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The influence of climate change and canopy disturbances on landslide susceptibility in headwater catchments

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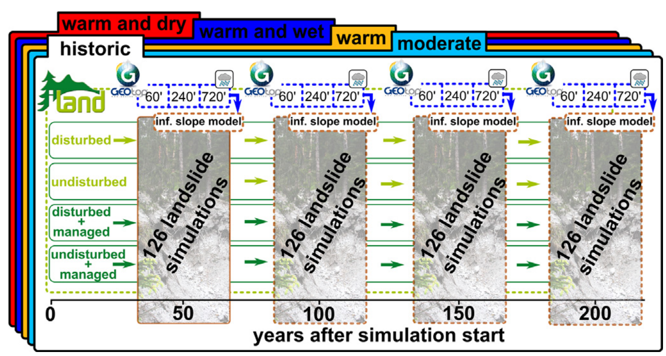
HIGHLIGHTS

- Climate change and disturbance regimes will alter the forest protective function against shallow landslides.
- Climate change generally increased landslide risk in our simulations.
- Only when future warming coincided with drying, the landslide risk decreased.
- The adaptation of tree species to future climate change conditions has a direct effect on the stability of forested slopes.
- Canopy disturbances reduce the risk of landslides, outweighing possible negative effects on the water cycle.

GRAPHICAL ABSTRACT



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ABSTRACT

Forests have an important regulating function on water runoff and the occurrence of shallow landslides. Their structure and composition directly influence the risk of hydrogeomorphic processes, like floods with high sediment transport or debris flows. Climate change is substantially altering forest ecosystems, and for Central Europe an increase in natural disturbances from wind and insect outbreaks is expected for the future. How such changes impact the regulating function of forest ecosystems remains unclear. By combining methods from forestry, hydrology and geotechnical engineering we investigated possible effects of changing climate and disturbance regimes on shallow landslides. We simulated forest landscapes in two headwater catchments in the Eastern Alps of Austria under four different future climate scenarios over 200 years. Our results indicate that climate-mediated changes in forest dynamics can substantially alter the protective function of forest ecosystems. Climate change generally increased landslide risk in our simulations. Only when future warming coincided with drying landslide risk decreased relative to historic conditions. In depth analyses showed that an important driver of future landslide risk was the simulated vegetation composition. Trajectories away from flat rooting Norway spruce (*Picea abies* (L.) Karst.) forests currently dominating the system towards an increasing proportion of tree species with heart and taproot systems, increased root cohesion and reduced the soil volume mobilized in landslides. Natural disturbances generally reduced landslide risk in our simulations, with the positive effect of accelerated tree species change and increasing root cohesion outweighing a potential negative effect of

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disturbances on the water cycle. We conclude that while the efficacy of green infrastructure such as protective forests could be substantially reduced by climate change, such systems also have a strong inherent ability to adapt to changing conditions. Forest management should foster this adaptive capacity to strengthen the protective function of forests also under changing environmental conditions.

1. Introduction

In steep headwater catchments, heavy rainfall events regularly lead to instabilities in soil masses, henceforth referred to as landslides. This is particularly relevant in areas with high population density and increasing land use development (Fuchs et al., 2017), where landslides caused not only damage to settlements and infrastructure but also personal injuries and even deaths (Andres and Badoux, 2018 Badoux et al., 2016 Dowling and Santi, 2014). However, in contrast to natural hazard processes also triggered by heavy precipitation events (e.g. avalanches, high sediment-laden floods or debris flows), the areas prone to landslides can rarely be identified prior to an event. This limits the implementation of technical protection measures, since such mitigation efforts are necessarily restricted to areas of high risk (van Westen et al., 2006 Choi and Cheung, 2013 Han et al., 2019). In the context of landslide protection “green infrastructure” is thus of high importance, i.e., the large-scale protective function of intact forest cover (Papathoma-Köhle and Glade, 2013 Schmaltz et al., 2017 Jaboyedoff et al., 2018). Protective forests can thus be seen as ecosystem-based solutions for disaster risk reduction (Eco-DRR), as many studies highlight the regulating function of forests on runoff (Beschta et al., 2000 Wang et al., 2012) and slope stability (Bathurst et al., 2010 Bezak et al., 2017 Moos et al., 2016).

A main function of protective forests in the context of landslide risk is the reduction and retention of water via interception, evaporation and sublimation (Aston, 1979 Hewlett, 1982). Interception and active transpiration by forests allows higher soil water storage, relative to areas without forest covers (Harding, 1992 Hudson, 1988 Markart, 2000). In addition, trees also influence the mechanical stability of soils (Keppeler and Brown, 1998 Rickli, 2001 Cohen and Schwarz, 2017). Specifically, forest vegetation can affect the stability of slopes (i) by acting as buttress piles or arch abutments in a slope (positive effect); (ii) through the weight of the vegetation (negative effect) and (iii) via uprooted trees (negative effect) (e.g. Gray and Megahan, 1981 Greenway, 1987 Philips and Watson, 1994). Modern landslide models, simulating the effect of vegetation on slope stability, therefore take both the modification of the soil moisture regime and the influence of root cohesion on the soil mantle into account (Anagnostopoulos et al., 2015 Burton and Bathurst, 1998 Cuo et al., 2008 Schwarz et al., 2010).

While forests provide important “green infrastructure” in the context of landslide risk protection, their regulating function is not constant over time. Forests are dynamic systems that naturally undergo a development through different vegetation stages. Forest structure (i.e., the vertical and horizontal distribution of biomass in a forest ecosystem) varies considerably over forest stand development, which in turn influences the protective function of forests. By modelling the spatial distribution of root reinforcement in spruce-dominated mountain forest landscapes of the Alps, Moos et al. (2016), for instance, suggest that forest structure, in addition to terrain and hydrological features, substantially influences slope stability. They found landslide susceptibility to be higher in forests with gap lengths of more than 20 m. The influence of forest structure on the regulating function of forests is crucial also in the context of forest management, because management can substantially modify forest structure.

In addition to natural stand development also the ongoing environmental changes can alter the structure and composition of forest ecosystems. In the context of expected increase in global average surface temperature of 3–5 °C by 2100 (IPCC, 2014) major threats to desired forest structures are natural disturbances (i.e., pulses of tree mortality triggered by climatic extremes) (Dale et al., 2001; Seidl et al., 2017). In Central Europe, for instance, disturbances have already increased in the past decades (Senf et al., 2018) and a climate-induced increase in forest disturbances is highly likely also for the future (Seidl et al., 2014). Based on data for more than 10,000 watersheds collected for the last 32 years in Austria Sebald et al. (2019) showed that such natural disturbances increase the probability of torrential hazard events in steep headwater catchments. They found that a regular occurrence of disturbances is the most detrimental reason for the occurrence of torrential events such as landslides. Markart et al. (2017) report that hillslope channel processes reached greater extents on windthrown areas compared to forested riverbanks.

Consequently, the future dynamics of forest structure and disturbance needs to be explicitly considered when assessing potential trajectories of future landslide risk protection. This is of particular relevance in areas such as Austria, where the current condition of protective forests suggests a high vulnerability to changes in climate and disturbance regimes (Seidl et al., 2011).

National Forest Inventory data, for instance, indicate that only half of the protective forests in Austria have satisfactorily ecosystem integrity (BMLFUW, 2015), which is attributed to a significant over-aging of protection forests (Niese, 2011) and a lack of regeneration, making these forests particularly sensitive to natural disturbances.

Although considerable efforts are being made to improve or maintain the protective effect through management measures (Frehner et al., 2005), the effects of climate-induced changes in natural disturbance regimes on the protective effect against landslides remain poorly understood.

Here we simulated the frequency, extent, and severity of natural disturbances under climate change for two forested headwater catchments and analysed the resultant responses of forest structure and composition on landslide susceptibility. Our work is structured as follows: After specifying the study area, a comprehensive description of the applied methodology is provided. We further elaborate on how the results of land development modelling are incorporated into hydrological and geotechnical calculations to determine the susceptibility of landslides. Subsequently, landslide simulations of the forested landscapes, driven by different climate change projections, are compared with landslide simulations accounting for forested landscapes without climate change assumptions. Finally, climatic conditions that pose a challenge to the existing vegetation, reflected by natural disturbances, are discussed in the context of a changed landslide susceptibility.

2. Materials and methods

We chose an interdisciplinary analysis approach that incorporates state-of-the-art methods from forestry, hydrology and geotechnical engineering. Fig. 1 shows we combined the applied methodologies to study future landslide risk at the catchment scale. Based on four climate scenarios, forest landscape simulations with the model iLand were conducted for two selected headwater catchments in order to determine the alteration of landslide-relevant forest indicators under particular consideration of future canopy disturbance regimes. The climate projections used in this study account for different combinations of temperature and precipitation change, representing a warm, warm and dry, as well as a warm and wet future; in addition, also a scenario of only moderate change in future climate conditions was considered. In addition, a

