SNOW AVALANCHES IN FORESTED TERRAIN

A thesis submitted to attain the degree of

DOCTOR OF SCIENCES

(Dr. sc. ETH Zurich)

presented by

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2013
Summary

Snow avalanches are a substantial natural hazard in mountainous regions, endangering people, settlements and infrastructure. Forests play a crucial role in avalanche control by hindering avalanche formation and, therefore, preventing avalanche releases as well as by limiting avalanche runout of small- to medium-scale avalanches. The goal of this PhD project was the investigation of avalanche-forest interactions in the avalanche track and runout zone and their implementation in simulation and evaluation tools to support natural hazard and protection forest management. To cope with future environmental changes, the thesis explicitly addressed climatically induced shifts in the importance and reliability of the protective effects of mountain forests against snow avalanches. The objectives were approached in six first- and five co-authored papers completed during this PhD project:

In Paper I, the protective effect of a single mountain forest against snow avalanches was evaluated in a spatially explicit manner. The core of the presented methodical framework was a GIS-based risk analysis accounting for the effect of different forest structures on avalanche release. The effect of forests on avalanche runout was analyzed by five forest cover scenarios and their influence on (1) avalanche simulation and (2) the resulting risk for a case study area. The paper highlights how a risk-based approach can help to quantify and illustrate the impact of differences in forest cover on the protective effects of mountain forests. The study thereby demonstrates the advantages of risk-based management strategies in providing quantitative and qualitative information for cost-efficient forest maintenance planning. However, the results also emphasized the need for further improvements of avalanche simulation models to better perform in forested terrain.

Therefore, to investigate how forests decelerate snow avalanches, two data sets from the European Alps were analyzed in Paper II about statistical dependencies between predictor variables on forest conditions, terrain features and avalanche characteristics (60 in total) and the response variable avalanche runout distance: Forest structural parameters had a significant effect on runout distances of small- to medium-scale avalanches which released in forests, but forest structure did not affect runout distances of medium- to large-scale avalanches which started above treeline. In particular, the starting zone stem density of trees with small diameters (1-15 cm) had a significant effect on runout distances of avalanches which released in evergreen coniferous and mixed forests. Beyond a runout distance threshold of 200 m this
effect was limited for avalanches which were still in motion. The detailed insights about avalanche-forest interactions gained in this paper contributed considerably to the improvement of avalanche simulation in forested terrain.

In Paper III, the important effect of forests in stopping small- to medium-scale avalanches was quantified and expressed in a detrainment function to directly extract the mass from the flowing snow which is stopped behind trees, groups of trees or remnant stumps. The relationship was parameterized by the empirical detrainment coefficient $K$, representing forest characteristics such as forest stand density or mean stem diameters. The detrainment function was implemented in a numerical avalanche dynamics program to account for avalanche-forest interactions and was tested with a numerical experiment. The results confirmed that the velocity dependent detrainment function leads to improved simulation results compared to the traditionally applied friction approach.

The detrainment function was extensively evaluated and operationalized in computational avalanche simulation in Paper IV. To account for and to analyze the potential effects of different forest characteristics and structures, the detrainment coefficient $K$ was varied when simulating 40 well-documented small- to medium-scale avalanches which released in and ran through forests of the Swiss Alps. A recently developed evaluation and comparison approach was used to define runout distances based on a pressure-based runout indicator in an avalanche path dependent coordinate system. This method allowed to automatically analyze the high number of two-dimensional simulation results to be comparable with the only one-dimensionally observed runout distances. Analyzing and comparing observations and simulations statistically revealed values for $K$ suitable to simulate the combined influence of four forest characteristics on avalanche runout: forest type, crown coverage, vertical structure and surface roughness, for example values for $K$ are higher for dense spruce and mixed spruce-beech forests compared to open larch forests at the upper treeline.

Regarding potential impacts of climate change on avalanches in forested terrain, Paper V focused on defining critical meteorological situations with a high probability of avalanche releases in forested terrain and on analyzing past changes in the occurrence of such situations in order to support forest avalanche forecasting. By applying a hierarchical clustering method, two forest avalanche types were distinguished: (1) ‘new snow forest avalanches’ and (2) ‘old snow forest avalanches’ (further referred to as ‘other forest avalanches’). We tested for long-term trends in the occurrence of the two favorable meteorological situations by applying a
logistic regression model. The observed negative trends suggest a further decrease of snow and weather conditions associated with avalanche releases in forests under climate change.

In addition, frequency and magnitude of forest avalanches are also likely to be affected by changes in forest cover. In Paper VI, we synthesized some results from Papers II and V as well as summarized recent findings from other studies on forest cover development and discussed their relevance in the context of global warming. The spatially explicit forest-landscape model TREEmig-Aval was employed to exemplify a possible development in a high alpine valley in Switzerland, accounting for avalanches and their effect on mountain forests and, therefore, future avalanche frequency: The simulation results showed a decreasing trend in the simulated total avalanche release area. Avalanches in forested terrain may therefore decrease in frequency and magnitude due to (1) shifts 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.

Five additional publications, Papers VII-XI (mainly co-authorship), are included in the appendix since they are related to or based on important findings gained within this PhD project.

This thesis is arranged at the interface between snow avalanches and forests and, therefore, diverging themes within the main topic “snow avalanches in forested terrain” are addressed and combined. The new insights gained from this research lead to recommendations which can support natural hazard and protection forest management.

As part of the interdisciplinary MOUNTLAND project (Competence Center Environment and Sustainability CCES of the ETH Domain), the achievements of this PhD project will improve the valuation of the ecosystem service “avalanche protection by forests” so it can be included in policy developments and innovative policy solutions more precisely.
Zusammenfassung


In der ersten Publikation (Paper I) wurde die Wirkung eines Schutzwaldes gegen Lawinen räumlich explizit quantifiziert und bewertet. Dabei wurde eine GIS-gestützte Risikoanalyse angewendet, mit der die Schutzleistung unterschiedlicher Waldstrukturen gegen Lawinenanrisse bewertet werden konnte. Die Wirkung des Waldes auf die Lawinenauslaufdistanz wurde anhand von fünf Waldzustandsszenarien und deren Einfluss auf (1) Lawinensimulationen und (2) das sich daraus ergebende Risiko für die Fallstudienregion analysiert. Die Studie zeigt auf, wie durch einen risikobasierten Bewertungsansatz die Schutzleistung unterschiedlicher Waldzustände abgebildet werden kann, um quantitative und qualitative Informationen für eine effektive und kosteneffiziente Schutzwaldbewirtschaftung bereitzustellen. Die Ergebnisse verdeutlichten aber auch die Notwendigkeit für detaillierte Untersuchungen der Wechselwirkungen zwischen Wald und Lawinen, um die Lawinensimulation in bewaldetem Gelände zu verbessern.

Deshalb wurden zwei gut dokumentierte Datensätze zu Lawinenereignissen in den europäischen Alpen bezüglich dem Einfluss des Waldes auf die Auslaufdistanz statistisch ausgewertet (Paper II). Insgesamt wurde für 60 Wald-, Schnee- und Geländeparameter analysiert, ob und wie sie die Auslaufdistanz von Walmdlawinen beziehungsweise von oberhalb der Waldgrenze angebrochenen Lawinen beeinflussten: Unterschiedliche Waldstrukturen hatten einen signifikanten Einfluss auf die Auslaufdistanz kleiner bis mittelgrosser


In Paper V wurden kritische meteorologische Situationen analysiert, welche in der Vergangenheit zu Lawinenanrissen im Wald führten. Durch die Anwendung einer Clusteranalyse konnten zwei typische Situationen von kritischen Schnee-


Fünf weitere Publikationen, Papers VII-XI (hauptsächlich Co-Autorenschaft), sind im Anhang enthalten, da sie in Zusammenhang zu oder basierend auf wichtigen Erkenntnissen dieser Dissertation stehen oder entstanden sind.


Als Teil des interdisziplinären Forschungsprojektes MOUNTLAND (Competence Center Environment and Sustainability CCES der ETH) können die Erkenntnisse dieser Dissertation die Bewertung der Ökosystemleistung "Lawinenschutz durch Wälder" verbessern und somit Entscheidungen im Hinblick auf eine nachhaltige Bewirtschaftung und Nutzung von Bergregionen unterstützen.
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Chapter 1

Introduction

1.1 General introduction

Snow avalanches are a substantial natural hazard in mountainous regions, endangering people, settlements and infrastructure. Forests play a crucial role in avalanche control, for example in Switzerland mountain forests are the most important protection measure against snow avalanches in terms of surface area (Margreth, 2004). Currently, approximately 43% of the Swiss forests provide direct or indirect protection against natural hazards in general (Brändli, 2010); protection against snow avalanches in particular is one of the main functions of forests in mountainous regions (Brang et al., 2006). The great importance of mountain forests in avalanche control was recognized as early as the Middle Ages in different Alpine regions in Europe (Sablonier, 1995). Since then, forests above mountain villages have been protected and declared untouchable (Schneebeli and Bebi, 2004). Thus, maintaining the protective function has a long tradition in mountain forest management (Kräuchi et al., 2000).

