POTENTIAL IMPACTS OF CLIMATE CHANGE ON SNOW AVALANCHES STARTING IN FORESTED TERRAIN

Michaela Teich[1,2,*], Natalie Zurbriggen[3,4], Perry Bartelt[1], Adrienne Grêt-Regamey[2], Christoph Marty[1], Melanie Ulrich[1,5] and Peter Bebi[1]
[1]WSL Institute for Snow and Avalanche Research SLF, Davos, Switzerland
[2]Planning of Landscape and Urban Systems PLUS, Swiss Federal Institute of Technology ETH, Zurich, Switzerland
[3]Swiss Federal Institute for Forest, Snow and Landscape Research WSL, Birmensdorf, Switzerland
[4]Forest Ecology, Institute of Terrestrial Ecosystems, Swiss Federal Institute of Technology ETH, Zurich, Switzerland
[5]Institute of Natural Resources Sciences, Zurich University of Applied Sciences ZHAW, Waedenswil, Switzerland

ABSTRACT: Frequency and magnitude of avalanches starting in forested terrain (forest avalanches) are likely to be affected by climate change. We addressed two important developments which will influence the forest avalanche regime: 1) trends in the occurrence of favorable snow and weather situations which increase the probability of forest avalanche releases, and 2) changes in the extent, composition and structure of mountain forests. We applied a logistic trend analysis over 41 years to investigate past changes in the occurrence of snow and weather conditions which are associated with forest avalanche releases in the Swiss Alps. We found negative trends for two typical situations, 'new snow forest avalanches' and 'other forest avalanches'. In combination with the currently observed increase in forest cover extent and density, it is thus likely that avalanche releases in forests will become less frequent. For avalanches started in forested areas, we found that higher densities of small-diameter trees (<15 cm) in the starting zone significantly reduced the runout distance. Repeated measurements of forest parameters in avalanche starting zones revealed an increase in density of small trees over the last 20-25 years which leads to the hypothesis that the destructive potential of such avalanches will be reduced in the future. In order to account for avalanches and their effect on mountain forests and forest avalanche frequency, we employed the forest-landscape model TreeMig-Aval to exemplify a possible future development in a high alpine valley in Switzerland.

1. INTRODUCTION

Mountain forests play a crucial role in avalanche control by preventing avalanche formation due to modified mechanical properties of snow in forests compared to open unforested areas (e.g. Bebi et al., 2001; Viglietti et al., 2010). The main effects of avalanche protection forests are 1) the interception of falling snow by trees, 2) the reduction of near-surface wind speed, 3) the modification of the radiation and temperature regime, and 4) the direct support of the snowpack by stems, remnant stumps and dead wood (Schneebeli and Bebi, 2004). However, due to the complex interactions between ecological conditions, terrain, snowpack and meteorological parameters the protective effect of forests may be reduced and, therefore, snow avalanches do occur in forests. These so-called 'forest avalanches' are usually small, but can be a threat to recreationists which often access forests while out-of-bounds (off-piste) skiing. Furthermore, forest avalanches may develop into larger avalanches which can pose a hazard to settlements and infrastructure below the forest as well as to the forest itself (Gubler and Rychetnik, 1991; Bebi et al., 2009). For already released avalanches, the secondary protective effect of mountain forests on avalanche runout, i.e. speed reduction and deceleration, becomes relevant (Bartelt and Stöckli, 2001; Takeuchi et al., 2011; Anderson and McClung, 2012). Especially within the first 100-200 m of the avalanche path, forests of a certain structure are able to significantly reduce runout distances of small to medium avalanches (Teich et al., accepted for publication).

Under climate change, frequency and magnitude of forest avalanches are likely to be affected by changing snow regimes and meteorological conditions (Teich et al., 2012) as

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[*] *Corresponding author address:*
Michaela Teich, WSL Institute for Snow and Avalanche Research SLF, Flüelastrasse 11, 7260 Davos Dorf, Switzerland; tel: +41 81 417 0284; email: teich@slf.ch

Table 1: Forest avalanche types defined by site, snow and weather conditions, which may be used for forest avalanche forecasting (according to Teich et al., 2012).