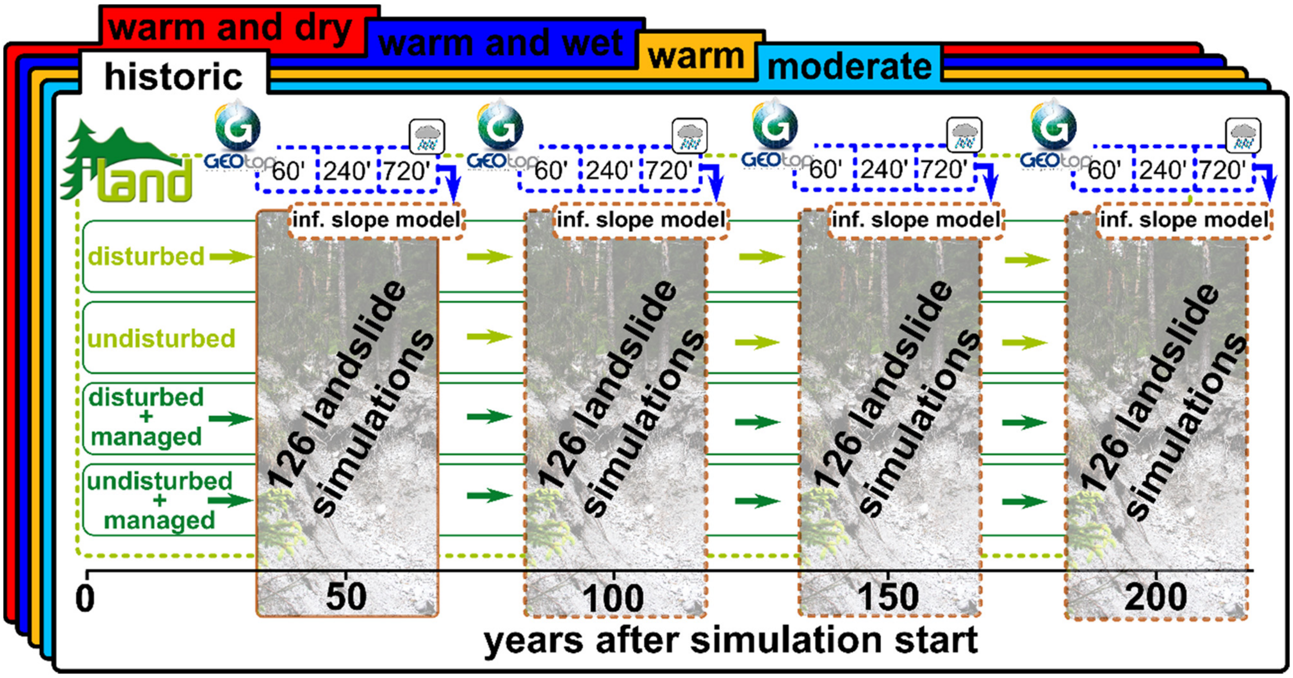


Fig. 1. Flowchart of the methodology, combining a forest landscape and disturbance model (iLand) with a hydrological model (GEOtop) and an adapted version of an infinite slope stability model, as applied for one catchment,.

reference scenario of stable historic climate was simulated to serve as benchmark for the analysis of climate change effects. All forest landscapes were simulated with and without management as well as with and without natural disturbances, allowing us to disentangle the effects of forest management and natural disturbances on forest development and landslide risk. The susceptibility of landslides within the simulated landscapes was then estimated for each climate scenario based on three different precipitation design events, using the distributed hydrological model GEOtop and an adapted version of an infinite slope stability model. All landslide simulations were compared to simulations under historic climate (i.e. assuming no climate change). In total, 840 forest landscape simulations and more than 5000 landslide simulations have been carried out. The high number of simulations was required to account for the stochastic nature of the processes under study.

2.1. Study area

The study area covers two steep headwater catchments, the "*Äußerer Lehnertalbach*" and the "*Innerer Lehnertalbach*", with approximate areas of 0.48 km^2 and 1.78 km^2, respectively. Both catchments are situated in the Stubai valley (Tyrol) in the western part of Austria (Fig. 2), and are characterized by a humid and temperate continental inner-alpine climate, with short wet and cool summers and long, cold and snowy winters. Situated in a high alpine moraine landscape, geology is dominated by metamorphic lithologies (mainly schist) with soils consisting of lime-free cambisols, showing a moderate water storage capacity and permeability. The current vegetation is a typical example of mountain forest ecosystems of the central eastern Alps, dominated by Norway spruce (*Picea abies* (L.) Karst.), European larch (*Larix decidua* L.) and Swiss stone pine (*Pinus cembra* L.). The "*Äußerer Lehnertalbach*" has a forest cover of 83%, whereas the "*Innerer Lehnertalbach*" has a forest cover of 36%.

The steepness in combination with the small size of the catchment area results in a high relief energy. Based on the geomorphological process type assessment method proposed by Heiser et al. (2015), debris flows are likely to be the dominant relocation process, which suggests that sediment availability and landslide susceptibility is high. For the "*Innerer Lehnertalbach*" a devastating debris flow event is documented to have occurred in October 1882. In addition, several multiple flood events with high sediment transport were reported in the course of the late 20th century - the last documented event occurred in 2005.

2.2. Forest landscape projections and climate scenarios applied

The future development of the forest landscapes for the study area was simulated with the individual-based forest landscape and disturbance model iLand (Seidl et al., 2012). iLand operates on the grain of individual trees and uses a light-use efficiency approach for resource utilization. Environmental constraints on resource utilization are considered on a daily time step. The model includes process-based disturbance modules for wind and bark beetles, directly influencing simulated forest development. For each output cell (10 × 10 m in this analysis), the years since the last disturbance were recorded. Further, forest management is simulated at a high level of detail in iLand (Rammer and Seidl, 2015). The model has been successfully applied in several Central European landscapes previously (Dobor et al., 2018 Seidl et al., 2019 Thom et al., 2017), and has been thoroughly tested and evaluated for the Stubai valley landscape under study here (Albrich et al., 2020 Seidl et al., 2019). For this study the results of iLand simulations are used as the basis for all hydrological and slope stability related assessments within the two selected headwater catchments.

To illustrate the influence of possible climate change scenarios, we chose four representative EUR-11 climate projections (Jacob et al., 2014) based on three different global circulation models and two representative concentration paths (RCP). Generally named after the anthropogenic radiative forcing at the end of the century, compared to the pre-industrial year 1850, RCP scenarios are expressed as the assumed increase in the radiative forcing per unit area (W/m^2). The applied global models have independently been conducted by the Irish Center for High-End Computing (ichec), the Pierre Simon Laplace Institute (ipsl) and the MetOffice Hadley Center (mohc). To cover a large variability of future greenhouse gas emissions we applied all three global models driven by the RCP 8.5 scenario – denoted as ichec8.5, ipsl8.5 and

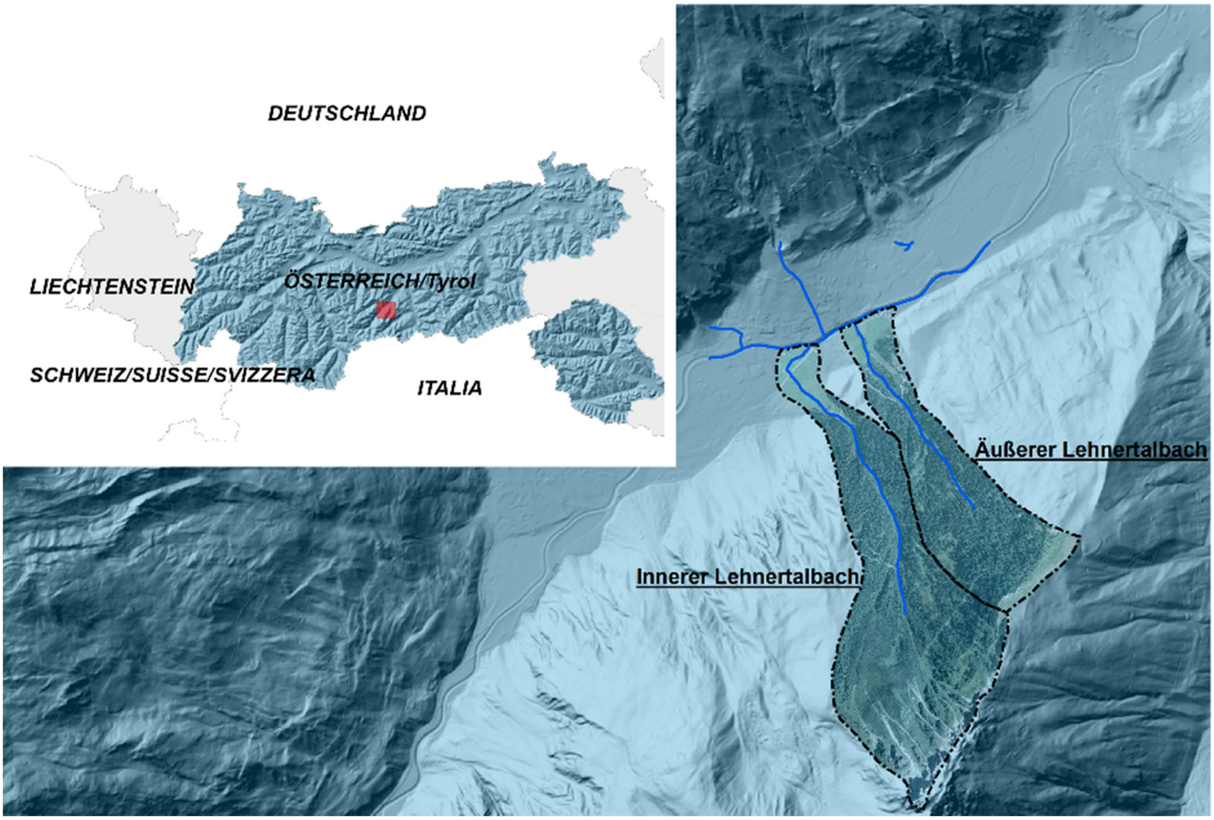


Fig. 2. Situation of the study area, showing the location of the two steep headwater catchments under consideration and their forested area.

mohc8.5. Those climate projections can be classified as high in terms of energy increase (8.5 W/m^2). Additionally, we also applied the ichec model driven by a RCP 4.5 scenario – denoted as ichec4.5- which accounts for a medium increase in radiative forcing of 4.5 W/m^2. All results from global climate modelling were downscaled to 100 m grid cells using a two-step approach of regional climate modelling and statistical downscaling. Henceforth we refer to the ichec4.5 scenario as "moderate", the ichec8.5 scenario as "warm", the ipsl8.5 scenario as "warm and wet" and the mohc8.5 as "warm and dry". The temperature and precipitation differences of all Eur-11 climate projections for the period 2071–2100 compared to 1981–2010 are shown in Fig. 3.