Mountain forests throughout the world provide a vast variety of ecosystem goods and services (EEA, 2010), collectively called ecosystem services (ES) to people living in the mountains as well as people living outside these areas (Grêt-Regamey et al., 2012a). Besides the protection against natural hazards, timber production, carbon sequestration and storage, fresh water regulation, recreation opportunities, habitat for plants and animals or the provision of scenic beauty are ES which have to be considered within sustainable mountain forest management strategies (e.g. Price, 2003; Körner, 2004; Zierl and Bugmann, 2007; Grêt-Regamey et al., 2008b; Briner et al., 2012; Elkin et al., 2013; Grêt-Regamey et al., 2013). Forest management in terms of multifunctional forestry needs to be supported by accurate and detailed information about the values of such ES, their trade-offs and spatial distributions (e.g. Farrell et al., 2000; Egoh et al., 2008; Chen et al., 2009; Patterson and Coelho, 2009; Nelson et al., 2009; Grêt-Regamey et al., 2013). For instance, in many mountain regions worldwide, the pressure for wood products may increase in the future, leading to large areas with a conflict of interests between avalanche protection, efficient wood production and other ES (Bebi et al., 2009).

1 ES are the benefits people obtain directly or indirectly from ecosystems (MEA, 2005).
In contrast to most of the mentioned ES, the ability of mountain forests to protect people, buildings and infrastructure against snow avalanches is an only locally available ecosystem service (Grêt-Regamey et al., 2012b). That is, the effect of protection forests in decreasing the risk\(^2\) of avalanches is spatially limited to areas with specific conditions such as a considerable damage potential below the forest, the distribution of forest structural parameters and that the forest is not vulnerable to avalanche disturbances that start too high above the forest (Bebi et al., 2009). The effectiveness of the protective function itself strongly depends on local conditions, i.e. stand characteristics such as tree height, stem density and the presence, size and spatial distribution of forest gaps, in combination with terrain and climate conditions (e.g. Bebi et al., 2001; Brang et al., 2006; Bebi et al., 2009; Viglietti et al., 2011).

The main effect of trees and forests growing in avalanche prone terrain is to prevent avalanche releases. In contrast to open unforested terrain, mountain forests of a certain structure modify the snow's mechanical properties, which in turn reduce the formation of continuous weak snowpack layers favoring slab avalanches (Schneebeli and Bebi, 2004). However, due to complex interactions between ecological conditions, topography, snowpack and meteorological parameters, the protective effect of forests may be reduced and, therefore, so-called ‘forest avalanches’ do occur. Avalanches released in forests are usually small; however, depending on ecological, meteorological, and topographical conditions, they may develop into larger avalanches endangering settlements and infrastructure below the forest and threatening recreationists who often access forested terrain while out-of-bounds (off-piste) skiing. For such avalanches, the secondary protective effect of mountain forests on avalanche runout becomes relevant, i.e. deceleration, and even the capability to stop small- to medium-scale avalanches (Bartelt and Stöckli, 2001; Takeuchi et al., 2011; Anderson and McClung, 2012).

The protective function of mountain forests is not a steady condition. In fact, benefits and effectiveness are influenced by several factors. Densely populated mountainous regions such as the European Alps are characterized by a constant pressure from economic and population growth (Spehn et al., 2002), which influences the distribution of the damage potential as well as entails a growing demand for environmental and recreational services (Grêt-Regamey et al., 2012a). In addition to these developments, changing environmental conditions will affect

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\(^2\) Risk is defined as the product of the probability of a damaging event and its consequences such as the expected number of fatalities, and damage to buildings, traffic routes or other infrastructure (e.g. Slovic, 2001).
mountainous regions considerably (e.g. Schröter et al., 2005; Nogués-Bravo et al., 2007; McCain and Colwell, 2011; Gottfried et al., 2012).

Regarding future avalanche risk management, climate change is a key issue and of great importance for inhabitants of alpine areas (Schneebeli et al., 1997; Martin et al., 2001). In particular, the frequency and magnitude of avalanches in forested terrain are likely to be affected by altered snow regimes and meteorological conditions as well as by changes in the composition, structure and extent of the forest cover. Due to potential land-use and climatic changes, future natural hazard and protection forest management need to be supported by detailed information on the protective effect of forests against snow avalanches as well as the spatial and temporal patterns of this function. Thus, there is a considerable interest in understanding how forests affect the occurrence, frequency and magnitude of snow avalanches (Gruber and Bartelt, 2007; Bebi et al., 2009), especially in populated areas where the risk of avalanches limits habitability (Grêt-Regamey and Straub, 2006). Furthermore, to optimally allocate resources and to better prioritize between different silvicultural interventions, the long-term development of protection forests including potential disturbance interactions needs to be taken into account (Wehrli et al., 2006), especially under changing climate conditions where forest management faces many uncertainties (Yousefpour et al., 2012).

Bebi et al. (2009) suggested three major points where future research is challenged to provide more insights into avalanche-forest interactions:

• An improved understanding of interactions between forests and small avalanches is necessary to support optimized and regionally adapted decisions. This aim is especially important in mountain areas where a conflict of interest between avalanche protection and other ES requiring more open forest structures exists.

• Improving spatially explicit modeling methods in a Geographical Information Systems (GIS) environment can help to designate areas where the maintenance of the protective function is essential and areas where the creation of gaps of certain sizes will not pose unacceptable risks of avalanches.

• Climatically induced shifts in the importance and reliability of the protective effects of mountain forests against snow avalanches have to be increasingly taken into account when considering the role of protection forests in natural hazard management.
The studies presented in this doctoral thesis explicitly address the research gaps pointed out by Bebi et al. (2009). The goal of the thesis was to characterize avalanche-forest interactions in the avalanche track and the avalanche runout zone, thereby improving our understanding of how implementing potential decelerating effects of forests in avalanche simulations can best support future natural hazard and protection forest management. A spatially explicit evaluation of the forests’ protective function provides the information needed to manage mountain forests efficiently. Finally, considering both past changes in snow and weather situations associated with avalanche releases in forests as well as past and future changes in the forest cover could help to predict the activity of avalanches in forested terrain in a changing environment.

1.2 This doctoral thesis

1.2.1 Major research questions and hypotheses

Important gaps of knowledge in forest avalanche research, pointed out in the previous section, are addressed by four key research questions and hypotheses:

1) How can the protective effects of forests be quantified in a spatially explicit manner in order to support decision-making in mountain forest and natural hazard management?

Hypothesis: The protective function of mountain forests as the abilities to prevent avalanche releases and to reduce the magnitude of smaller avalanches is spatially limited to areas with specific conditions such as the distribution of forest structural parameters. These protective effects can be quantified and evaluated in a spatially explicit manner by applying risk analyses in combination with avalanche simulation models since varying structural conditions and forest extents have an influence on avalanche release and avalanche runout.

2) What structural conditions of forests are needed to decelerate or even stop snow avalanches of a certain size?

Hypothesis: Forest structure, determined by single tree parameters, stand characteristics and their spatial distribution, affects the flow of snow avalanches differently in (1) the starting zone, (2) the avalanche track, and (3) the runout zone. In addition, avalanche size and destructive forces are determined by forest structure in combination with topography and snow conditions.
3) How can numerical avalanche simulation models be improved by implementing knowledge on avalanche-forest interactions?

Hypothesis: Forests growing in the avalanche path reduce the avalanche flow mass. Trees act like obstacles and are capable to stop mass immediately, i.e. the granular snow flow, by a combination of impact, rubbing dissipation, deflection, cohesion and jamming which leads to significant deceleration and runout shortening of small- to medium-scale avalanches. These avalanche-forest interactions can be expressed with a detrainment function depending on forest structural conditions such as stand density, stem diameters or undergrowth which determines the volume of snow stopped behind trees. Implemented in a numerical avalanche simulation model, simulations of real avalanche events released in forests will reveal the forest parameters which determine the simulated avalanche runout distances to parameterize the detrainment function.

