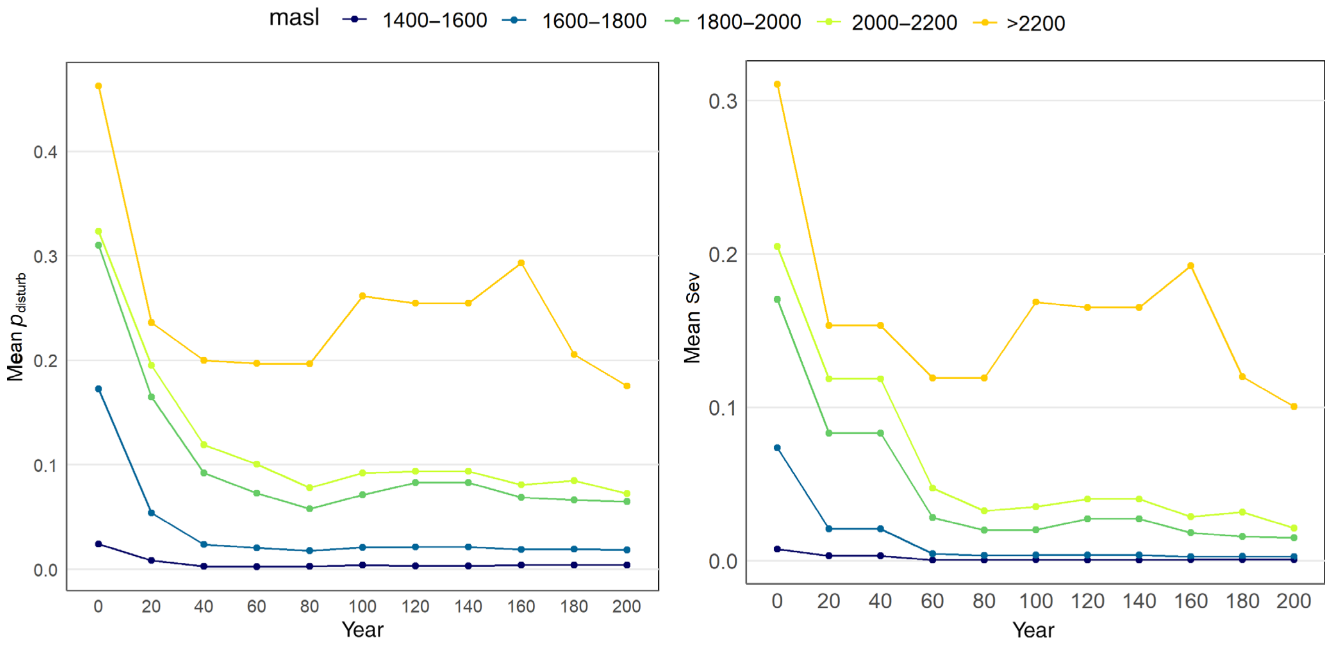

FIGURE 8 Evolution of mean disturbance probability (left) and severity (right) of the stand with rockfall-forest feedback over a period of 200 years and for different elevations

parts with low rockfall activity. The bA varies between ~8 m^2/ha in the rockfall-prone area and 40 m^2/ha in the less active zones.

The bA of the total forest is slightly reduced with rockfall disturbance compared to the undisturbed forest (disturbance probability = prob_0) with differences being relatively small on stand scale (Figure 4). The mean bA and mean dbh of the forest's end state are significantly lower with than without disturbance for both *L. decidua* and *P. abies*. Likewise, the total biomass of the stand also decreases with increasing disturbance, with the effect increasing with elevation (Figure 5). With an enhanced disturbance probability (prob_2, prob_3), the model predicts small abundances of *P. sylvestris* and *Fagus sylvatica* (<5 m^2/ha; not shown) in the lower part of the slope (Figure 5 and Appendix S3).

Comparison with current forest cover

The comparison of the modeled bA to the LiDAR-derived bA showed a distinctly better agreement when considering the rockfall disturbing effect (Figure 6 and Appendix S4). Without disturbance, the bA is clearly overestimated for a part of the cells with low bA (marked orange in Appendix S4, on the left). This corresponds to the highly active rockfall zone in the upper part of the slope, where the forest line is actually lowered due to the disturbing effect of rockfall and other natural hazard processes. Without rockfall disturbance, this part is forested in the model (Figure 6b). With rockfall disturbance (disturbance probability = prob_1; Figure 6c), the forest extent comes closer to the actual forest cover (Figure 6a).