Variable to observe	New snow forest avalanches	Other forest avalanches
Aspect	North-exposed slopes	All aspects
Elevation	>1700 m asl	<1700 m asl
Forest type	Open coniferous forests	Deciduous and mixed forests
Temperature	1-, 3- and 5-day mean air temperature <0°C	3- and 5-day temperature difference >0°C
Sunshine duration	1-day sum of sunshine duration <30 min 3-day sum of sunshine duration <60 min 5-day sum of sunshine duration <210 min	1-day sum of sunshine duration >30 min 3-day sum of sunshine duration >90 min 5-day sum of sunshine duration >240 min
New snow height	1-day sum of new snow height >10 cm 3-day sum of new snow height >50 cm	1-day sum of new snow height <10 cm 3-day sum of new snow height <40 cm
Snow depth	Total snow depth >100 cm	Total snow depth >30 cm
Wind	1-day mean wind speed >3 m/s 3-day maximum wind speed >17 m/s	-
Main time to occur	February	February - March

well as by changes in composition, structure and extent of the forest cover (Bebi et al., 2009; Krumm et al., 2011). In addition, future changes in land use as well as other forest disturbances caused by wind, fires or bark beetles, which might become more frequent due to changing climate conditions, are likely to have considerable impacts on forest cover and composition (Dale et al., 2001). Due to such potential changes, the frequency and magnitude of forest avalanches could increase or decrease depending on elevation and ecological shifts (Bebi et al., 2009).

All these factors combined create feedback loops between forests and avalanches (Fig. 1), where frequent avalanches as well as other natural disturbances prevent the forest from recovering and maintain a risk of future avalanche release (Zurbriggen et al., in prep. a).

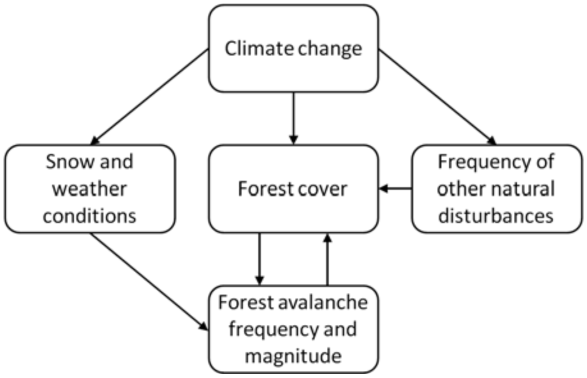

Figure 1: Factors and feedback effects which influence the future forest avalanche regime.

In this paper, we present an overview of new findings in forest avalanche research from the Swiss Alps and discuss their relevance in the context of global warming. Analyzing both past changes in snow and weather situations associated with avalanche releases in forests as well as changes in forest cover could help to predict the activity of forest avalanches in the future. Furthermore, simulating the dynamics of mountain forests, avalanches, and their feedbacks under climate change scenarios applying a spatially explicit forest-landscape model could support the future protection forest as well as natural hazard management.

2. PAST TRENDS IN SNOW AND WEATHER CONDITIONS ASSOCIATED WITH FOREST AVALANCHE RELEASES

2.1 Types of forest avalanches

Recently, Teich et al. (2012) presented a study on snow and weather conditions associated with avalanche releases in forests. In order to support avalanche warning and forest services in forecasting forest avalanches, they distinguished between the two characteristic situations ‘new snow forest avalanches’ and ‘other forest avalanches’ (previously defined as ‘old snow forest avalanches’). These can be described by snow and meteorological parameters which increase the probability of avalanches releases in forests (Table 1). The analyses were based on 189 naturally released forest avalanches which occurred in the winters between 1985/86 and 2005/06 at elevations from 700 to 2200 m asl in the Swiss Alps. A set of 21 snow and weather variables as well as of five additional variables describing site conditions was generated for each avalanche event using different spatial and non-spatial interpolation methods (for details see Teich et al., 2012). Applying Ward’s (1963) hierarchical clustering method revealed two different clusters best representing the underlying structure of the initial dataset.

It should be noted that in contrast to ‘new snow forest avalanches’, conditions under which ‘other forest avalanches’ are likely to occur are not that clearly definable. This cluster includes various types of climax forest avalanches containing old snow (48%) and wet snow (52%) avalanches released as slab, loose snow and glide avalanches.