4) What are the potential impacts of changing climate conditions on avalanches in forested terrain?

Hypotheses: Frequency and magnitude of avalanches in forested terrain are likely to be affected by changes in snow regimes and meteorological conditions as well as by changes in composition, structure and extent of the forest cover. Concerning such potential changes, several hypotheses can be defined: (1) Meteorological conditions associated with forest avalanche releases are clearly distinguishable from snow and weather conditions critical for avalanche releases in open unforested terrain. The definition of thresholds for meteorological contributory factors supports the forecasting of forest avalanches. (2) Due to rising temperatures, less heavy snowfall and more frequent rain events in the winter season, the frequency of dry snow avalanches will probably decrease while the frequency of wet snow avalanches might increase. (3) Past forest cover expansions and increasing forest densities caused by climate as well as land-use changes will continue in the future with positive consequences for avalanche protection, i.e. the frequency and magnitude of forest avalanches will decrease. However, high uncertainties still exist about the influence of changing climate conditions on other natural disturbances such as wind, fire or bark beetle outbreaks and their effect on the protective function of mountain forests.
1.2.2 Overview of the thesis

The research questions are addressed in six main publications; four papers are published in peer-reviewed (ISI) journals (Chapters 3, 4, 5, and 7), one article has been submitted and is already published as a discussion paper (Chapter 6), and one paper is a conference proceedings publication (Chapter 8). In addition, five papers (mainly co-authorship) are included in the appendix since they are related to or based on important findings gained within this PhD project.

Chapter 2 provides a brief overview and background information on the broad topics which are addressed in the single articles (Chapters 3 to 8). This chapter also includes supplementary material on topics which were not addressed explicitly in this PhD thesis, but are nonetheless important for future protection forest and natural hazard management under a changing environment.

Chapter 3

*Evaluating the benefit of avalanche protection forest with GIS-based risk analyses – A case study in Switzerland*

In this chapter, the protective effect of a single mountain forest against snow avalanches is evaluated in a spatially explicit manner. The core of the presented methodical framework is a GIS-based risk analysis accounting for the effect of different forest structures on avalanche release. The effect of forests on avalanche runout was analyzed by five different forest cover scenarios and their influence on (1) avalanche simulations and (2) the resulting risk for the case study area. The paper highlights how a risk-based approach can help to quantify and illustrate the impact of differences in forest cover on the protective effects of mountain forests. The study thereby demonstrates the advantages of risk-based strategies in providing quantitative and qualitative information for cost-efficient forest maintenance planning. However, the results also emphasize the need for further improvements of avalanche simulation models to better perform in forested terrain.

Chapter 4

*Snow avalanches in forested terrain: Influence of forest parameters, topography and avalanche characteristics on 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
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forests on avalanche runout. To investigate how forests decelerate snow avalanches, two data sets from the European Alps are analyzed about statistical dependencies between predictor variables on forest conditions, terrain features and avalanche characteristics (60 in total) and the response variable avalanche runout distance. One important finding presented in this chapter is that forest structural parameters have a significant effect on runout distances of small- to medium-scale avalanches which release in forests while forest structure does not affect runout distances of medium- to large-scale avalanches which start above treeline. The detailed insights about avalanche-forest interactions gained in this paper contributed considerably to the modeling of avalanche-forest interactions and the improvement of avalanche simulation in forested terrain which are presented in Chapters 5 and 6.

Chapter 5
Observations and modeling of the braking effect of forests on small and medium avalanches (co-authorship)

Avalanche dynamics models have traditionally been employed to predict runout distances and impact pressures of extreme avalanche events and have assigned a minor role to forests in dissipating flow energy. In this chapter, the important effect of forests in stopping small- to medium-scale avalanches (see Chapter 4) is quantified and expressed in a detrainment function to directly extract the mass from the flowing snow which is stopped behind trees, groups of trees or remnant stumps. The relationship is parameterized by the detrainment coefficient \( K \), representing forest characteristics such as forest stand density or mean stem diameters. The detrainment function was implemented in a numerical avalanche dynamics model to account for avalanche-forest interactions and was tested with a numerical experiment. The results confirm that the velocity dependent detrainment function leads to improved simulation results compared to the traditionally applied friction approach. I contributed to this work primarily by preparing data and discussing the applied methods and results.

Chapter 6
Computational snow avalanche simulation in forested terrain

In this chapter, I present an evaluation and improvement of the detrainment function presented in Chapter 5. To account for and to analyze the potential effects of different forest characteristics and structures, the detrainment coefficient \( K \) was varied when simulating 40 well-documented small- to medium-scale avalanches which released in and ran through
forests of the Swiss Alps. Furthermore, to systematically analyze the high number of two-dimensional simulation results with the one-dimensionally observed runout distances, a recently developed evaluation and comparison method defining runout distances based on a runout indicator in an avalanche path dependent coordinate system was used. Comparing and analyzing observed and simulated runout distances statistically revealed the values for $K$ suitable to simulate the combined effects of the forest characteristics forest type, crown closure, vertical structure and surface roughness.

Chapter 7

Snow and weather conditions associated with avalanche releases in forests: Rare situations with decreasing trends during the last 41 years

In contrast to avalanche releases in open unforested terrain, much less is known about meteorological contributory factors of avalanche releases in forests. This chapter focuses on defining critical meteorological situations with a high probability of avalanche releases in forested terrain and on analyzing past changes in the occurrence of such situations in order to support forest avalanche forecasting. By applying a hierarchical clustering method, two forest avalanche types were distinguished: (1) ‘new snow forest avalanches’ and (2) ‘old snow forest avalanches’ (further referred to as ‘other forest avalanches’). We tested for long-term trends in the occurrence of the two favorable meteorological conditions by applying a logistic regression model. The observed mainly negative trends suggest a further decrease of snow and weather conditions associated with avalanche releases in forests under future climate change. However, these findings do not challenge the importance of an effective protection forest management since other natural hazards as well as forest disturbances caused by wind, fires or bark beetles might become more frequent due to changing climate conditions.

Chapter 8

Potential impacts of climate change on snow avalanches starting in forested terrain

Frequency and magnitude of forest avalanches are likely to be affected by climate change by (1) shifts in the occurrence of favorable snow and weather situations which increase the probability of forest avalanche releases (see Chapter 7), and (2) changes in the extent, composition and structure of mountain forests. This chapter addresses both aspects by synthesizing some results from Chapters 4 and 7 as well as by summarizing recent findings from other studies on forest cover development and discusses their relevance in the context of global warming. In addition, the spatially explicit forest-landscape model TREEMIG-AVAL
(see Appendices C and D) was employed to exemplify a possible development in a high alpine valley in Switzerland, accounting for avalanches and their effect on mountain forests and, therefore, future forest avalanche frequency.

Chapter 9 summarizes the conclusions of this PhD thesis, highlights its social and scientific contributions and ends with an outlook on future directions in the area of forest avalanche research.

Appendices A-E provide additional publications (mainly co-authorship) which are related to or based on important findings gained within this PhD project. I contributed to these papers primarily by analyzing data and writing the respective sections (Appendices A and E) or by providing/preparing data for further analysis and/or discussing the applied methods and results (Appendices C and D). An additional conference proceedings publication (Appendix B) is related to the work presented in Chapters 5 and 6, and outlines a theoretical framework for probabilistic calibrations of avalanche simulation in forested terrain.

1.2.3 The project MOUNTLAND

This doctoral thesis was embedded in the interdisciplinary project “MOUNTLAND”3 funded by the Competence Center Environment and Sustainability of the ETH Domain (CCES). MOUNTLAND focused on different aspects of land-use and climate change in three study regions in Switzerland (Jura Mountains, Jura Vaudois; Visp region, Central Valais; Davos, Grisons) aiming to contribute to the development of adapted land-use practices and innovative policy solutions for mountain regions (Huber et al., 2012a, b). The project included researchers from multiple disciplinary backgrounds, including ecology, socio-economy and political sciences organized in three different tasks. This study was part of Task 2, which addressed the socio-economic research and encompassed two major aspects: first, the valuation and change in ES, and, second, the modeling of ES with regard to management activities. Within the MOUNTLAND project, this doctoral thesis contributes to a better understanding of avalanche-forest interactions, their quantification and modeling, and potential changes in the role of mountain forests as an effective biological protection against snow avalanches under a changing environment. Regarding the goals of MOUNTLAND, the findings gained within this PhD project will improve the valuation of the ecosystem service “avalanche protection” so it can be included in policy developments and innovative policy solutions more precisely.