Rockfall-forest feedback

The accuracy of the statistical models for predicting disturbance probability and severity depending on the changing forest properties was good. The model for p_{disturb} ($\mathrm{GLM}_{\mathrm{disturb}}$) yielded a R^2 of 0.91 and a root mean square error (RMSE) for the validation data from the second site of 0.65 (compared to a RMSE of 0.41 for the calibration data; see Appendix S5). The R^2 of the model for Int ($\mathrm{GLM}_{\mathrm{Int}}$) is 0.93 and the RMSE of the validation data 0.63 (compared to a RMSE of 0.38 for the calibration data; see Appendix S5).

p_{disturb} and Sev with a forest cover of 10–350 years are significantly smaller than p_{disturb} and Sev for the bare ground situation. The disturbance probability is reduced approximately by half and the disturbance severity to one-third after 10 years of simulations (Appendix S6: Figure S1). This effect can on the one hand be explained by the fact that standing trees stop and decelerate falling blocks and thus reduce the impact probability of trees further downslope. On the other hand, the bare ground disturbance severity is based on the general propagation probability of blocks in a cell, while the disturbance severity with forest cover corresponds to the modeled probability of the trees being actually killed by a block ($p_{\mathrm{kill\_tree}}$). The latter is significantly lower than the tree's probability of being hit ($p_{\mathrm{imp\_tree}}$; Appendix S6: Figure S2). The statistical models further revealed a clear decrease in the disturbance probability and severity with increasing bA_cum (Figure 7).

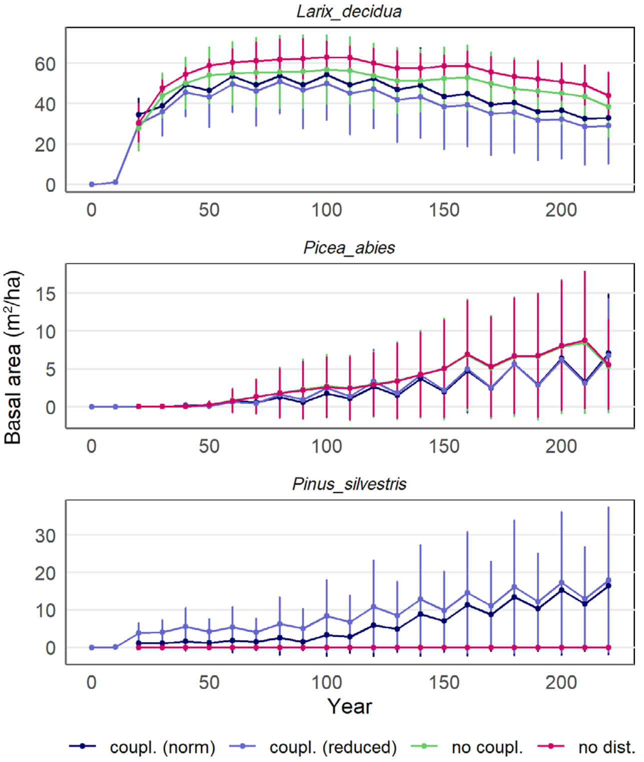

FIGURE 9 Mean basal area with standard deviation of *Larix decidua*, *Picea abies*, and *Pinus sylvestris* over 200 years of forest development simulated with constant disturbance (no coupl.), feedback disturbance with reduced bucket size in the high-intensity rockfall areas (coupl. reduced) and without reduced bucket size (coupl. norm.) and no disturbance (no dist.)

Based on the simulation with forest-rockfall feedback, both disturbance probability and severity clearly decrease after 10–40 years of forest development (Figure 8). In the lower part of the forest (<2000–2200 m asl), they then remain constantly low in our simulation, but increase partially in the upper part, where rockfall activity is highest. However, they generally remain below the initial bare ground disturbance probability and severity.

The total bA of the forest after 200 years of forest development with forest-rockfall feedback is comparable to the bA with constant disturbance (prob_1) and slightly