In addition to making projections under future climate scenarios, forest landscape simulations were conducted assuming no climate change, serving as a reference scenario with stable environmental conditions. This climate scenario is denoted as "historic" throughout the text and was based on observations for the period 1961 to 2015. Historical climate data is based on combined 1 × 1 km INCA and SPARTACUS data provided by the Central Institute for Meteorology and

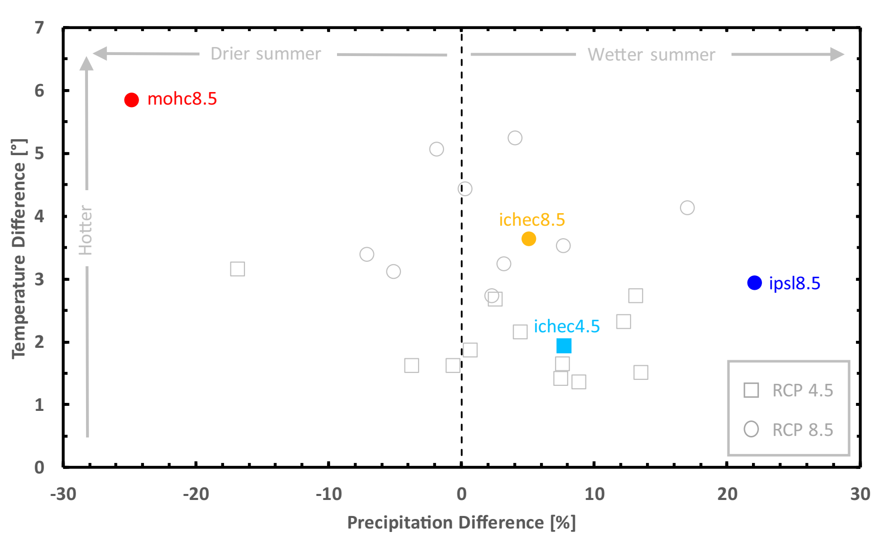


Fig. 3. The climate scenarios studied here (labelled and filled) relative to the full EUR-11 dataset (blank), expressed as average temperature and precipitation differences of the period 2071–2100 relative to 1981–2010 for the summer season. The four filled and coloured datapoints are the climate scenarios used in this study: **mohc8.5**: "warm and dry", **ichec8.5**: "warm", **ichec4.5**: "moderate" and **ipsl8.5**: "warm and wet". (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Geodynamics (ZAMG) and observation series of ZAMG weather stations, as well locally installed climate monitoring. An overview of the iLand simulations is provided in Table 1.

For each of the four climate change projections, the development of the forest landscape was simulated over 200 years. All climate forcings were simulated as the full combination of disturbed and undisturbed as well as managed and unmanaged scenarios (cf. Table 1). To faithfully represent the disturbance regime of the area, simulations were conducted for the forest area of the entire valley rather than the two small focal catchments of the current study. Furthermore, 20 replicates were simulated to account for stochastic effects of disturbance.

The simulated future forest share and the distribution of forest parameters of the study areas form the basis for estimating key indicators to predict landslide susceptibility. Table 2 lists the forest indicators used for landslide prediction, which have been derived either directly or indirectly from the iLand simulations.

2.3. Landslide modelling

To analyse landslide susceptibility, areal information on subsurface flow and groundwater related effects, influencing soil moisture content, are important phenomena when simulating slope stability. Hence, distributed hydrological models provide the greatest possible spatial information – although their parametrization is complex. For this study, simulations have been carried out with the physically based, grid-distributed hydrological model GEOtop (Rigon et al., 2006). GEOtop calculates the interactions between different processes of the atmosphere, biosphere, hydrosphere, cryosphere and lithosphere. The model has been extensively tested and validated (Bertoldi, 2004), providing accurate simulations of evapotranspiration and soil moisture dynamics (Bertoldi et al., 2014 Chiesa et al., 2014). GEOtop has been extended for soil erosion by rainfall and overland flow (Zi et al., 2016) and for landslide occurrence (Simoni et al., 2008). Similar to the landslide prediction model proposed by Simoni et al. (2008), we here combined GEOtop (to compute soil moisture content in 3-D) with a slope stability model following the infinite slope concept. The applied slope stability model in this study used key forest indicators as input values, as provided by the iLand landscape simulations (Table 2).

Table 1
iLand landscape setup scenarios as applied in Seidl et al. (2019).

Landscape development scenarios (iLand)	Description
General	
Simulation perimeter (forest)	4811 ha; Stubai-valley surrounding the two study catchments "*Äußerer Lehnertalbach*" and "*Innerer Lehnertalbach*"
Elevation range forest	900–2000 (m asl)
Simulated time period	2001–2200
Spatial grain	Individual tree
Management scenarios	
Managed	The entire landscape is managed, including salvage harvests according to recommendations of the local forest management agency (Amt der Tiroler Landesregierung, 2013). Management is based on a skyline track system with small-scale openings of the canopy in slit-shaped gaps.
Unmanaged	No active forest management, no salvaging.
Disturbance scenarios	
Disturbed	Influence of natural disturbances on landscape development is dynamically simulated in iLand. Modules for wind and bark beetles are employed. Information about the occurrence of wind events is derived from climate scenarios.
Undisturbed	No influence of disturbances on landscape development
Climate scenarios	
ichec4.5 "moderate"	Global model: ICHEC-EC-EARTH Regional model: KNMI-RACMO22E Radiative forcing scenario: RCP 4.5
ichec8.5 "warm"	Global model: ICHEC-EC-EARTH Regional model: KNMI-RACMO22E Radiative forcing scenario: RCP 8.5
ipsl8.5 "warm and wet"	Global model: IPSL-CM5A-MR Regional model: IPSL-INERIS-WRF331F Radiative forcing scenario: RCP 8.5
mohc8.5 "warm and dry"	Global model: MOHC-HadGEM2-ES Regional model: CLMcom-CCLM4-8-17 Radiative forcing scenario: RCP 8.5
"historic"	Combined INCA and SPARTACUS grid data for the period 1961–2015

Changes in slope stability were examined spatially explicitly and for different soil depths after 50, 100, 150 and 200 simulation years of the forest landscape model. Modelling of soil moisture content and subsequent slope stability simulations were conducted for three design rainfall events with high intensities and low recurrence intervals, independently of the climate scenarios used for landscape simulations. Table 3 shows an overview of the simulation design and number of simulations conducted for each catchment.

Topographical information of the current conditions of the selected catchments were based on digital elevation models (DEM) with a grid size of 10 × 10 m.

2.3.1. Design rainfall event

To simulate soil moisture, we defined three design precipitation events of varying duration (60 min, 240 min and 720 min) based on a 100-year recurrence interval. The design precipitation events resulted from the area-averaged MaxMod precipitation data of grid points close to the study catchments (Table 4). Design precipitation probabilities of MaxMod values are provided by the Austrian Federal Ministry for Sustainability and Tourism via eHYD (https://ehyd.gv.at/; October 16th, 2019). MaxMod values are based on simulation models calibrated with measured data and accounting for local topography.

2.3.2. Soil moisture simulations

In GEOtop land use influences the hydrological storage capacity of the catchment. This influence is represented by considering different vegetation classes, consisting of a non-arable and several forested classes. In our study, forested classes were the result of the forest indicators leaf area index, crown cover and root depth – derived directly from iLand and averaged over the 10 × 10 m simulation grid size. Leaf area index and crown cover could be directly derived from iLand simulations, whereas rooting depth was estimated based on the iLand simulation output regarding tree species, diameter at breast height and leaf area index (c.f. Table 2). The simulation range of GEOtop in this study runs from 07:00 in the morning until the same time the following day with a time step of 60 s to solve the energy and water balance. Discharge was extracted every 5 min whereas spatially distributed soil moisture values were recorded every 30 min.

Surface runoff in the channel and along the hillslopes was determined by routing the effective precipitation (part of total precipitation that reaches stream channels as direct runoff) based on rainfall duration and recurrence as well as the time of concentration i.e. the time a water particle needs (without any significant soil storage) from the outermost point of the watershed to the area outlet. Besides form parameters for the watershed such as slope and length of the flow the time of concentration depends on the resistance to flow, which is reflected by Manning's empirical hydraulic approach. The interaction with the lithosphere is described by soil physical parameters. Pedological characteristics differ with depth. Each soil type consists of different soil layers which are individually characterized by their physical properties (Table 5). The determination of soil type and soil texture is based on existing field surveys of the study areas.

Beside the maximum saturation for each soil type, additional capacity and conductivity parameters of the individual soil layers were

Table 2
Key forest indicators (derived from iLand at the level of 10 × 10 m grid cells), with information on their relevance in the hydrogeomorphic simulations.

Forest indicators for predicting landslide susceptibility	Landscape output (iLand)	Hydrological input (GEOtop)	Infinite slope model input
Leaf area index LAI [m²/m²] *Defined as the single-sided green leaf area per unit ground surface area.*	Direct output	*For land use clustering.*	–
Vegetation height [m] *Describing the mean height of all tree per pixel*	Direct output	Direct input.	–
Diameter at breast height DBH [cm] *The mean tree diameter measured at 1.3 m height from the ground.*	Direct output	*For land use clustering.*	–
Canopy cover [0–1] *Defined as proportion of the ground area that is covered by tree crowns.*	Direct output	*For land use clustering.*	–
Tree species *Defined as the identity of each tree species*	Direct output	–	*Defines root system classification (tap-, heart- and flat root system)*
Rooting depth [m] *Average soil depth reached by the roots of an individual tree.*	–	*For land use clustering.*	Direct input. *Based on literature values for rooting systems/tree species and quantile matching of root mass distribution.*
Biomass in stem, branch and foliage compartments [kg] *Dry mass in different compartments of a tree*	Direct output	–	Direct input.
Root mass [kg] *Biomass in fine- and coarse-root compartments*	Direct output		Direct input. *Defines root cohesion and root depth* via *quantile matching of root mass distribution.*
Root cohesion [kPa] *Apparent cohesion of roots that can mechanically reinforce shallow soils in forested landscapes*	–	–	Direct input. *Based on literature values for rooting systems/tree species and quantile matching of root mass distribution*

defined by the water content at wilting point, field capacity, as well as the conductivity at saturation and unsaturation, respectively. All soil parameters were determined by means of pedotransfer functions based on the soil texture content proposed by Saxton and Rawls (2006). We assumed isotropic soils, meaning that the hydraulic conductivity in horizontal and vertical directions is identical. The conductivity in the unsaturated soil matrix is calculated by van Genuchten values. Those values can be determined from soil texture according to Carsel and Parrish (1988).