3 URL: http://www.cces.ethz.ch/projects/sulu/MOUNTLAND (accessed July 2013)
Chapter 2

Theoretical background

2.1 Protective effects of mountain forests

The protective effects of a forest against snow avalanches can be defined as its effect on avalanche formation (e.g. Salm, 1978; de Quervain, 1979; Gubler and Rychetnik, 1991; Schneebeli and Meyer-Grass, 1993; Schneebeli and Bebi, 2004; Viglietti et al., 2011) and its influence on the runout distance and pattern of an avalanche (e.g. Butler, 1979; Butler and Malanson, 1992; McClung, 2003; Takeuchi et al., 2011; Anderson and McClung, 2012).

A comprehensive overview of recent research about interactions between avalanches and forests was given in Bebi et al. (2009) and is explained in more detail in the articles presented later in this PhD thesis. Here I will briefly summarize important aspects of avalanche-forest interactions and give relevant background information on snow avalanche formation and dynamics.

In general, snow avalanches are snow masses that rapidly descend steep slopes after releasing as loose snow avalanches or slab avalanches (Schweizer et al., 2003). Loose snow avalanches start from a point in a relatively noncohesive surface layer of either dry or wet snow. In contrast, slab avalanches release as a cohesive snow slab over an extended plane of weakness (Perla, 1980) triggered by (1) localized rapid near-surface loading, for example skiers or explosives (artificial triggering), (2) gradual uniform loading, typically caused by strong snowfall events, or (3) changing snowpack properties, such as surface warming (natural triggering or spontaneous release) (Schweizer et al., 2003). An “extended plane of weakness” could consist of a buried layer of kinetic growth crystals, such as surface hoar, (near-surface) faceted crystals, or depth hoar, which can create persistent weak layers in the snowpack (Jamieson and Johnston, 1992).

Forest effects on snow avalanche formation

Avalanche formation involves the complex interaction between terrain, snowpack, and meteorological conditions. A review on the formation of slab avalanches in particular was given by Schweizer et al. (2003). A comprehensive summary of various aspects of snow avalanches in general can be found in McClung and Schaeerer (2006). However, to emphasize
the importance of protection forests for avalanche control, I briefly summarize the main contributory factors which are related to the avalanche formation process (e.g. Atwater, 1954; de Quervain, 1966; Perla, 1970; Schweizer et al., 2003):

- **Terrain:** Terrain is the only contributory factor that is constant over time. Usually, a slope angle close to 30° is required for dry snow slab avalanche releases (van Herwijnen and Heierli, 2009). In addition, avalanches are more frequent in starting zones with concave cross-slope profiles (McClung, 2001). Terrain roughness hinders the formation of continuous weak snowpack layers since a minimum snow depth of 0.3-1 m is required to smooth out most height undulations (Schweizer et al., 2003).

- **Precipitation** (especially new snow): In general, a new snow height accumulation of about 30-50 cm during a storm is necessary for naturally released avalanches; a new snow height of about 1 m is considered the critical threshold for the initiation of extreme avalanches (Schweizer and Föh, 1996).

- **Wind:** Wind contributes to snow loading, especially after new snow events, by producing irregular snow deposits with locally increased loading rates. Therefore, variations in wind speed and snow drift form layers of different density or hardness, creating stress concentrations within the snowpack (e.g. Schmidt, 1980).

- **Temperature and radiation effects:** Changes in air temperature affect snow stability in various ways. In general, there are two competing effects on (1) metamorphism and creep and (2) mechanical snow properties, for example rising temperatures during a storm and rapid temperature increase shortly after a storm event contribute to snowpack instability (e.g. Reuter and Schweizer, 2012). Large temperature gradients near the snow surface resulting from the heat loss by outgoing longwave radiation leads to the formation of near-surface faceted crystals and/or the development of surface hoar (e.g. Schweizer et al., 2003; Helbig and van Herwijnen, 2012). Slab avalanches can follow from the failure of a buried layer of such kinetic growth crystals creating persistent weak layers in the snowpack.

- **Snowpack:** Snow cover stratigraphy is the key contributing factor for the formation of dry snow slab avalanches. If no weakness exists in either the snowpack or at the snow surface, loading by new or wind-driven snow or any temperature increase would have no effect on snow stability (e.g. McClung and Schaerer, 2006).
Forests growing in avalanche prone terrain can prevent avalanche releases by modifying most of these main contributory factors which are related to the avalanche formation process. Therefore, the formation of continuous weak snowpack layers favoring slab avalanches is reduced by:

- **The interception of falling snow by tree crowns:** In contrast to open unforested terrain, snow depth in forests is lower since interception by tree crowns reduces the amount of snow reaching the ground by 10 to 50% (McClung and Schaefer, 2006). Moreover, the intercepted snow falls out irregularly and creates a more heterogeneous snowpack around the stems within a typical distance of about 1.5 times the crown projection.

- **The reduction of near-surface wind speeds:** Wind speeds in forests are reduced which prevents extreme snow accumulation in gullies and depressions as they tend to occur in open areas (Schneebeli and Bebi, 2004). Maximum snow accumulation usually occurs in gaps with widths of 1 to 2 times the height of the surrounding trees (Imbeck and Ott, 1987).

- **The modification of the radiation and temperature regimes:** Due to shielding effects of the canopy, fluctuations in snowpack surface temperatures are more moderate than outside forest areas (Höller, 1998). Forests reduce both incoming shortwave and effective longwave radiation escape and, therefore, surface hoar as a major cause of slab avalanche formation is much smaller in forests, if any (Lutz and Birkeland, 2011; Shea and Jamieson, 2010).

- **The direct support of the snowpack:** Stems, remnant stumps and dead wood disturb and support the snowpack especially in dense forests (Schneebeli and Bebi, 2004).

Forest structure, namely crown closure, tree density and size and distribution of forest gaps, in combination with topography directly influences the probability of avalanche release in forests (e.g. Bebi et al., 2001; Schneebeli and Bebi, 2004; Viglietti et al., 2010). For example, the analysis of 110 avalanches which released in subalpine spruce- and larch-dominated forests in the Swiss Alps has shown that forests with a crown cover of less than 30% can hardly prevent avalanche formation. For crown cover densities between 30% and 50%, avalanches may occur on steep slopes (>30°) if the minimum gap length exceeds 25 m or if trees are deciduous. Finally, the minimum gap width required for avalanche formation at a
crown cover density of 60% and a steepness of 35° is 5-20 m, depending on tree species mixture (Bebi et al., 2009).

Forest effects on avalanche runout

In a released avalanche, the snow cover breaks into blocks and particles of various shapes and sizes as soon as it is set in motion due to interactions with the roughness features of the terrain. As the descent continues, the particles become smaller as they continually collide with each other and the sliding surface and fracture under impact. The diverse array of particle interactions produces a wide variety of flow behaviors depending on particle properties (size, hardness, dry or wet) and terrain characteristics (Bartelt et al., 2012b) and, therefore, result in different flow forms ranging from heavy dense flowing avalanches to powder suspension currents, and various transitional and mixed avalanche forms (Issler and Gauer, 2008; Bartelt and McARDell, 2009; Simpson, 2010). Important characteristics of avalanche motion in open unforested terrain are: (1) acceleration is very rapid in the early stages of the motion due to the high downslope driving force and the fairly low bottom friction after the release, and (2) deceleration is very rapid at the end of the motion, which implies high friction in the runout zone.

Released avalanches that exceed a certain threshold of magnitude cannot be stopped immediately by forests, but forests are still able to reduce avalanche speeds and runout distance (Takeuchi et al., 2011; Anderson and McClung, 2012). Most snow avalanche events released more than 150 m above treeline are sufficiently strong to break or uproot trees (Schneebeli and Bebi, 2004). Therefore, the critical length of forest openings for the release of avalanches lies between 50 and 150 m (Bebi et al., 2009). Tree fracturing consumes relatively little of the energy of an avalanche, and large avalanches can therefore destroy forests without a significant deceleration (de Quervain, 1979; Bartelt and Stöckli, 2001; Margreth, 2004). Stem breakage or uprooting of trees depends on tree species (Frey, 1977; Schönenberger, 1978; Butler, 1979; Johnson, 1987), tree height (Rikli, 1908; In der Gand, 1983; Kajimoto et al., 2004), tree diameter (Mears, 1975; Johnson, 1987) and snow pressure (de Quervain, 1979; Margreth, 2008). Critical snow pressures can already be found in relatively small avalanches and after short running distances of about 50 m; however, speed reduction of small avalanches by forest has not yet been investigated and quantified (Bebi et al., 2009).
Valuing the protective effects of forests

Long-term sustainable protection forest management should include both protective effects of mountain forests within management concepts and strategies. Ecological studies that attempted to quantify the protective function of forests and their dynamics emphasize the importance of translating the protective effect of forests into an economic value to support a multifunctional forestry (e.g. Bebi et al., 2001, 2009). A few evaluation studies have been conducted that apply contingent valuation techniques (Löwenstein, 1995), replacement cost methods (Goio et al., 2008; Notaro and Paletto, 2012) or estimates of the willingness-to-pay for avalanche protection based on choice experiments (Olschewski et al., 2012, see Appendix A). In addition, spatially explicit risk analyses which consider forests as an effective and cost-efficient biological protection measure against snow avalanches have been applied successfully to value the ES “avalanche protection” (Grêt-Regamey and Straub, 2006; Grêt-Regamey et al., 2008a, 2008b, 2012b, 2013). However, these studies did not account for varying effects of different forest structures on both protective functions of mountain forests: the effect on avalanche formation and the influence on avalanche runout.