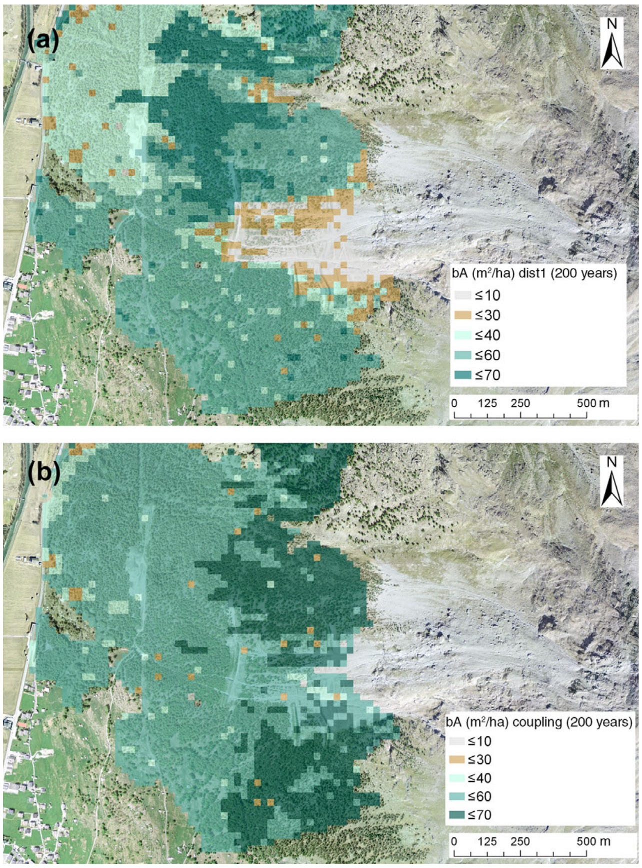

FIGURE 10 Basal area (bA) after 200 simulated years with constant bare ground disturbance (a) and forest-feedback disturbance (b)

reduced compared to the simulations without disturbance (prob_0) (Figure 9). With forest-rockfall feedback, however, *P. sylvestris* grows in the lower part of the slope. Furthermore, the highly active rockfall zone, which is hardly forested with constant bare ground rockfall disturbance, gets almost entirely invaded by *L. decidua* trees and the bA of *L. decidua* in the upper part of the slope is higher (Figure 10). Reducing the bucket size in the high-intensity rockfall zones results only in a slightly smaller bA in the respective cells.

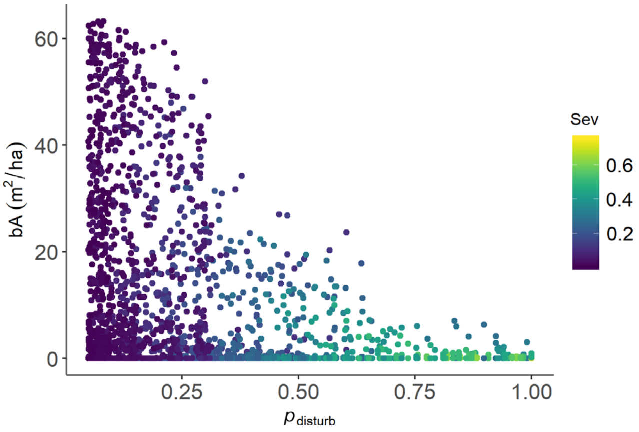

FIGURE 11 Basal area (bA) after 220 years of forest simulation with temporally constant disturbance (prob_1; sev_1) as a function of the disturbance probability (*y*-axis) and severity (color)

DISCUSSION AND CONCLUSION

The methodological framework presented in this study allows for integration of the disturbing effect of rockfall in the dynamic forest model TreeMig by an indirect coupling with rockfall simulations. The forest simulations with a constant rockfall disturbance resulted in a more realistic representation of the forest cover. Only when considering the disturbing effect of rockfall, forest growth could be suppressed in the highly active and tree-free rockfall zone. This is generally in line with the results of a recent empirical study on the disturbing effect of rockfall (Moos et al., 2020). They found significantly reduced tree diameters and bA with increasing rockfall disturbance at the same site. In general, the simulated forest stand was denser with lower diameters compared to the current forest. Thereby, diameters clearly decreased in the last 50 years of the simulations (Appendix S7). This indicates that the current forest corresponds rather to an earlier simulation state (~300 years). Stoffel et al. (2005), who took cores of 135 trees on the slope, reported an average age of 297 years of the sampled trees, which well corresponds to our simulation results. It is very likely that the forest was extensively used in the part adjacent to the village until the beginning of the 20th century due to the large dependence of the mountain population on wood and other forest products (Mather & Fairbairn, 2000; Stuber & Bürgi, 2002).