For the selected torrential catchments, like for nearly 96% of all torrential catchments in Austria, no information about past rainfall-runoff events exists (Kohl et al., 2010 Blöschl et al., 2018). This is mainly because of the lack of continuous discharge measurement devices (water gauges). For this reason, we validated GEOtop with the precipitation/runoff (P/R) model ZEMOKOST – an event-based concept-model, specially developed for the application in small to medium-sized (<100 km²) ungauged torrential catchments (Kohl, 2011 Stepanek et al., 2004). The main input parameters of ZEMOKOST, runoff coefficient and surface roughness, were determined in the field, following the approach developed by Markart et al. (2011). ZEMOKOST was then calibrated and checked for plausibility for the two catchments using the existing precipitation and discharge time series.

Table 3
Design matrix of conducted forest, soil and slope stability simulations for each catchment.

Forest landscape model runs for each climate scenario					
Climate scenarios	ichec 4.5	ichec 8.5	ipsl 8.5	mohc 8.5	"historic"
Disturbance scenarios	Disturbed		Undisturbed		
Management scenarios	Managed	Unmanaged	Managed	Unmanaged	
Number of iLand simulations	20	20	1	1	

Soil moisture and slope stability modelling for all climate scenarios												
Years after simulation start (YaSS)	50 years			100 years			150 years			200 years		
iLand simulations for all climate scenarios per YaSS	210[a]			210[a]			210[a]			210[a]		
Design precipitation duration [min]	60	240	720	60	240	720	60	240	720	60	240	720
Number of conducted simulations per YaSS	630			630			630			630		
Number of total simulations	2520											

[a] The number results from 40 disturbed (managed/unmanaged) plus 2 undisturbed (managed/unmanaged) iLand-Simulations times 5 climate scenarios.

2.3.3. Slope stability simulations

Changes in landslide susceptibility were determined based on a modified version of an infinite slope stability model which estimates the factor of safety as the ratio between the sum of resisting forces and sum of driving forces at a certain soil depth. Safety factors of less than one correspond to unstable hillslopes or slopes at risk of sliding.

The applied slope stability model predicts the factor of safety for each soil layer. It accounts for root cohesion (bonding) that may act in each soil layer, pore water pressure as well as additional pressure from the weight of vegetation. Hence, the factor of safety for a specific soil column of simulation i is a function of forces acting at soil depth l and the simulated soil moisture at time t (with $\Delta t = 30min$), and can be estimated by:

$$FS_i(l,t) = \frac{B + \left(A - \sum_{k=1}^{l} h(k) * m_i(k,t)\right) * \frac{\tan(\phi(L))}{\tan(\beta)}}{A} \quad (1)$$

In Eq. (1), $h(k)$ denotes the depth of layer k, $\phi(L)$ is the internal angle of friction constant for the whole soil depth L and β is the slope angle of

Table 4
Design precipitation values simulated for the two study catchments.

Recurrence [years]	Duration [min]	Design precipitation [mm/h]	
		"Äußerer Lehnertalbach"	*"Innerer Lehnertalbach"*
100	60	94.65	88.85
	240	23.66	22.21
	720	7.89	7.40

Table 5
Maximum saturation and soil texture of different soil types per soil layers.

Cumulative depth [m]	Maximum saturation θ_s [−] and soil texture[a] of soil types									Layer
	Fi9	Fs1	Fs3	FT1	FT2	La2	La5	Zi1	Fs8	
	0.56 (SL)	0.59 (SL)	0.71 (Si)	0.55 (L)	0.62 (L)	0.59 (SiL)	0.60 (SL)	0.60 (SL)	0.60 (SiL)	1
0.05										
			0.66 (SiL)	0.39 (L)	0.47 (L)	0.45 (SiL)		0.42 (SL)		2
0.09										
		0.53 (SL)	0.46 (SiL)							3
0.12										
		0.41 (SL)			0.45 (L)		0.42 (SL)			4
0.22										
	0.42 (SL)	0.40 (SCL)					0.47 (SL)			5
0.36										
							0.42 (SCL)	0.47 (SL)		6
0.45										
		0.39 (SCL)						0.42 (SCL)		7
0.51										
	0.40 (SL)		0.39 (L)				0.40 (SCL)			8
1.00										

[a] Soil texture according to NRCS: L (loam), SCL (sandy clay loam), Si (silt), SiL (silty loam) and SL (sandy loam).

the soil column. The saturation of layer k at time t is denoted as $m_i(k,t)$ given by Eq. (2):

$$m_i(k,t) = \frac{\theta_i(k,t)}{\theta_{sat}(k)} \tag{2}$$

where $\theta_i(k,t)$ is the soil water content of layer k at the time t for simulation i, as calculated by GEOtop. $\theta_{sat}(k)$ is the saturated water content (c.f. Table 5), $\gamma_{sat}(k)$ is the specific weight of the saturated soil and $\gamma(k)$ is the specific weight of the dry soil.

The term A in equation ( ) equals to the effective normal stress factor, resulting from the soil and plant weight - reduced by the pore water pressure. It is derived by means of Eq. (3):

$$A = \gamma_w^{-1} * \left(q_i + \sum_{k=1}^{l} h(k) * [m_i(k,t) * (\gamma_{sat}(k) - \gamma(k)) + \gamma(k)] \right) \tag{3}$$

with γ_w, the specific weight of water and q_i the additional pressure due to the weight of the vegetation.

The cohesion component of the resisting forces, denoted as B in Eq. (1), is estimated according to:

$$B = \frac{2 * (C_s(l) + C_{r,i}(l))}{\gamma_w \sin(2\beta)} \tag{4}$$

In Eq. (4), $C_s(l)$ denotes the soil cohesion and $C_{r,\,i}(l)$ the root cohesion for the individual climate scenarios i.

Based on Eq. (1), $FS_i(l,t)$ values below one indicate that the soil column is instable at the soil depth l and at time t.

The geotechnical characteristics of the soil column were derived from typical values according to the texture of the layers (see Table 6). To account for uncertainty in the parameters, Monte Carlo sampling was used to randomly choose the cohesion, internal friction angle, specific dry and specific saturated weight of the soil from independent uniform distributions. The ranges of the uniform distributions are stated in Table 6. To keep the computational time reasonable, 500 samples were used, after checking the convergence with larger number of samples.

The root system of trees increases the resistance of soils against shallow landslides (c.f. Cohen and Schwarz, 2017; Ghestem et al., 2011; Schmaltz and Mergili, 2018; Schwarz et al., 2015). Following the approach of our slope stability model, the rooting of the soil acts as an additional cohesion force. To model the additional apparent cohesion due to the root system, data on typical apparent cohesion values (Appendix A.1) and information on the potential depth (Kutschera and Lichtenegger, 2013) to which the apparent cohesion applies, were compiled in a meta-analysis of scientific publications on the topic. Because published data on individual tree species were scarce, species were grouped according to their root system into tap-, heart-, and flat root system. For each of the three groups we assumed that the variability in root cohesion and potential rooting depth can be approximated by a normal distribution.

If provided, mean (μ) and standard deviation (σ) of the root cohesion and potential root depth were directly used to characterize the normal distribution of a specific root system. Some studies on root cohesion only provided information on the range, i.e. minimum and maximum values. In such a case we equate the minimum and maximum values with the limits of the interval containing 99.7% of all values in a normal distribution ($\mu \pm 3\ \sigma$).

The parameters for the normal distribution of root cohesion and rooting depth of each root system are given in Table 7.

The effective root cohesion for each cell $C_{r,\,i}(l)$ at root depth l and simulation i (c.f. Eq. (4) was estimated by quantile matching with the root mass distribution for the whole Stubai Valley for each tree species, derived from the iLand simulation, irrespective of the climate scenario and time frame (Seidl et al., 2019). We first compared the root mass of each tree within the study area with the root mass distribution of the entire forested Stubai Valley and estimated the corresponding probability. The root mass probability for each tree was then used to match

Table 6
Geotechnical parameters of the soil and their parameter range used for Monte Carlo sampling.

Texture[1]	C_s [Pa]		ϕ [°]		γ [kNm^{-3}]		γ_{sat} [kNm^{-3}]	
	Min	Max	Min	Max	Min	Max	Min	Max
L	4000	5000	29.56	35.08	14,715	15,500	18,168	17,383
SCL	4000	5000	32.69	36.32	15,009	15,696	18,392	17,705
Si	4000	5000	27.27	34.78	15,206	15,794	18,014	17,426
SiL	4000	5000	25.75	33.55	14,126	15,598	17,895	16,423
SL	4000	5000	31.12	35.72	15,304	15,598	18,280	17,986

[1] Soil texture according to Natural Resources Conservation Service (USDA): L (loam), SCL (sandy clay loam), Si (silt), SiL (silty loam) and SL (sandy loam).

Table 7
Parameters (mean ± standard deviation) for root cohesion and rooting depth derived from the literature for different rooting system. Number indicates the number of literature sources compiled.

Root system	Root cohesion [kPa]	Number	Rooting depth [m]	Number
Tap	12.0 ± 3.6	19	1.14 ± 0.47	4
Heart	6.8 ± 1.1	22	0.64 ± 0.01	3
Flat	6.4 ± 1.9	20	0.39 ± 0.05	3

the quantile of the according root cohesion and root depth distribution, respectively. The root cohesion as well as root depth of each tree within the study area was finally equated with the derived quantile. The effective root cohesion for simulation i at root depth l, $C_{r,\,i}(l)$, reflects the average value over all trees in the considered cell.

Beside the reinforcing effect on the soil, trees also exert normal and shear stresses on hillslopes due to their weight. This weight of the trees was derived directly from the iLand simulation by summing the stem, branch and foliage mass, denoted as q_i in Eq. (3).

3. Results

The future development of growing stock varied strongly with climate change scenario in the forest landscape simulations (Seidl et al., 2019). Notably, forest vegetation declined sharply under the “warm and dry” (mohc8.5) scenario. No significant influence of canopy disturbances on the runoff behaviour for both watersheds and all climate projections were found (see Appendix A.2). We therefore assumed that canopy disturbances do not directly influence soil moisture content. However, landscape simulations showed a climate- and disturbance-mediated change in tree species composition and a corresponding shift in the prevailing root systems within the study area, influencing slope stability.