2.2 Avalanche modeling in forested terrain

Knowledge on avalanche dynamics affect hazard mitigation strategies and, thus, avalanche dynamics models have become important tools for practitioners to determine runout distances, velocities and impact pressures of snow avalanches (Barbolini et al., 2000), for example blocktype avalanche models (Perla et al., 1980; Salm et al., 1990), flowing avalanche models (Savage and Hutter, 1989, 1991; Hungr, 1995; Volk and Kleemayr, 1999; Naaim et al., 2003, 2004; Gruber and Bartelt, 2007) and powder snow avalanche models (Fukushima and Parker, 1990; Ancey, 2004; Sampl and Zwinger, 2004; Turnbull et al., 2007).

The effect of mountain forests as an effective biological protection measure against avalanches has rarely been addressed in hazard zoning and engineering (Berger and Rey, 2004; Gruber and Bartelt, 2007); traditionally, the protective capacity of mountain forest is quantified as its effect to prevent avalanche releases (see Section 2.1). The influence of forests on avalanche runout is seldom considered in this context as many observations show that trees can fracture, break and be uprooted by large-scale avalanches without a significant deceleration (de Quervain, 1979; Bartelt and Stöckli, 2001). Therefore, forests are often neglected in hazard mitigation strategies under the assumption that extreme large avalanches easily destroy the forest. However, modeling how mountain forests decelerate or even stop
small- to medium-scale avalanches is an important issue (Casteller et al., 2008; Christen et al., 2010a; Anderson and McClung, 2012), especially since small frequent avalanches are often a threat to roads, railways and ski-runs below the forest (Techel et al., 2013).

Numerical avalanche dynamics models often employ a ‘Voellmy-fluid’ friction relation assuming small shear strains in the flow body (Salm et al., 1990; Bartelt et al., 1999). This Voellmy-type relation splits the total basal friction into a velocity independent dry-Coulomb term which is proportional to the normal stress at the flow bottom (friction coefficient $\mu$), and a velocity dependent “viscous” or “turbulent” friction (friction coefficient $\xi$) (Voellmy, 1955; Salm, 1993). Therefore, the stopping behavior of avalanches is controlled by frictional processes that are greatly influenced by mass fluxes in combination with low slope angles (Bartelt and Buser, 2010). One possibility to model the decelerating effect of forests on avalanche flow is by increasing friction for forested areas compared to open unforested terrain (Bartelt and Stöckli, 2001); this approach has already been applied by several authors (Gruber and Bartelt, 2007; Casteller et al., 2008; Christen et al., 2010a; Takeuchi et al., 2011). Bartelt and Stöckli (2001) confirmed its general applicability by applying a model based on the principle of conservation of energy and accounting for woody debris entrainment, tree overturning and fracture; however, they focused on the effect of forests on large-scale fast-moving avalanches only. Speed reduction of small avalanches by forest has not yet been investigated and quantified (Bebi et al., 2009). This is also due to the fact that avalanche-forest interactions for small- to medium-scale avalanches may be only poorly represented within the framework of this model. For such avalanches, decelerating effects of forests on avalanche flow are highly non-linear and local, and difficult to model with a Voellmy-type relation at a grid scale. Since proposed $\mu$- and $\xi$-values for forested areas are based on mechanical processes like tree overturning or fracturing (Bartelt and Stöckli, 2001), the friction approach may not be adoptable to simulate small- to medium-scale avalanches in forested terrain. During such events trees often do not break but remain standing, and spatial variations of forest structural conditions may influence the avalanche flow differently.

So far, no reliable tool exists to quantify the decelerating effects of different forest structures on avalanche flow to be applicable for hazard mitigation. Moreover, this effect has generally not yet been implemented in avalanche models (Anderson and McClung, 2012).
2.3 Climate change and avalanche protection

Climate change will affect mountainous areas considerably over the next century (Beniston, 2003). Under changing environmental conditions, the protective effect of mountain forests will be affected by (1) shifts in snow regimes and meteorological conditions (Marty, 2008; Serquet et al., 2011), and (2) changes in composition, structure and extent of the forest cover (Keller et al., 2000; Elkin et al., 2013). Moreover, since impacts of changing climate conditions will not only be driven by seasonal changes in average temperature and precipitation but also through changes in the frequency and intensity of ‘extreme’ events (Anderson, 2012; Orlowsky and Seneviratne, 2012; Reyer et al., 2013), increasing risks for other forest disturbances caused by wind, fires or bark beetle outbreaks will also affect the forest cover and influence mountain forests’ protective capacity.

Future avalanche activity

The effect of climate change on the avalanche activity is currently poorly understood, despite its great importance for inhabitants of alpine areas (Schneebeli et al., 1997; Martin et al., 2001; Jomelli et al., 2007). Recent studies have suggested that climate change during the past decades has had little impact on avalanche frequency in the European Alps (Laternser and Schneebeli, 2002; Eckert et al., 2010a). In contrast, decreases in runout elevation and, thus, in avalanche magnitude have been observed over the past 61 years (Eckert et al., 2010a) which could be partially explained by shifts from dry snow to higher frequencies of wet snow avalanches (Martin et al., 2001).

Changes in the mountain snow cover will undoubtedly influence future avalanche activity considerably. Decreasing trends in snow cover have already been shown, for example for the European Alps (Hantel et al., 2000; Laternser and Schneebeli, 2003; Scherrer et al., 2004; Wielke et al., 2004; Marty, 2008; Schoner et al., 2009), especially at lower elevations. Decreasing trends in snowfall days relative to precipitation days observed over 100 years at 76 meteorological stations in Switzerland were clearly related to increasing temperatures both in spring and in winter (Serquet et al., 2011). However, a study by Marty and Blanchet (2011) suggested that extreme snow depth and snow fall may decrease in the Swiss Alps at all elevations. The development of corresponding extreme avalanche events remains highly uncertain (Schneebeli et al., 1997).
Impacts of climate change on mountain forest ecosystems

The combined effects of rising temperatures and declining water availability have impacted the ecological function of mountain forests over the past half-century (Trujillo et al., 2012). Temperature increases are expected to continue during the 21st century in mountain ecosystems across the globe, with a rate of warming projected to be two to three times higher than that recorded during the 20th century (Pepin and Seidel, 2005). In the European Alps, temperatures in mountain regions are estimated to increase by approximately 4°C towards the end of the 21st century under the Intergovernmental Panel for Climate Change (IPCC) high emission scenario A2 (IPCC, 2007; Nogués-Bravo, 2007).

Changes in vegetation in the southeast Swiss Alps have already accelerated since 1985, consistent with the effect of changing climate conditions (Walther et al., 2005). Mountain ecosystems are very sensitive to changes in temperature, precipitation, snow cover duration and snowpack accumulation (Thuiller et al., 2005; McCain and Colwell, 2011; Rössler et al., 2012). All of these factors can have considerable influences on the growth, regeneration, mortality and displacement and/or extinction of various tree species (e.g. Jolly et al., 2005; van Mantgem et al., 2009; Loarie et al., 2009; Trujillo et al., 2012). Even moderate warming can lead to migration processes (Grabherr et al., 1994) that influence the structure, composition and extent of mountain forests (Keller et al., 2000; Elkin et al., 2013). Regarding potential shifts at the upper treeline, Lenoir et al. (2008) observed an overall upward trend in species optimum elevation for 171 forest plant species in western European mountains during the 20th century, with mountainous species experiencing larger shifts than more ubiquitous species. However, current studies also emphasize that, despite higher temperatures, several other factors such as grazing, snow cover duration or competition by dwarf shrubs and other vegetation can limit forest expansion at the upper treeline (e.g. Motta et al., 2006; Gehrig-Fasel et al., 2007; Harsch et al., 2009; Barbeito et al., 2012). The effects of changing vegetation patterns and forest expansion on avalanche control in particular are still highly uncertain (Keller et al., 2000).