The forest biomass is sensitive to the disturbance severity and probability on local scale, whereas only small differences can be observed on stand scale. The results of our study indicate that forest growth is impeded in case rockfall disturbance severity and frequency reach certain thresholds. A clear decrease in the bA is observable for $p_{\text{disturb}} > 0.25$ and $\text{Sev} > 0.3$. With $p_{\text{disturb}} > 0.6$ and $\text{Sev} > 0.4$, forest growth is almost completely suppressed (Figure 11). This means that a cell is impacted more than every 2 years and 40% of the cell is destroyed. This is a rather high disturbance probability and severity for single falling blocks, but quite realistic in the high-intensity rockfall zone in the uppermost part of our study site, whereas impacts are probably more frequent on average, but with a lower intensity. Interestingly, an enhanced rockfall disturbance (prob_2, prob_3) led to a small abundance of *P. sylvestris* in the lower part of the slope. This is likely due to the increased mortality of the competitors *L. decidua* and *P. abies* also in the lower parts of the slope, where temperature is not limiting for the growth of *P. sylvestris*.

The dependence of disturbance probability and severity on rockfall propagation and forest characteristics could be well captured with the implemented statistical models. The validation of the models with data from the second site in Nax suggests that they can be satisfactorily transferred to other rockfall forests. The coupled simulations revealed a clear feedback effect of rockfall disturbance and forest development. Disturbance probability and severity clearly decreased with advancing forest development and increased again in the upper part of the slope, which is probably an effect of self-thinning of the forest. In the beginning, the forest grows very fast due to low concurrence and high light availability resulting in high stem densities and a high bA and, thus, a reduction of the rockfall disturbance in the lower parts. With decreasing stem density and bA, the rockfall disturbance increases again. However, the comparison with the actual forest cover indicates that the disturbing effect of rockfall is underestimated in the coupled simulations compared to the simulations with a constant disturbance. The disturbed areas are recolonized very fast when the disturbance decreases slightly due to low competition. A problem might be that the effect of difficult soil conditions in the rockfall-prone areas (e.g., missing soil material, loose material, and remobilization of soil) is underestimated in the model, even though we assumed a decreased water holding capacity in the high-intensity rockfall zones. However, along with water availability, nutrients may be limited and thus impede recolonization of the highly disturbed areas. This implies that a more complex deterministic model of soil generation, water and nutrient availability (e.g., Speich et al., 2018), and its effect on regeneration would be necessary to satisfactorily represent the rockfall-forest feedback. The fast recolonization could also be related to a general overestimation of *Larix* biomass and overshooting effects in the first 50 years. Furthermore, other disturbances, such as snow avalanches, may enhance the rockfall effect at our case study site (Stoffel et al., 2005).

In addition to a better representation of the effect of changing soil conditions, future development of this adapted version of TreeMig should include the consideration of long-term effects of the rockfall disturbances. Pests and diseases may affect damaged trees through scars causing tree death after several years (Stoffel & Hitz, 2008; Woltjer et al., 2008). However, quantitative knowledge on the severity and the temporal evolution of these consequential damages is missing. Generally, the severity of tree damage depends on the size of the block, its impact velocity, the position of the impact, the tree's diameter, and species (Dorren & Berger, 2006). It is thus difficult to determine general long-term survival rates of impacted trees.

In conclusion, the presented rockfall disturbance module clearly improved the modeling of a rockfall protection forest with TreeMig. It provides new quantitative evidence on the impact of rockfall disturbance on forest structure and development, which can support the management of protection forests. Differences are observable mainly on local scale and, thus, the inclusion of the rockfall module is particularly relevant for small-scale studies requiring a detailed representation of spatial differences in forest cover. This is, for example, the case in natural hazard risk assessments and protection forest planning (e.g., Moos et al., 2016). Still, a cell-based forest model remains limited in representing local differences in forest structure potentially relevant for the protective effect of the forest. Our case study further indicates that the protective effect of the forest remains generally stable despite the regular rockfall disturbances. Over the total forest complex, the bA changes only slightly, and, thus, the protective effect will only be marginally affected. This is, however, only valid for relatively small and diffuse rockfall events, and not for large rock avalanches that can destroy entire parts of the forest.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

Data and code are available from Zenodo as follows: input of rockfall simulations and calculated disturbance probabilities and severities (Moos, 2021a), https://doi.org/10.5281/zenodo.5670505; results of the forest simulations with TreeMig (Moos, 2021b), https://doi.org/10.5281/zenodo.5670307; and R code of statistical "metamodel" of rockfall disturbance (Moos, 2021c), https://doi.org/10.5281/zenodo.5670562. The code of the forest model TreeMig including the adaptations made in this study (Moos & Lischke, 2021) is available from Zenodo: https://doi.org/10.5281/zenodo.5670596.

ORCID

Christine Moos https://orcid.org/0000-0001-9792-0345

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SUPPORTING INFORMATION

Additional supporting information may be found in the online version of the article at the publisher's website.

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