3.1. Effect of canopy disturbance on slope stability

We here present the results for a design rainfall event with a duration of 240 min and a return period of 100 years. The general findings were robust also when the duration was changed from 240 min to 60 or 720 min, with the only difference that for the 60-minute scenario less volume and for the 720-minute scenario more volume was mobilized compared to the 240-minute scenario. Slope stability for both torrential catchments is reflected by the mobilized volume, i.e. the number of 100 m^2 cells times the soil depth at which a factor of safety below one (Eq. (1) was predicted. Figs. 4 and 5 illustrate the evolution of slope stability for each simulated catchment and compare climate change projections with and without disturbances and management treatments, respectively. The change of slope stability due to climate change impacts on forest development is presented as the difference between the sum of mobilized volume of the climate change projection under consideration and the sum of mobilized volume of landscape development based on historical climate data.

Regardless of climate scenario and catchment, simulations under climate change show higher mobilized quantities from simulation year 100 onwards compared to the expected quantities under historic climate (series without disturbances, empty symbols in Figs. 4 and 5). Climate change thus increases landslide risk in our study area. An exception is the “warm and dry” climate scenario (mohc8.5), where the mobilized volume shows a reverse trend 200 years after the start of the simulation, approaching again the expected mobilized volume under historic climate in the “*Äußerer Lehnertalbach*”. Management had a generally negative influence on slope stability, i.e., unmanaged conditions had generally lower mobilized volumes. The exception to this trend is again the warm and wet mohc8.5 scenario. Disturbances influenced slope stability positively across all simulated scenarios and

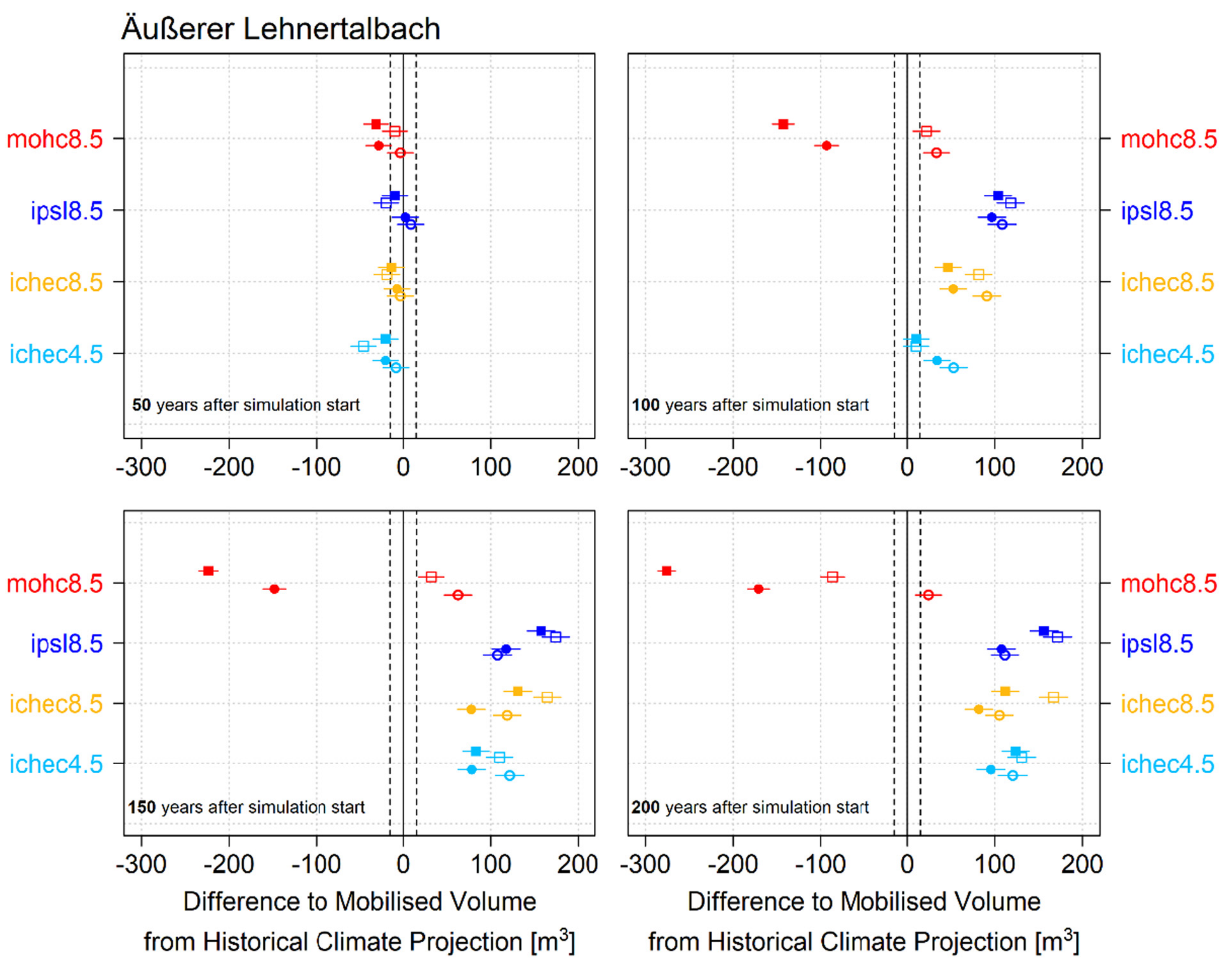


Fig. 4. The influence of climate and disturbance scenarios on slope stability for the “Äußerer Lehnertalbach”. Squares denote scenarios with management, while circles are scenarios without management. Filled symbols are scenarios under the influence of disturbances, and empty symbols represent scenarios without the influence of disturbances. The dashed lines correspond to the 95% confidence interval of the mobilized volume for the historical climate projection and was estimated based on 2500 bootstrap samples.

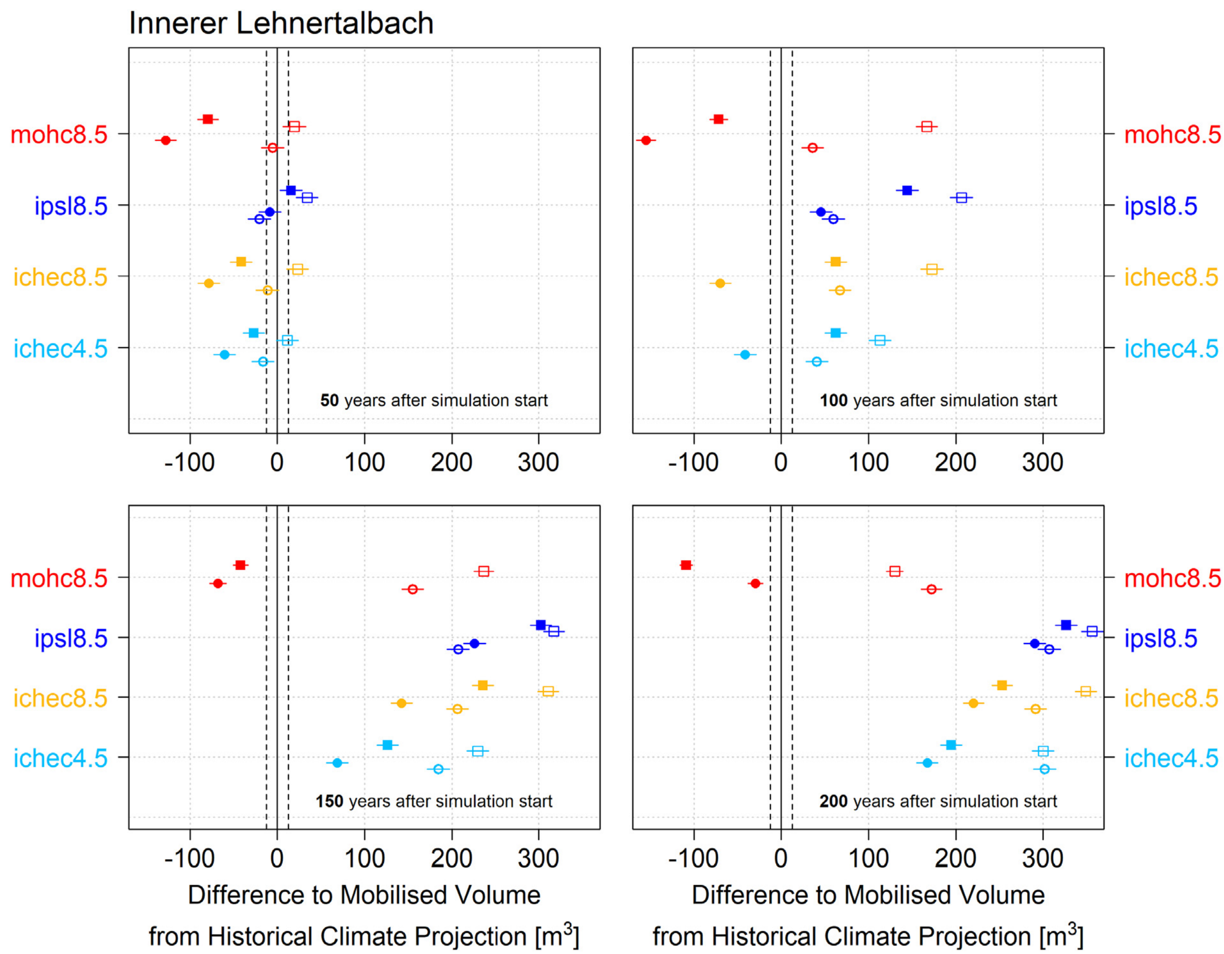


Fig. 5. The influence of climate and disturbance scenarios on slope stability for the "Innerer Lehnertalbach". Squares denote scenarios with management, while circles are scenarios without management. Filled symbols are scenarios under the influence of disturbances, and empty symbols represent scenarios without the influence of disturbances. The dashed lines correspond to the 95% confidence interval of the mobilized volume for the historical climate projection and was estimated based on 2500 bootstrap samples.

time steps. In general, management and disturbance effects were, however, smaller than climate effects.