Climate change and other natural forest disturbances

Mountain forests and, therefore, associated ES are increasingly influenced by climate-driven ‘extreme’ events such as drought, wind, insect outbreaks or forest fires (e.g. Lindner et al., 2008; Rigling et al., 2012; Elkin et al., 2013). In addition, such disturbances are often interdependent, i.e. increases in one disturbance can increase the occurrence and/or intensity
of others (Dale et al., 2001; Raffa et al., 2008; Seidl et al., 2011). Although the development of frequency and magnitude of natural disturbances other than snow avalanches was not considered in this PhD project, I will give a brief overview on the most relevant disturbances which may affect the structure, composition and extent of mountain forests and, thus, their protective function:

- **Wind**: Windstorms are a major disturbance in European forests (Wohlgemuth et al., 2008). The magnitude of wind disturbances and the vulnerability of forest stands to storm damages depend on complex interactions between meteorological, site and forest conditions. There is no clear evidence that the number of European storms with high wind speeds has increased in recent years (Albrecht et al., 2009), and model results have not shown clear tendencies toward increased wind speeds under changing climate conditions (Blennow and Olofsson, 2008). However, there are factors that suggest higher frequencies and magnitudes of storm damages in the future: (1) with increasing temperatures and soil moisture contents, the vulnerability of forests to storm damage is higher compared to dry conditions and frozen soils (Usbeck et al. 2009) and (2) increased standing volumes and forest densities associated with increasing temperature and land-use change (Bebi et al., 2009).

- **Forest fires**: Periodicity and severity of forest fires are influenced by climate effects (Swetnam and Betancourt, 1998; Ehle and Baker, 2003; Hessl et al., 2004). As temperatures rise, an increase in fire occurrence and extent can be expected (Schumacher and Bugmann, 2006; Zumbrunnen et al., 2011; Holsten et al., 2012). For example, in the western United States increases in regional spring-summer temperatures and earlier snowmelt since the mid-1980s were strongly correlated with a higher forest wildfire activity (Westerling et al., 2006).

- **Bark beetles**: Bark beetles, in particular *Ips typographus* (L. Scol. Col.), are the most important biotic disturbances in protection forests located in the European Alps (e.g. Seidl et al., 2009). Recent studies suggest increasing bark beetle damages with rising temperatures under global warming (Wermelinger, 2004; Seidl et al., 2009; Bentz et al., 2010). In addition, potential increases in storm damages might influence the frequency and magnitude of bark beetle outbreaks since they are often linked to such disturbances (Wermelinger, 2004).
• *Snow damage* (not associated with avalanches): Snow accumulation on trees is strongly dependent on climatic conditions. Temperature influences the moisture content and, therefore, the weight and accumulation of snow, which in turn affects how much tree damage occurs due to breaking crowns and branches. Snow accumulation is highest at temperatures between 0.6°C and -3°C (Saeki and Sugiyama, 1965). Due to increasing temperatures under climate change, the risk of snow damage could increase at elevations above approx. 1000 m asl (Hanewinkel et al., 2011). In contrast, snow damage in lower regions might decrease in the long-term because snowfall events are assumed to be less frequent and severe at lower elevations (Bebi et al., 2012a).

Due to changing climate conditions in combination with observed and predicted trends of forest cover expansion and increasing forest densities in the Swiss Alps, natural disturbances such as wind, forest fires, bark beetle outbreaks and snow damage might become more important in the future with long-term negative consequences on several ES (Elkin et al., 2013). Regarding the protective effect of mountain forests, such forest disturbances can create new avalanche release areas and 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).

Undoubtedly, climate change will have an impact on the protective effects of mountain forests due to several concurrent developments; however, high uncertainty remains.
Chapter 3

Paper I

Evaluating the benefit of avalanche protection forest with GIS-based risk analyses – A case study in Switzerland

Received 30 April 2008
Received in revised form 16 January 2009
Accepted 28 January 2009

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Abstract

The protection of people, buildings and infrastructure against natural hazards is one of the key functions of mountain forests. Since the protective function strongly depends on small-scale local conditions such as terrain and stand characteristics, spatially explicit evaluation methods are necessary to provide information required for an effective and cost-efficient forest management. Risk analyses are recognized as the best method for estimating the danger from various natural hazards. Currently, however, risk-based strategies are rarely addressed in the management of protection forest. We present and discuss a risk-based approach to evaluate the protective effect of mountain forests in a spatially explicit manner to demonstrate the advantages of future risk-based protection forest management. We illustrate the approach by performing a GIS-based risk analysis in the case study area ‘Bannwald of Andermatt’ (Switzerland) for a 300-year snow avalanche event. Classifying forest structures based on aerial photographs allowed developing different forest cover scenarios and modeling potential avalanche release areas within the forest. Potential avalanche release areas above the forest and the avalanche runout distances under five different scenarios of forest cover were calculated by using a two-dimensional avalanche simulation model. We calculated the annual collective risk for each scenario and compared the change in risk to reveal the spatial distribution of the protective effect of the forest. Resulting risks differed strongly between forest cover change scenarios. An enlargement of an existing wind-disturbed area within lower parts of the slope resulted only in a slight increase of risk. In contrast, the effect of an unforested area in the upper parts of the observed forest more than doubled the risk. These results show how a risk-based approach can help to quantify and illustrate the impact of differences in forest cover on the protective effect of mountain forests. It is a promising approach to determine the economic value of protection forests and thus provide quantitative and qualitative information for cost-efficient forest maintenance planning. With regard to the achievements of research to date, the presented approach may serve as a valuable method to support decision-making in a future protection forest management.

Keywords: Protection forest, Risk analysis, Snow avalanches, GIS, Forest structure, Process-model
3.1 Introduction

One of the main functions of forests in mountainous regions is to protect people, buildings and infrastructure against natural hazards, such as avalanches and rockfall (Brang et al., 2006). The effectiveness of this protective function strongly depends on small-scale local conditions. Beside terrain and climate conditions, stand characteristics such as tree height and stem density, and presence, size and spatial distribution of gaps determine the dimension, intensity and thus the probability of damaging events (Bebi et al., 2001; Dorren et al., 2005; Brang et al., 2006).

Therefore, a spatially explicit approach is needed to evaluate the protective function of mountain forests and to provide the necessary information to manage protection forests efficiently (Bebi et al., 2001). Forest managers and local authorities can obtain spatially explicit information using geographic information systems (GISs). Progress in GIS-technology and increased availability of digital data have enabled the use of GIS as a practical technique, even for non-specialized users.

In Switzerland the management and maintenance of protection forest are subsidized by public funds (BAFU, 2004). Since these funds are limited, the forest sector is under pressure to work more cost-efficiently while maintaining adequate protection against natural hazards. Therefore, transparent support tools are needed for decisions about silvicultural interventions.

The concept of risk is a framework for handling safety problems in general (e.g. Slovic, 2001). It has been used successfully in the field of natural hazard management to evaluate protection measures (Wilhelm, 1997; Borter, 1999; Fuchs and McAlpin, 2005; Bründl et al., 2006). Currently, however, risk-based strategies are rarely addressed in the management of protection forests (Bebi et al., 2004). Spatial process models for natural hazards have improved tremendously over the last decades and are increasingly used in risk-assessment (e.g. Renschler and Harbor, 2002; Dorren, 2003; Dorren et al., 2004; Fuchs et al., 2004; Stoffel et al., 2006). In Switzerland, the two-dimensional numerical model AVAL-2D (Gruber, 1999; Gruber, 2001; Maggioni and Gruber, 2003) is used in practice to predict snow avalanche runout distances, flow velocities and impact pressures in three-dimensional terrain (Gruber and Bartelt, 2007). Using AVAL-2D Grêt-Regamey and Straub (2006) performed risk calculations considering the avalanche protection forest for the administrative district of Davos (Switzerland). However, the snow avalanche risk was only calculated for two extreme
scenarios, i.e. with and without the protection forest. Variations in forest cover were not considered in that study.

In this paper, we present and discuss a spatially explicit approach for a risk-based forest management, illustrated with a case study in the Swiss Alps. The approach combines already established methods of forest- and risk-assessment and aims for a methodological framework which considers forests as an efficient biological protection against snow avalanches on a local scale. The approach can be considered as a methodological framework for further investigations and applications of risk-based approaches for an effective and cost-efficient protection forest management also regarding other natural hazards.