2.2 Trends in the occurrence of favorable snow and weather situations

To investigate potential impacts of climate change on the occurrence of forest avalanches, Teich et al. (2012) analyzed if the frequency of typical snow and weather conditions changed during the winters of 1970/71 to 2010/11. The investigation period was limited by the number of snow and weather stations (SWS) where all necessary meteorological parameters were available as consistent long-term records in a daily resolution. Combinations of contributory factors and associated thresholds determined through the cluster analysis, adapted with expert knowledge (for details see Teich et al., 2012), were used to identify and count the number of potential forest avalanche days between November and May. A logistic regression model was then applied for estimating long-term trends in the occurrence of favorable conditions for forest avalanches at 14 SWS in total, and tested for statistical significance ($p \leq 0.10$).

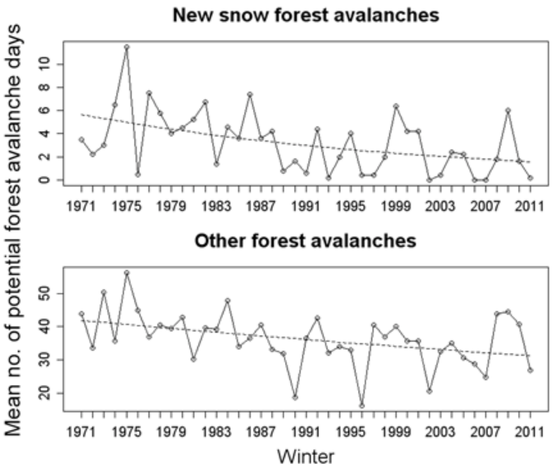

Figure 2: Mean number of potential new snow (top) and other forest avalanche days (bottom) of 14 SWS above 1500 m asl and the fits of the logistic trend model to the data (dashed line).

It was shown that the number of days with conditions increasing the probability of new snow forest avalanche releases decreased at 11 of the investigated 14 stations (79%); also trends for other forest avalanche days were negative at 12 of 14 stations (86%) independent from elevation and climatic region. The decreasing trends were significant at four of the stations for both situations. In addition, the overall mean of all SWS as well as mean values of potential forest avalanche days at stations above 1500 m asl (Fig. 2) showed significant negative trends. Mean trends for stations below 1500 m asl were also negative, but not statistically significant. These findings can be seen as an indication for possible impacts of climate change on favorable snow and weather conditions for forest avalanche occurrence.

3. TRENDS IN FOREST DEVELOPMENT

3.1 Changes in forest cover

Mountain forests of the Swiss Alps changed considerably within the last decades. Above 1000 m asl, forest areas increased by approx. 4% between the two inventory periods 1979-1985 and 1992-1997. In particular, forests which grow in potential avalanche release areas (slope angle>30°) above 1400 m asl expanded significantly (Bebi et al., 2009). This is due to changes in land use as well as in climate conditions; however, at the upper treeline the effect of climate change on forest expansion is not significant in contrast to the effect of changes in land use (Gehrig-Fasel et al., 2007). Current studies emphasize that despite higher temperatures, several other factors such as grazing, snow cover duration or competition by dwarf-shrubs and other vegetation limit a rapid forest expansion at the upper treeline (e.g. Motta et al., 2006; Harsch et al., 2009; Barbeito et al., 2012). Changes in frequency and magnitude of extreme climate events as well as in temperature, precipitation and snow cover duration will have considerable impact on the growth, regeneration and mortality of various tree species (e.g. Jolly et al., 2005; van Mantgem et al., 2009). Regarding changes in forest cover density in potential avalanche release areas, Bebi et al. (2009) analyzed transitions between non-forested land, open forests and closed forests between the two inventory periods (1979-1985 and 1992-1997). Although forest expansion was generally more frequent above 1400 m asl, transitions from open forests to closed forests, i.e. an increase in forest cover density, were less frequent at very steep slopes compared to other areas.

If these trends continue, we can expect a further increase in mountain forest cover extend and density in the Alps; however, the effects on avalanche control in particular are still highly uncertain. Moreover, other natural disturbances such as wind, fires or bark beetle outbreaks can increase the risk of subsequent avalanche releases if woody debris is removed after the disturbance or if the debris decays before post-disturbance vegetation reaches heights sufficient to control avalanche activities (e.g. Frey and Thee, 2002; Germain et al., 2005; Rammig et al., 2007).