Overall, the mohc8.5 scenario remains the only one with a development towards a reduction of mobilized volume. All other scenarios resulted in increased mobilization, with generally higher effects in the undisturbed compared to the disturbed scenarios. Scenario ipsl8.5 is indifferent to the presence or absence of disturbances but shows a general increase in the mobilized volume. The effect persists also when the effects of management and disturbances are considered jointly (filled squares).

3.2. Evolution of tree species and influence on slope stability

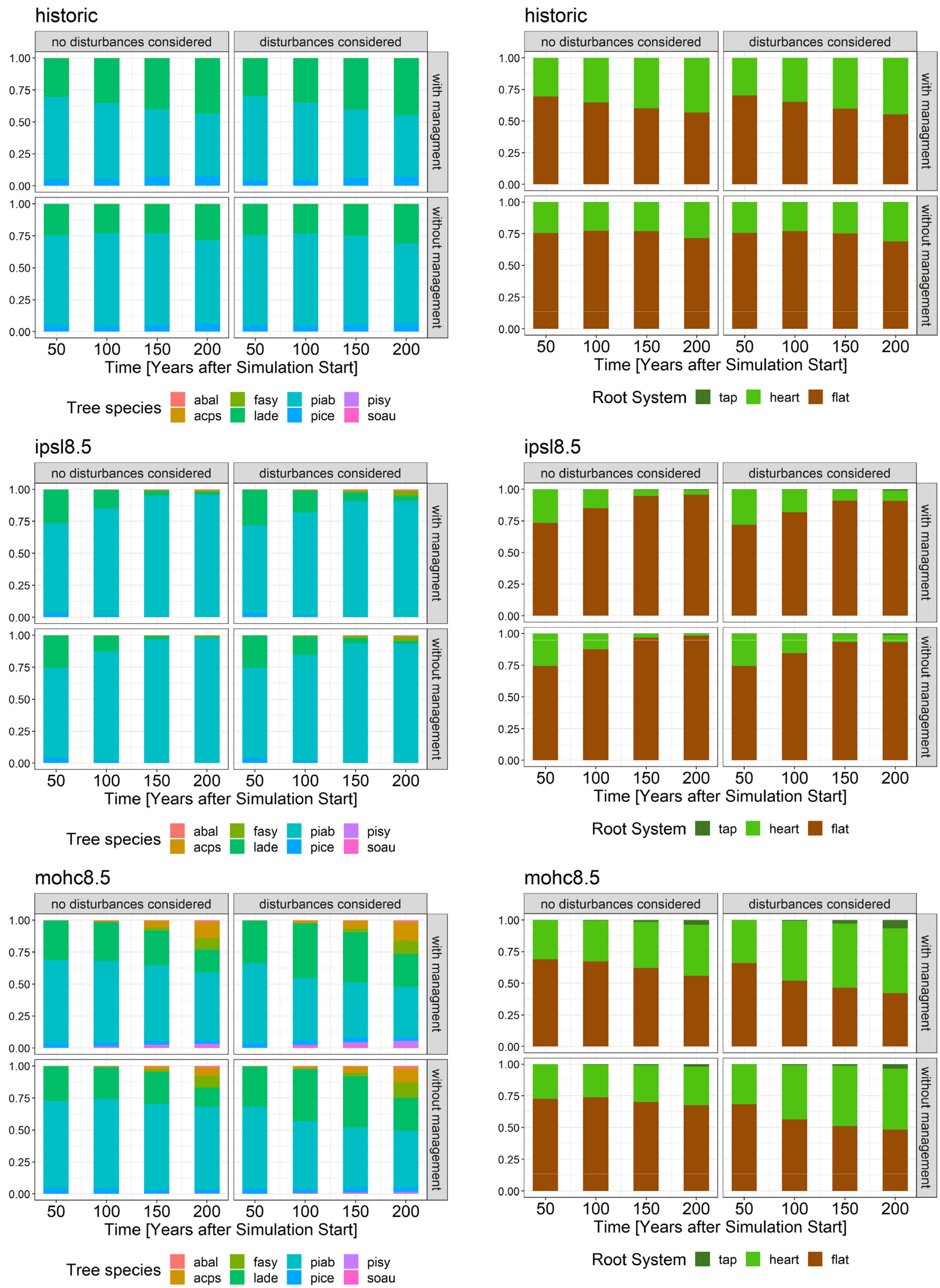
Different tree species develop different root systems, which imply differences in the corresponding root cohesions and rooting depths, influencing the stability of forested slopes. Fig. 6 illustrates the development of tree species and corresponding root systems across the study area for the "warm and wet" (ipsl8.5) and "warm and dry" climate (mohc8.5) projections. The development of tree species and corresponding root systems under the "moderate" (ichec4.5) and "wet" (ichec8.5) climate projections are given in Appendix A.3.

Under historic climate, management has a greater influence on the tree species composition than canopy disturbances. In total, the tree species share remains constant over time, with approximately 25% larch (*Larix decidua*) and 75% spruce (*Picea abies*), mixed with Swiss stone pine (*Pinus cembra*).

Under future climate scenarios the influence of canopy disturbances on the prevailing rooting systems increases. Without the influence of disturbances, the proportion of spruce (*Picea abies*) and thus the prevalence of flat root systems reaches almost 100% under climate change scenarios "moderate" (ichec4.5), "warm" (ichec8.5) and "warm and wet" (ipsl8.5), since Norway spruce gains competitiveness even at the high elevation portions of our study system. The development is, however, markedly different in the "warm and dry" (mohc8.5) climate scenario. Here, a general shift of tree species can be observed, and is amplified by the influence of disturbances. As the simulation time progresses, the proportion of tree species with shallow-root systems is displaced by tree species with heart- or taproot systems.

The variation in differences of mobilized volumes is shown in Figs. 7 and 8 as a function of the difference of the cumulative root cohesion (for the entire catchment), compared to the expected quantities projections under historic climate. In the case of the "*Äußerer Lehnertalbach*" and the climate change scenario mohc8.5, root cohesion increases significantly under the influence of disturbances, resulting in a considerable reduction of the mobilized volume. For all other climate change scenarios, root cohesion is either reduced or increased in a similar range. Regarding the development of root cohesion as a function of management, considerably fewer deviations for climate change scenarios under the influence of management can be identified.

Although lower in magnitude, a similar trend of mobilized volume as a function of the root cohesion was observed for the "*Innerer Lehnertalbach*". Again, the mohc8.5 scenario shows a significant increase in cumulative root cohesion for the entire catchment, compared to projections under historic climate. The influence of management on root


historic
no disturbances considered
disturbances considered
with managment
without management
1.00
0.75
0.50
0.25
0.00
50
100
150
200
Time [Years after Simulation Start]
Tree species
abal
acps
fasy
lade
piab
pice
pisy
soau
Root System
tap
heart
flat
ipsl8.5
mohc8.5

cohesion is, however, not as strong as observed for the "*Äußerer Lehnertalbach*".

Figs. 9 and 10 show the development of root cohesion for all climate change scenarios as a function of rooting depth.

For both catchment areas all scenarios show a reduction in rooting depth regardless of management and disturbance scenario considered. The exception to this trend is again the "warm and dry" climate change scenario mohc8.5, for which rooting depth increases. A reduction in rooting depth leads to a reduction in root cohesion, which results in increased mobilization under the climate scenarios ichec4.5, ichec8.5 and ipsl8.5. The opposite effect is visible for to the climate change scenario mohc8.5, where an increase in rooting depth results in an increase in root cohesion and a reduction in mobilized volumes.

4. Discussion

In this study we analysed long-term effects of disturbance-driven forest landscape development on the susceptibility of landslides in steep headwater catchments. We combined a forest landscape model and a theoretical root architecture approach with a hydrological–geotechnical model. We analysed hydrogeological responses to disturbed and undisturbed forest development scenarios by keeping the triggering conditions constant (see also Gariano and Guzzetti, 2016). According to Borgatti and Soldati (2010), first time failures of slopes, such as emphasized in this study, are the result of long-term evolutionary processes of the slope rather than the near-immediate response to a specific climatic trigger. Thus, our work does not focus on a detailed representation of the hydrological and geotechnical processes but rather aims at a comparison of the landslide disposition under changing forest stand developments in response to altered climate and disturbance regimes.

Information on soil water content, required for the slope stability model, was preliminary derived by means of hydrological modelling, whereby the maximum runoff was determined for all 2520 scenarios. The pooled results of the applied hydrological simulation models (Zemokost and GEOtop) do not show any significant influence of canopy disturbances on runoff behaviour, based on the extreme precipitation events studied here (see Appendix A.2). We suggest that the impacts of the disturbances simulated here are small enough to remain within the range of the structural uncertainty of the hydrological simulations, which is a consequence of the simplifying assumptions made in approximating the actual environmental system with a mathematical model (c.f. Renard et al., 2010).

Our slope stability model was designed to consider the effective root cohesion at different depths, spatially averaged over a relatively small area (10 × 10 m) and incorporating the soil water distribution determined from hydrological simulations. A disadvantage of the model is that it disregards the lateral root cohesion effect, despite that fact that it apparently affects shallow landslide initiation (e.g. Chiatante et al., 2002 Schwarz et al., 2010). This limitation results from the cell-based approach taken here, but also relates to the scarcity of available lateral root cohesion data. The model further does not account for the hydrological effect of roots, i.e. the reduction in pore-water pressure through root water uptake. In the context of our study design we did not consider this limitation to be of particular influence, given the trigger rainfall durations studied here. Based on analytical solutions of hydrological and mechanical effects of roots with different rooting architectures on shallow slope stability, Feng et al. (2020) concluded that after rainfall, the hydrological effect almost vanishes regardless of slope angle. Consequently, the positive effect of roots on slope stability mainly relies on the mechanical effect of roots (i.e. root reinforcement). A novelty of our methodological approach is the linking of forest landscape simulation with geo-hydrological simulation. Based on the key forest indicators identified for this study, the protective function of simulated forest stands against shallow landslides could be directly derived from simulations with the forest landscape and disturbance model iLand. Our modelling approach thus has high potential to support first order hazard analyses and quantify disaster risk reduction in protection forests in steep headwater catchments.