3.2 Methods

3.2.1 General approach

The methodological framework explored in this study consists of five major steps summarized in Figure 3.1 and described in detail in the Sections 3.2.3 to 3.2.6.

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**Fig. 3.1.** Methodical framework for a risk-based approach using GIS consisting of five major steps. Comparing the risk under different forest-cover scenarios led to spatially explicit information for an effective and cost-efficient protection forest management.
To obtain information about the influence of changes in forest cover on the avalanche risk of an investigation area, realistic forest cover scenarios were developed. By analyzing aerial photographs, forest structures were mapped and classified in GIS (Bebi et al., 2001). This information was used to generate forest cover scenarios and to calculate potential avalanche release areas within the forest. The risk of an extreme avalanche event with a recurrence period (T) of 300 years under each forest cover scenario was calculated, following the recommended uniform procedure for risk analyses (e.g. Wilhelm, 1997; Borter, 1999; Fuchs et al., 2004). The avalanche runout distances were determined by using the two-dimensional dynamic avalanche simulation model AVAL-2D (Gruber, 1999; Gruber, 2001; Maggioni and Gruber, 2003). With this approach it is possible to compare the change in risk depending on the forest cover extent.

### 3.2.2 Case study area

Andermatt is a small village in the Central Swiss Alps with roughly 1300 inhabitants and 1500 tourist accommodations. The forest located above Andermatt on a north-facing slope, the so-called ‘Bannwald’, plays a crucial role in the protection of people, buildings, traffic routes and other infrastructure against snow avalanches (Fig. 3.2). The climatic conditions in Andermatt are harsh with a mean annual temperature of 2.7°C and an annual precipitation rate of 1480 mm at 1460 m asl. A large amount of the precipitation falls as snow, leading to average snow depths of 1.7 m in winter with maximum values of up to 3.2 m (Küttel, 1990). This makes snow avalanches the most important natural hazard in the area. The forested area spans an altitude ranging from 1460 to almost 2000 m asl. The upper part of the slope is particularly steep with a slope inclination of more than 30°, which makes it a potential avalanche starting zone. Due to the combined effect of land-use changes and avalanche disturbances, the Bannwald of Andermatt decreased to an area of approx. 4 ha about 200 years ago. It was a relict of the ancient extensive forests, which once existed throughout the whole study area (Küttel, 1990).

Since several avalanche events occurred, e.g. in the avalanche winters of 1951/52 and 1974/75, large reforestation projects combined with installations of snow-bridges in potential avalanche starting zones above the forest have been realized (Oechslin, 1986). Today the forest covers an area of approx. 24 ha and mainly consists of Norway spruce (*Picea abies* (L.) H. Karst) mixed with individuals of European larch (*Larix decidua* Mill.) and Swiss stone pine (*Pinus cembra* L.). Due to legacies of former afforestations, highly competitive ground
vegetation and the harsh climatic conditions, natural regeneration within the forest of the study area is very limited.

During the storm Vivian in 1999 a small area of the lower part of the forest was blown down. This disturbed part of the forest was reforested with Norway spruce. At the time of observation in 2005, the regeneration did not reach a height of 2 m. Therefore, given the mean and maximum snow depth in the area, this part of the forest must be considered as non-protective against the release of snow avalanches according to Saeki and Matsuoka (1969), Brang and Duc (2002) and Bebi et al. (2009).

Fig. 3.2. Case study area. The district of Andermatt (Switzerland) is protected by the forest located directly above the village (black area) named ‘Bannwald’ and currently installed snow-bridges (hatched area) above the forest.
3.2.3 Analysis of forest structures

We used the classification system of Bebi et al. (2001) for delineating and digitizing the forest structures of the 'Bannwald' in a GIS on the basis of digital Orthophotographs (Swisstopo, 2005). This approach was already successfully applied to forest structure analysis in GIS (Lardelli, 2003). The mapped structure classes were verified with an existing map of forest stands and information from terrestrial observations. We then transformed the delineated forest structures into a raster map with 5 m resolution. This raster map of forest structure classes provided a basis for defining potential avalanche release areas within the forest (see Section 3.2.4) and for developing different forest cover scenarios (see Section 3.2.5) needed for avalanche simulations with AVAL-2D (see Section 3.2.6).

3.2.4 Potential avalanche releases within the forest

Forest structure and topographical factors are decisive for the probability of avalanche releases within the forest (Schneebeli and Bebi, 2004). At this stage the avalanche simulation model AVAL-2D assumes no releases in forest areas. Therefore, we followed the modeling approach of Bebi et al. (2001) to map potential avalanche release areas within the forest. In this approach, a logistic model, which is based on the analysis of 150 avalanche releases within forest during the winters of 1985/86 to 1989/90 throughout the Swiss Alps (Meyer-Grass and Schneebeli, 1992), was combined with topographical and forest structural parameters of the study area. Key factors determining avalanche control of the forest in the model are canopy density, gap width, mean slope inclination and change of slope inclination (see Bebi et al., 2001). The model was implemented for a spatial application in a GIS with an Arc-Macro-Language (AML) program, i.e. the identified key factors were linked with variables deduced from the map of forest structure classes (see Section 3.2.3). Topographical information was derived from the DEM25, a digital elevation model with a 25 m horizontal resolution (Swisstopo, 2005). Potential additional avalanche release areas within the forest calculated by this approach were implemented manually in AVAL-2D.

3.2.5 Forest cover scenarios

To calculate how risk varies with changing forest conditions, we developed five scenarios. These represent different situations of forest cover extent combined with or without the effect of currently installed snow-bridges (Fig. 3.3). Scenario 1 describes the current forest cover under the assumption that the current forest regeneration in the small wind-disturbed area in
the lower part of the forest does not prevent avalanche releases. In addition, protection against avalanches is provided by the currently installed snow-bridges in the potential release areas above the protection forest. Scenario 2 shows the current forest situation with the same assumption as in Scenario 1 but without the existing snow-bridges above the forest. For Scenario 3, the unforested area in the lower part of the forest, destroyed during the storm Vivian in 1999, was enlarged, mainly in forest stands older than 250 years. Based on Scenario 3, we extended the unforested area in Scenario 4 into some upper parts of the slope. In both scenarios, i.e. Scenarios 3 and 4, the existing snow-bridges were not included in the simulations. Additionally, an extreme scenario (Scenario 5) shows the situation without forest cover or additional protection measures.

In this particular context, forest cover is defined as such only if the tree height in the area is at least 2 m. Using this definition, we developed a forest cover raster map for each scenario to calculate potential avalanche release areas above the forest and to run the avalanche simulations in AVAL-2D.
### 3.2.6 The risk analysis

Risk can be defined as the product of the probability of a damaging event and its consequences (e.g. Slovic, 2001). Public authorities are mainly concerned about the total damage, which is described as the collective risk in terms of expected number of fatalities and damage to buildings, traffic routes and other infrastructure per year. Forest managers can use changes in collective risk due to changes in forest conditions to plan silvicultural interventions and to explain their decisions to the public and the local authorities.

The annual collective risk is given by the product formula:

\[
R_i = \sum p_i A_i
\]  

(3.1)

where \( R_i \) is the risk, depending on scenario \( i \), \( p_i \) is the probability that scenario \( i \) occurs and \( A_i \) is the damage potential as the sum of damage to objects affected in scenario \( i \).

This basic formulation can be adjusted, according to specific requirements to account for additional components like reduction factors (Wilhelm, 1997) or vulnerability factors (e.g. Cutter, 1996) (see Eq. 3.2). In this study, the collective risk for the village of Andermatt was calculated for a 300-year avalanche event for the five forest cover scenarios. This procedure was implemented following the work steps recommended for risk analyses (e.g. Borter, 1999; Fuchs et al., 2004).

**Risk assessment and avalanche modeling**

Analyzing the type and dimension of the identified natural hazards in an objective way is crucial for the risk assessment. Therefore, we used AVAL-2D to simulate possible avalanche runout distances. This model is a two-dimensional dynamic avalanche simulation model, which is used in Switzerland for avalanche prediction and hazard zone mapping (Gruber, 1999; Gruber, 2001; Maggioni and Gruber, 2003). The avalanche runout distances under each forest cover scenario are calculated in two steps. First the model identifies the sizes of potential avalanche release areas outside the forest according to terrain characteristics and snow fracture depths. Second, the model predicts runout distances, flow velocities and the impact pressures of dense snow avalanches.