3.2 Changes in forest structure in former avalanche release areas

The protective effect of mountain forests is highly controlled by forest structure in terms of crown closure, tree density and size and distribution of forest gaps (e.g. Bebi et al., 2001; Schneebeli and Bebi, 2004; Viglietti et al., 2010). In order to investigate trends in forest structure development, in 2008 we repeated measurements of forest parameters in starting zones of avalanches released between 1986 and 1990 in forests around Davos, Switzerland (Schneebeli and Meyer-Grass, 1993). The 23 sample sites are located at elevations between 1900 and 2080 m asl in subalpine forests close to the upper treeline. The forests dominated by Norway spruce (*Picea abies* (L.) H. Karst.) and/or European larch (*Larix deciduas* Mill.) grow at north- to north-east-exposed slopes with a mean slope angle ranging between 34 and 65°. The parameters measured can be classified in single tree parameters (tree species, diameter at breast height (DBH), tree height) and stand parameters (crown coverage, stand height, number of stems/ha per species and mean DBH class). Statistical analyses were conducted by applying the Wilcoxon signed-rank test for paired and the Wilcoxon rank-sum (Mann-Whitney-U-) test for unpaired samples respectively (level of significance α=0.05).

The comparison between data collected in 1986/90 and 2008 revealed an increase in forest density and tree height in former forest avalanche release areas (Fig. 3). Especially the number of stems per ha of trees with a DBH≤7 cm increased significantly (approx. 66%), while the increase was not that strong for trees with DBH>7 cm (approx. 31%). However, these changes differed considerably between the sample sites. In particular forests with high competition, less coarse woody debris and regular snow disturbances, did not change significantly regarding their protective effect which emphasizes the findings gained from analyzing inventory data (see Section 3.1).

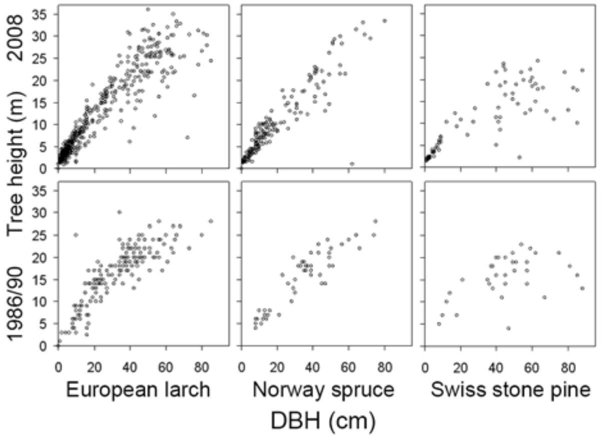

Figure 3: Development of DBH and tree height of three tree species between 1986/90 (bottom) and 2008 (top). The data were collected in 23 former forest avalanche release areas around Davos, Switzerland.

3.3 Influence of forest structure on avalanche runout distance

While the protective effect of forests on avalanche formation in potential starting zones is relatively well understood, much less is known about the secondary protective effect of forests on avalanche runout. Therefore, we analyzed the influence of forest parameters, terrain features and avalanche characteristics on forest avalanche runout distances (Teich et al., accepted for publication). Among 57 collected variables we identified the most important ones which affect avalanche runout distances (ranging between 50 and 700 m) of 43 small to medium forest avalanches observed during the winters 1986-1990 in the Swiss Alps. We calculated Spearman's rank correlation coefficient (r_S) to determine statistical dependencies between the independent predictor variables and avalanche runout distance. Significant correlations ($p \leq 0.05$) were found for the predictor variables avalanche type (slab, loose snow or glide snow), cross-slope curvature in the avalanche track and the runout zone (concave, convex or flat), surface roughness in the starting zone, flow distance through forest, forest type (mixed, evergreen or deciduous coniferous), number of stems per hectare (DBH<15 cm), the mean diameter at breast height (DBH>1 cm), the vertical drop and whether an avalanche did or did not stop in forests (for details see Teich et al., accepted for publication).

In the context of climate change and related changes in mountain forest structure (see Section 3.2), it should be highlighted that in particular the starting zone stem density of trees with small DBH (1-15 cm) significantly reduced runout distances of small to medium avalanches which released in evergreen coniferous and mixed forests (r_S=-0.3; p=0.015) (Fig. 4).