In general, our results indicate that canopy disturbances enhance slope stability. This is somewhat contradictory to previous analyses, reporting that natural regeneration after disturbance is often not able to compensate for the loss of protective function from tree mortality. While many of these studies refer to forest dynamics after fires (i.e. Gehring et al., 2019 Vergani et al., 2017) or are related to harvesting methods as different disturbance types (Bischetti et al., 2016), they commonly report that root cohesion and thus also root reinforcement steadily decreases in the first 10–20 years post disturbance. Particularly at high altitudes, this period of time may not be long enough for a new generation of trees to take over a stabilising role in the soil (Ammann et al., 2009). To the best of our knowledge none of these previous studies considers the effect of disturbances on tree species composition, which in turn affects rooting strength. At the larger spatio-temporal scales of our analysis disturbances might thus play a different role as suggested in previous studies. The importance of investigating disturbance interactions with natural hazards at multiple scales is also emphasized by Buma and Johnson (2015): Analysing the effects of windstorm exposure and yellow cedar decline on landslide susceptibility in southeast Alaskan temperate rainforests, they report that a reduction in root strength as a result of tree mortality was not significantly associated with landslide initiation.

We here found that disturbances positively affected the mobilized volume as a result of their catalysing effect on tree species change. Specifically, the adaptation of tree species to future climate conditions, and thus a change in rooting systems away from the currently prevailing flat roots, is accelerated by canopy disturbances. This is in line with previous findings from unmanaged systems in the Alps, underlining that disturbances act as catalysts of species adaptation (Thom et al., 2017). The share of total root cohesion and root depth increases especially under the warm and dry climate scenario (mohc 8.5). This is in line with previous findings reporting stands dominated by Norway spruce to be highly vulnerable to future drought and heat (Honkaniemi et al., 2020 Netherer et al., 2019 Peters et al., 2019). Accelerated by canopy disturbances, this leads to a transformation into mixed stands, which, consist of an increasing number of fir, beech and maple trees and thus, on average, lead to higher root reinforcement down to deeper soil layers caused by the change in root system (flat to heart or even tap). Such a difference in the performance of tree species is also confirmed by the studies of Chiaradia et al. (2016) or Ghestem et al. (2011).

In contrast, management does not appear to reduce slope instability in our simulations. The reason for the low effect of management might be that the management strategy applied in this study is a generic mountain forest management strategy recommended for the area (considering a wide range of forest functions), but not one specifically tailored to reducing the hazard of landslides. Imaizumi et al. (2008) and Sidle (1991) clearly show that vegetation management can have a significant influence on the development of landslide susceptibility. We also note that the management strategy simulated here did not consider active adaptation to climate change (e.g., via a targeted change in the tree species composition) but rather constituted the continuation of business-as-usual practices. Our results suggest that it is necessary to convert forests on sites prone to landslides into more stable climate-

Fig. 6. Proportion of tree species (left) and rooting systems (right) for the study area under historic climate, ipsl8.5 ("warm and wet") and mohc8.5 ("warm and dry") future climate scenarios. Tree species are annotated as follows: **abal**: Abies alba; **acps**: Acer pseudoplatanus; **fasy**: Facus sylvaticum; **lade**: Larix decidua; **piab**: Picea abies; **pice**: Pinus cembra; **pisy**: Pinus sylvestris; **soau**: Sorbus aucuparia.

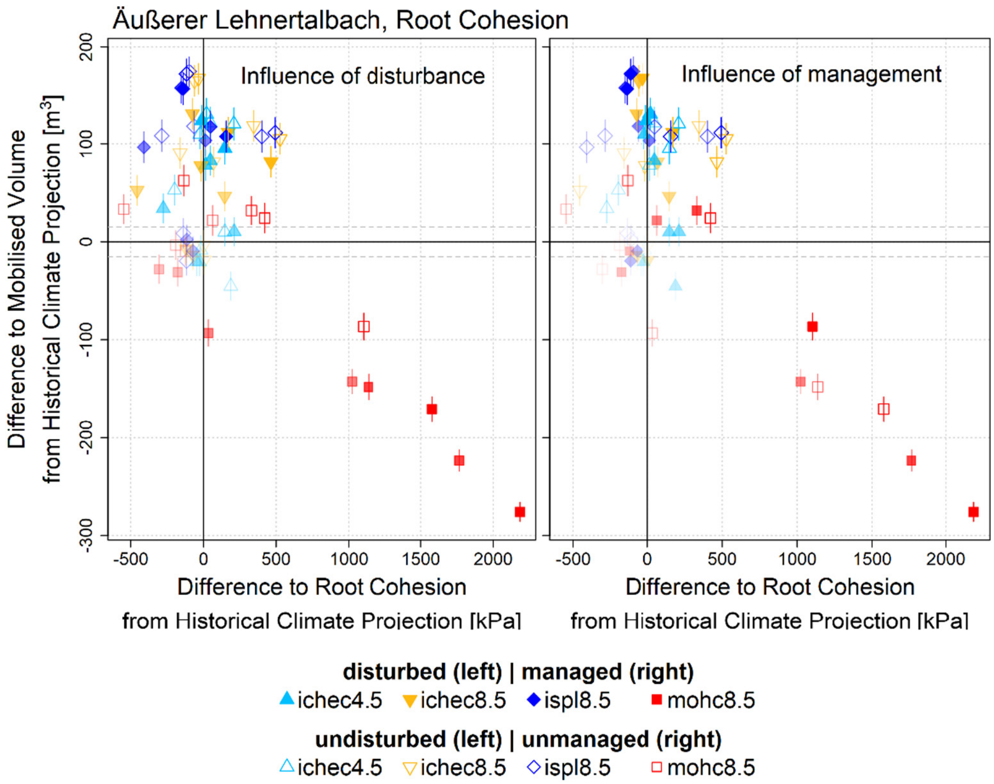


Fig. 7. Difference of the mobilized volume at the "Äußerer Lehnertalbach" as a function of the difference in root cohesion from the projections under historic climate. The transparency of the symbols decreases from the year 50 to the year 200. Left: Influence of disturbance, right: influence of management. The dashed lines correspond to the 95% confidence interval of the mobilized volume for the historical climate projection and was estimated based on 2500 bootstrap samples.

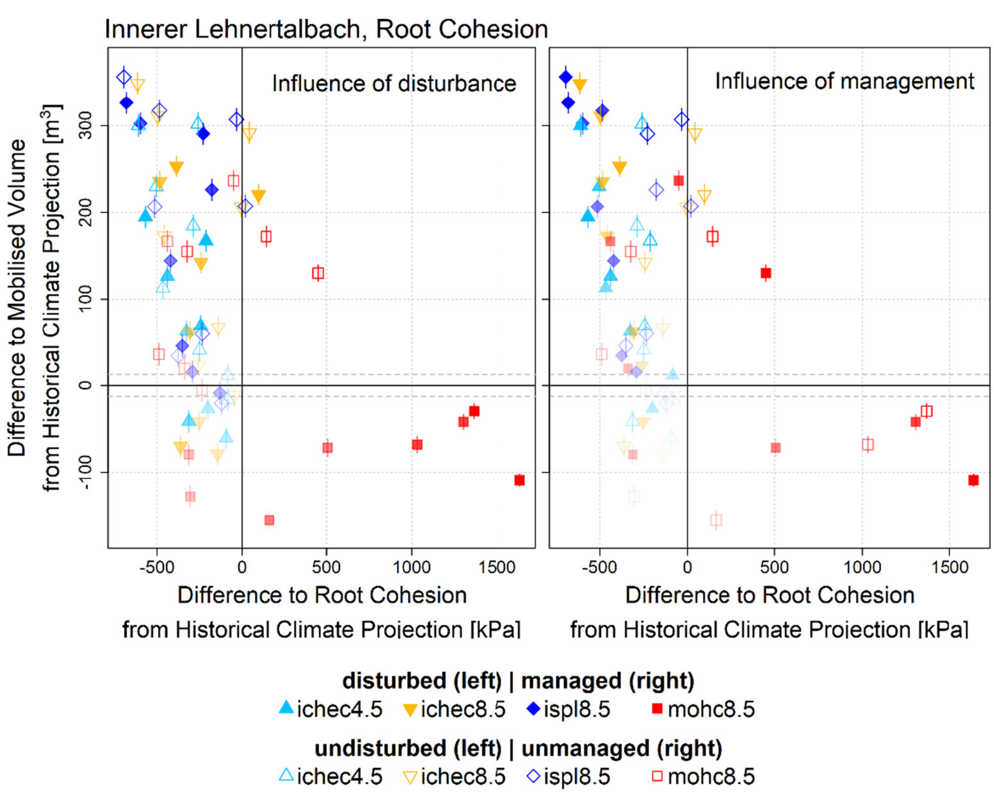


Fig. 8. Difference of the mobilized volume at the "Innerer Lehnertalbach" as a function of the difference in root cohesion from the projections under historic climate. The transparency of the symbols decreases from the year 50 to the year 200. Left: Influence of disturbance, right: influence of management. The dashed lines correspond to the 95% confidence interval of the mobilized volume for the historical climate projection and was estimated based on 2500 bootstrap samples.