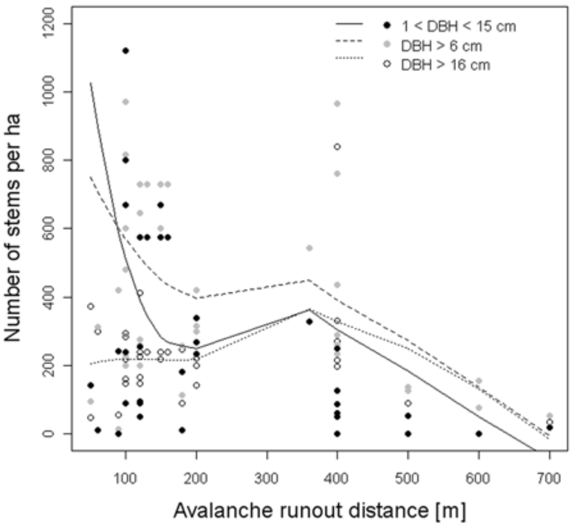

Figure 4: Relationship between number of stems per hectare in the starting zone and avalanche runout distance of 43 small to medium forest avalanches for groups of trees with 1<DBH<15 cm, DBH>6 cm and DBH>16 cm. Loess curves were fitted to the data built on locally weighted non-linear regressions.

4. CASE STUDY: POSSIBLE FUTURE TRENDS IN FOREST AVALANCHE FREQUENCY

For potential adaptations in natural hazard and forest management, it is important to not only consider past trends, but also possible future scenarios under environmental change. Due to the interactions and feedbacks between forests and avalanches, dynamic models explicitly taking into account changes in forests, avalanches, and their interactions over time are a promising tool for future scenario analyses. Therefore, in a case study for a 4.6x3.4 km area in Davos, Switzerland, we used the spatially explicit model TreeMig-Aval (Zurbriggen et al. in prep. a, in prep. b) to simulate past and future forest and avalanche dynamics in yearly time steps. TreeMig-Aval is a grid-based forest-landscape model coupled with a probabilistic avalanche module, where avalanche release, flow direction and length are determined stochastically, based on spatially explicit probabilities calculated from local topography, climate, and forest composition and structure (for details see Zurbriggen et al. in prep. a, in prep. b). We ran 30 simulations to account for this stochasticity, each simulation based on observed climate data from 1900-2000, and the IPCC A2 climate scenario for 2000-2100 as an extreme example of future temperature changes. A spin-up phase was run from 1500-1900, using climate data extrapolated from 1900-1920.

We analyzed the simulated number of avalanches per year, released in grid cells without forest, with coniferous forest, or with mixed forest. The yearly total number of cells releasing avalanches is reported as percentage of the total simulation area, while the yearly number of avalanches released from forested cells (both coniferous and mixed) is reported as percentage of all avalanches, and the yearly number of avalanches released from coniferous forest cells is reported as percentage of all forest avalanches (Fig. 5).

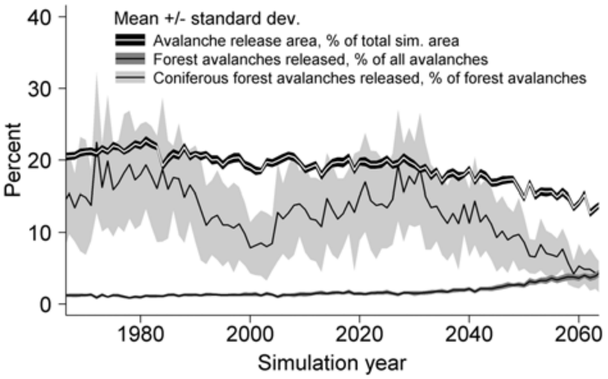

Figure 5: Yearly mean (+/- standard deviation, sd) avalanche release area in percent of the total simulated area (white mean, black sd), forest avalanches released in percent of all avalanches (black mean, dark grey sd), and coniferous forest avalanches released in percent of all forest avalanches (black mean, light grey sd), resulting from 30 stochastic simulations.