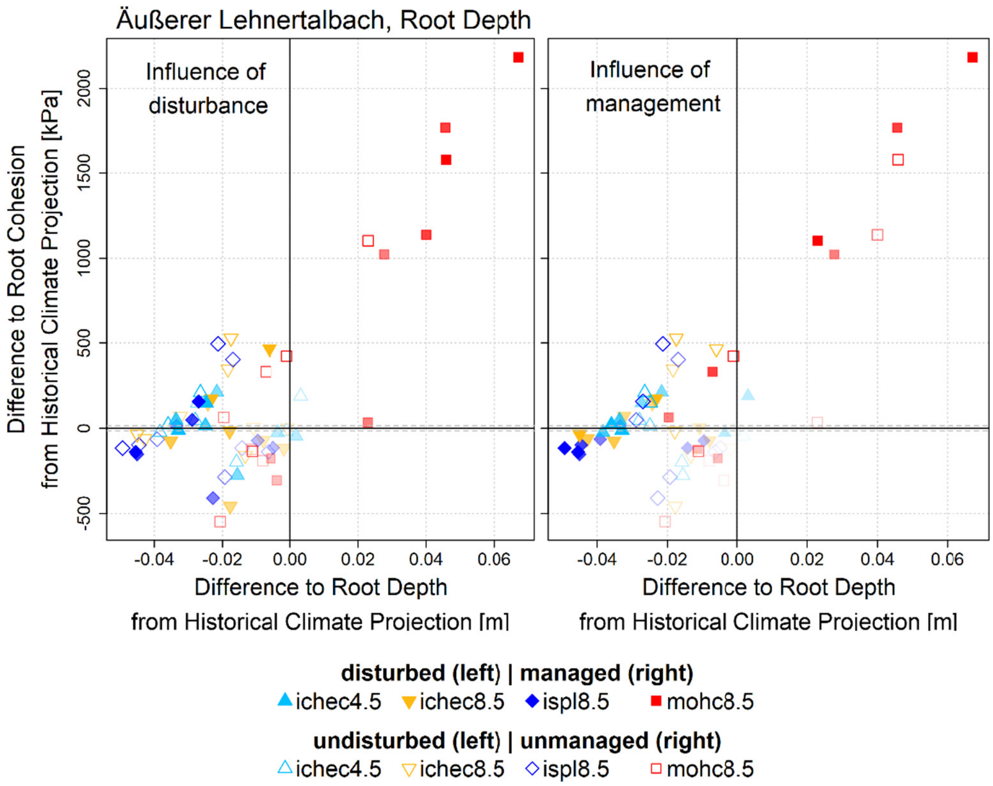


Fig. 9. Change in rooting depth as a function of the change in root cohesion relative to the historic climate scenario for the "Äußerer Lehnertalbach" catchment. The transparency of the colour decreases from the year 50 to the year 200. Left: Influence of disturbance; right: influence of management. The dashed lines correspond to the 95% confidence interval of the mobilized volume for the historical climate projection and was estimated based on 2500 bootstrap samples. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

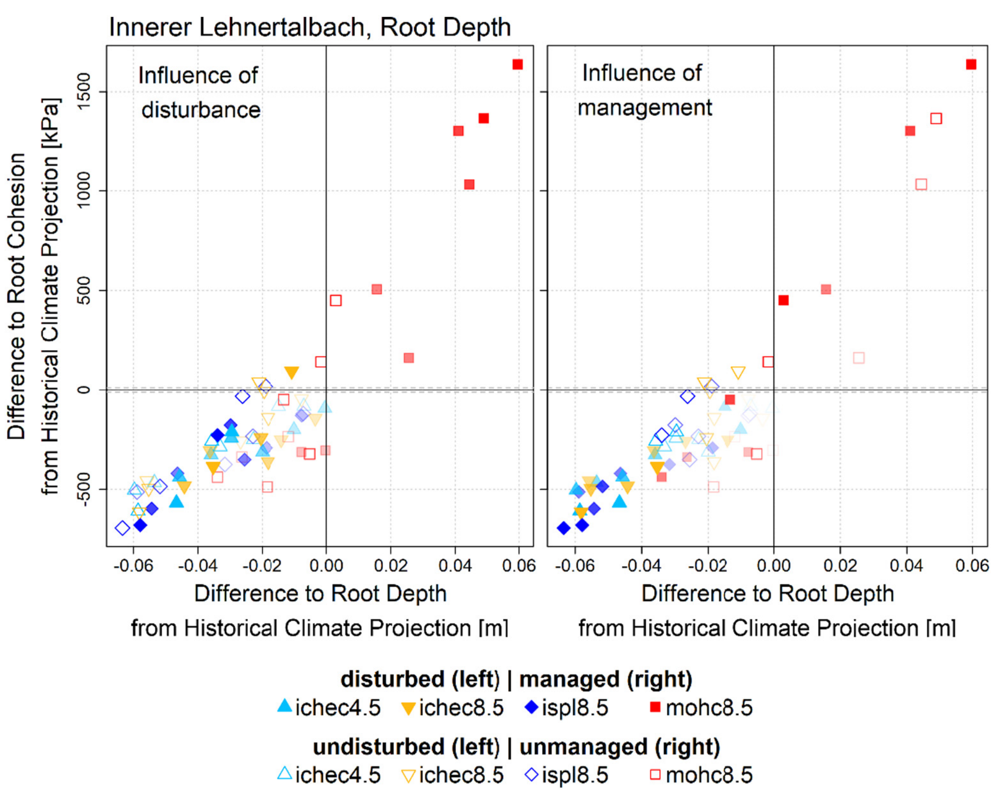


Fig. 10. Change in rooting depth as a function of the change in root cohesion relative to the historic climate scenario for the "Innerer Lehnertalbach" catchment. The transparency of the colour decreases from the year 50 to the year 200. Left: Influence of disturbance; right: influence of management. The dashed lines correspond to the 95% confidence interval of the mobilized volume for the historical climate projection and was estimated based on 2500 bootstrap samples. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

adapted stands of deep-rooting species in order to increase the protective function of forests. Rickli (2001), for instance, found hardly any landslides on sites where the stands had well-adapted tree species, few gaps and a diverse stand structure. This observation was also confirmed by other studies (Markart et al., 2007 Schmidt et al., 2001).

Future slope stability varied considerably between climate scenarios. For climate change projections which assume a positive trend in precipitation in addition to a rise in temperature (wetting climate scenarios, ichec4.5, ichec8.5 and ipsl8.5), our projections show higher slope instabilities (i.e. higher mobilized volumes) in the future. Here, Norway spruce prevails as the dominant species, with negative effects on stand stability (i.e., high risk for wind and bark beetle disturbances) and slope stability (i.e., flat root system). In contrast, the drying climate scenario mohc8.5 showed a significant reduction in mobilized volumes, which - assuming equal trigger intensities - means that slopes get more stable. This is mainly the result of a pronounced change in the vegetation composition in this scenario, and the increasing prevalence of trees with tap and heart root systems (e.g., Silver fir, European larch). Additional differences between climate scenarios might arise from changes in the frequency of extreme precipitation events, an element not considered here. Analysing extreme annual maximum 1-day precipitation events (Rx1day) in Switzerland, Brönnimann et al. (2018) identified clear differences between drying and wetting climate scenarios. They found that wetting climate scenarios showed little change in the seasonality of precipitation or an increased frequency of the occurrence of Rx1day events in summer. For wet climate scenarios it can therefore be assumed that extreme precipitation events, which can act as triggers for landslides, will occur regularly also in the future. On the other hand, Brönnimann et al. (2018) suggest that extreme precipitation events are likely to decrease in drying climate scenarios, which corresponds to a decrease in the frequency of triggering events for shallow landslides.

5. Conclusion

The impact of changing climate and disturbance regimes significantly influences the susceptibility of landslides in forested steep headwater catchments. We generally found an increase in landslide risk under climate change, suggesting that the protective function of forests might increase in importance in the future. Our results also underline that a continuation of current management is not able to maintain or improve the protection against shallow landslides. Adapting forest management to the changing environmental conditions is thus of paramount importance to strengthen their role as important green infrastructure in the European Alps. Important pathways for adaptation are an increase in the structural complexity of mountain forests (fostering their resilience to natural disturbances) and the conversion to mixed forests of species with different root architecture (increasing slope stability). We here show that such a change in the tree species composition can significantly reduce the mobilized soil volume from shallow landslides. Somewhat surprisingly we found that landslide risk decreased as the result of disturbances and in the most extreme (warm and dry) climate scenario. These conditions had a particularly negative impact on the prevailing vegetation dominated by Norway spruce, and accelerated the change towards more site-adapted and deep-rooting species. We thus conclude that conditions that are generally associated with a decrease in forest health, posing substantial challenges for regular forest management, can in fact improve the protective function of forests in the long term, because they mobilize the considerable autonomous adaptive capacity of mountain forest ecosystem. Our study highlights that the susceptibility of shallow landslides in mountain forests changes dynamically with changes in vegetation structure and composition. This underlines that forest management offers considerable leverage to influence this important ecosystem service, which is important as other factors contributing to the occurrence of landslides such as the geology, pedology, climate and topography of an area cannot be influenced directly by humans. Hence, a focus on green infrastructure and its management holds potential to reduce the risk of natural hazards such as shallow landslides in the future.

Nomenclature

j	climate scenario (ichec4.5, ichec8.5, ipsl8.5, mohc8.5)
$YaSS$	years after simulation start (50, 100, 150, 200), [year]
i	number of forest landscape projections, [1−210]
d	design precipitation duration (60, 240, 720), [min]
k	number of soil layers
l	soil depth, [m]
$FS_i(l,t)$	factor of safety for a specific soil depth l at time t, [−]
$h(k)$	depth of soil layer k, [m]
$\phi(l)$	internal angle of friction, [°]
β	slope angle of the soil column, [rad]
$\theta_i(k,t)$	soil water content of soil layer, [−]
$\theta(k)$	saturated water content of soil layer, [−]
$\gamma_{sat}(k)$	specific weight of the saturated soil layer, [kNm^{-3}]
$\gamma(k)$	specific weight of the dry soil layer, [kNm^{-3}]
γ_w	specific weight of water, [kNm^{-3}]
q_i	additional pressure due to the weight of the vegetation, [kNm^{-2}]
$C_s(l)$	soil cohesion of soil layer, [Pa]
$C_{r,\ i}(l)$	root cohesion of soil layer, [Pa]

CRediT authorship contribution statement

Christian Scheidl: Project administration, Funding acquisition, Conceptualization, Supervision, Writing - original draft, Writing - review & editing.**Micha Heiser:**Data curation, Methodology, Software, Conceptualization.**Sebastian Kamper:**Software, Writing - original draft.**Thomas Thaler:**Conceptualization, Supervision.**Klaus Klebinder:**Data curation, Investigation, Conceptualization, Writing - original draft.**Fabian Nagl:** Data curation, Software.**Veronika Lechner:**Data curation, Investigation.**Gerhard Markart:**Funding acquisition, Conceptualization, Supervision, Writing - original draft, Writing - review & editing.**Werner Rammer:**Data curation, Methodology, Writing - original draft.**Rupert Seidl:**Funding acquisition, Conceptualization, Supervision, Writing - original draft, Writing - review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2020.140588.

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