For the future climate scenario, a decreasing trend was found in the simulated total avalanche release area, which may be attributed both to decreasing snow cover depth and duration, and to increasing forest coverage in the simulated area. However, the proportion of avalanches released from forested areas increased after 2040, which is mainly due to increases in forest area in avalanche prone regions of the simulation area. The proportion of avalanches released from coniferous forests, as a fraction of all forest avalanches, showed strong fluctuations over time. We hypothesize that several interacting factors influenced these simulated trends, and that the importance of the different factors changed over time. During 1970-2000, we found a decreasing trend of simulated avalanches released from coniferous forests, similar to the decrease in potential forest avalanche days shown in Fig. 2. This trend is mainly related to rising temperatures, which gradually decrease snow cover depth and duration. At the same time, increasing temperatures contributed to increases in simulated density of coniferous forests. Surprisingly, during 2000-2030, the proportion of avalanches released from coniferous forests showed an increasing trend. We hypothesize that this is an effect of rising treelines in the simulations, accompanied by a shift of avalanche-prone slopes from non-forested to forested areas, and therefore a shift of non-forest avalanches to forest avalanches. After ca. 2030, a second decrease in the simulated proportion of avalanches released from coniferous forests was found, which we attribute to increasing proportions of simulated broadleaf tree species due to the high emission climate scenario (A2). This effect is likely influenced by the size of the simulation area: Because the simulated treeline had reached the highest point in the simulated area, the area of coniferous forests was not able to increase at the same rate as the shift of coniferous to mixed forest cover, leading to an overall decrease in avalanches released from coniferous forests. Furthermore, some known limitations of TreeMig-Aval, such as a tendency to overestimate both succession speed and the proportion of broadleaf tree species (Zurbriggen et al. in prep. b), in addition to uncertainties in species parameters and climate, may have further contributed to a shift in forest types. However, we hypothesize that the decrease in the proportion of simulated avalanches released from coniferous forests is not solely an artifact of the simulations, but that decreases in coniferous forests may be expected with climate change over long time periods (Zimmermann et al., 2006) and that more avalanches may be released from mixed forests with lower proportions of coniferous tree species.

In the case study described here, further uncertainty results from limitations in the knowledge of the effect of different forest types and large-scale disturbances on avalanche release. Therefore, we suggest that increased emphasis should be placed on distinguishing effects of different forest types on avalanches, their interactions and feedbacks, and especially their development under a changing environment.

5. SYNTHESIS AND CONCLUSIONS

This overview on recent findings in forest avalanche research highlights two important developments which will influence frequency and magnitude of avalanches starting in forested terrain under global warming effects: 1) trends in the occurrence of snow and weather situations associated with forest avalanche releases, and 2) changes in the extent, tree species composition and structure of mountain forests.

Studies on the influence of climate change on avalanches in open unforested terrain suggest that climate change has recently had little impact on avalanche frequency (Laternser and Schneebeli, 2002). However, our analyses showed that especially new snow forest avalanches might become less frequent due to a decrease in the occurrence of extreme snow fall events and warmer temperatures associated with decreasing snow depths and a shorter snow cover duration (Marty, 2008; Marty and Blanchet, 2011; Serquet et al., 2011). In contrast, other forest avalanches, i.e. old snow and wet snow avalanches, are not that clearly predictable and, even if trends are also negative, their future occurrence might be more influenced by an assumed replacement of dry by wet snow avalanches (Martin et al., 2001) as well as by changes in forest composition (Schumacher and Bugmann, 2006).

Regarding the decreasing trends in the occurrence of favorable snow and weather situations in combination with the observed forest expansion and increasing forest cover density in the Swiss Alps, we can expect less frequent forest avalanche events in the future. However, the spatial patterns of mountain forest development and the effects on avalanche control are highly dependent on site conditions, i.e. the protective effect of forests located on very step north-exposed slopes with frequent snow movements might not increase significantly.

Increasing densities of small-diameter trees in forest avalanche starting zones in combination with their influence on runout distances of small to medium forest avalanches suggest a decreasing trend in avalanche magnitude as already observed for avalanches in open unforested terrain (Eckert et al., 2010). Therefore, destructive forces of avalanches which start in forests may be reduced and avalanches may stop in forests more frequently before reaching the valley bottom.

While a general upward movement of the treeline can be expected in the long term, the influence of trends in tree species composition and their effects on avalanche control are highly uncertain. The simulation results of TreeMig-Aval exemplify one possible development for a high alpine valley in Davos, Switzerland. The model includes forest-avalanche feedback effects, i.e. climatically altered performance of trees which interact with altered avalanche regimes. However, expected higher frequencies of other natural disturbances such as wind, fires and bark beetle outbreaks will also shape mountain forests and can at least temporally increase the risk of subsequent avalanche releases by creating new potential avalanche release areas.

Developments in meteorological contributory factors for forest avalanche releases, and changes in the extent, composition and structure of mountain forest will challenge the future natural hazard management as well as the management of avalanche prone ecosystems. Forest management concepts and guidelines are often well adapted to regionally specific forest-avalanche interactions (e.g. Weir, 2002; Brang et al., 2006); however, climatically induced shifts in the importance and reliability of avalanche protection provided by mountain forests should be more considered in future.

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