Since the model assumes no releases in forest areas at this stage, we added the previously calculated avalanche release areas within the forest (see Section 3.2.4) manually to the release areas identified by AVAL-2D. This helped us to better account for the effect of different
forest structures on the probability of avalanche releases. We verified all potential release areas with data from the avalanche register before running the simulation process. Information about snow fracture depths was gathered from tables and graphs for different regions in Switzerland. These were built upon statistical analyses of historical maximum snow accumulation data for 3-day periods (Salm et al., 1990; Burkhard and Salm, 1992). We applied a snow fracture depth of 1.6 m for the case study area. Topographical information needed for the simulation was derived from the 25 m digital elevation model (DEM25).

The flow simulation model employs a ‘Voellmy-fluid’ flow law, which assumes small shear strains in the flow body (Salm et al., 1990; Bartelt et al., 1999). Flow resistances, given by a dry-Coulomb type friction (\(\mu\)) and a velocity squared friction (\(\xi\)), are assumed to be concentrated at the base of the avalanche. The magnitude of the two friction parameters is based on observed field events and extensive model calibration (Gruber, 1999). The presence of forest in the avalanche path is modeled by an increase in the turbulent friction parameter \(\xi\) of 400 m/s\(^2\). The forest cover raster maps for each forest cover scenario and the DEM25 are the main inputs to the dynamic avalanche model. The output is a grid with the maximum pressure of the simulated avalanche event at each cell of the runout areas. Following the Swiss guidelines for hazard zone mapping, the runout areas were classified into red and blue zones (BFF/SLF, 1984). For the recurrence period of up to 300 years assumed in this study, red zones are defined as areas with pressures of more than 30 kN/m\(^2\). Blue zones are characterized by pressures less than 30 kN/m\(^2\). In our case study we chose a 300-year avalanche recurrence period to reveal the effect of an extreme avalanche event. The consequences of such an extreme event given in the resulting risk provide an adequate basis for forest managers to plan silvicultural interventions and to explain their decisions to the public and the local authorities (Fuchs and McAlpin, 2005). The generated intensity-maps show the avalanche situation of Andermatt under each forest cover scenario.

The friction parameters \(\mu\) and \(\xi\) are the main input factors for avalanche runout simulations in AVAL-2D. In the current state of the model, forest cover is implemented by increasing \(\mu\) and \(\xi\) compared to unforested areas. However, the defined values are constant and do not account for potential friction effects of different forest structures and their spatial variation. Therefore, we performed a sensitivity analysis to determine the effect of using alternate values \(\mu\) and \(\xi\) for forest areas on the simulated runout areas and the resulting collective risk. Both friction parameters were assigned three different values, resulting in nine possible combinations...
(Table 3.2). For this analysis, we simulated only Scenario 2, which represents the current forest cover without the existing snow-bridges.

**Damage assessment and consequence analysis**

The Vector25 data set provided by Swisstopo (2005) was used to identify potentially endangered objects in GIS. On the basis of aerial photographs and existing field data from former surveys, we assigned an object-type to each building (Table 3.1). The outcome of the damage assessment is a detailed digitized object-type map.

<table>
<thead>
<tr>
<th>Object-type</th>
<th>Object-value in CHF</th>
<th>Number of persons per object</th>
<th>People’s presence in h/day</th>
</tr>
</thead>
<tbody>
<tr>
<td>Agricultural building</td>
<td>375,000</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Depot/garage</td>
<td>62,500</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>One-family house</td>
<td>625,000</td>
<td>2.4</td>
<td>20</td>
</tr>
<tr>
<td>Multiple-family house</td>
<td>1,000,000</td>
<td>4.8</td>
<td>20</td>
</tr>
<tr>
<td>Administration</td>
<td>1,250,000</td>
<td>20</td>
<td>8</td>
</tr>
<tr>
<td>Hotel/restaurant</td>
<td>1,250,000</td>
<td>20</td>
<td>14</td>
</tr>
<tr>
<td>Commercial building</td>
<td>1,250,000</td>
<td>6.8</td>
<td>10</td>
</tr>
<tr>
<td>Church</td>
<td>1,500,000</td>
<td>20</td>
<td>1</td>
</tr>
</tbody>
</table>

The location and number of affected objects and persons were determined for each forest cover scenario by overlaying the intensity-maps with the object-type map in GIS. GIS-queries provided the information needed for calculating the damage potential for objects located inside the avalanche runout area of the particular scenario:

\[
A_i = \sum A_{Oj} P_{Oj,Si} \nu_{Oj,Si}
\]

(3.2)

where \( A_i \) is the damage potential, depending on scenario \( i \), \( A_{Oj} \) is the value of the object \( j \), \( P_{Oj,Si} \) is the probability of exposure of object \( j \) to scenario \( i \) and \( \nu_{Oj,Si} \) is the vulnerability of object \( j \) depending on scenario \( i \).

The number of endangered persons can be calculated on the basis of the number of affected domiciles (Table 3.1). Insured reinstate values of buildings are often used as object values. If such data are unavailable, the values can be estimated using reference values (e.g. Borter,
1999). We added values for objects (Table 3.1) for probability of exposure and vulnerability factors based on Borter (1999). The availability of such data reduces the effort for costly and time-consuming fieldwork.

Calculation and comparison of risk

The annual collective risk for each forest cover scenario was determined by multiplying the damage potential with the avalanche probability (Eq. 3.1). The avalanche probability is calculated as the reciprocal of the mean recurrence period $T$ of 300 years. The monetary value of potential endangered persons is based on the amount people are willing to pay to protect themselves. According to the concept of risk categories, we assumed the value of 5 million CHF per prevented fatality (PLANAT, 2005). This allowed us to compare the annual collective risk for the five forest cover scenarios and the risk reducing effect of specific stands, according to their spatial location.

3.3 Results

3.3.1 Avalanche modeling

Avalanche releases within the forest cover as a function of the spatial distribution of forest structures and slope inclination are prevented by the forest in approx. 85% of the forest area (Fig. 3.4). A small potential avalanche release area was calculated in the lower part of the forest in the previous wind-disturbed area, which has an area of approx. 0.67 ha and a maximum width of approx. 70 m. In all other parts of the forest no potential avalanche release areas were calculated, due to slope inclination <30° or because of forest structural characteristics on steeper slopes.

Potential avalanche release areas above the forest identified by AVAL-2D and simulated avalanche runout distances change strongly under the effect of the five forest cover scenarios. According to spatial variations in forest cover and slope inclination, the potential release areas show the following differences (Fig. 3.3): the unforested area in the lower part of the study area (Scenario 3) increases the dimension of the potential release areas only up to approx. 26.8 ha compared to the current state of forest cover (Scenario 2: approx. 25.9 ha). The increase under Scenario 4 is more substantial (approx. 28.2 ha), resulting from the extended unforested area in upper parts of the slope. A considerable increase between these scenarios (2-4) and the extreme scenario (Scenario 5: approx. 37.7 ha), which shows the situation without any protection measures, highlights the protective role of the protection forest (Fig.
3.3). The smallest possible release area (approx. 13.2 ha) was calculated under Scenario 1, which describes the current forest cover and existing snow-bridges.

![Image]

**Fig. 3.4.** Possibility of avalanche releases within the forest-cover (in %). Probability calculated for the time period of 5 years by a logistic model depending on canopy density (classified structure categories), gap width, mean slope inclination and change of slope inclination. Spatially applied with an Arc-Macro-Language (AML).

Even stronger spatial differences in the protective effect of forests are revealed, when simulated runout distances of small-scaled snow avalanches are compared under each forest cover scenario (Fig. 3.5). The runout areas vary substantially between the forest cover Scenarios 3 and 4, which both describe a situation of disturbed forest cover, respectively mainly in the lower part and in the upper part of the slope. Runout areas, however, differed slightly between Scenario 2 (current forest cover) and Scenario 3 (extension of unforested area in the lower part of the forest area). The smallest avalanche runout area was calculated under Scenario 1 (approx. 72.6 ha), the largest, as expected, under the extreme Scenario 5 (approx. 130.4 ha).
Fig. 3.5. Avalanche runout distances calculated by the process-model AVAL-2D for a 300-year avalanche event under five scenarios of forest-cover change. The runout areas are classified into zones of different pressure: light grey >30 kN/m²; dark grey <30 kN/m²; Settlement and infrastructure in the study area are black.

3.3.2 The avalanche risk in Andermatt

Under current conditions (Scenario 1) a minimum risk of approx. 72,000 CHF/a exists for Andermatt (Fig. 3.6). Without the currently installed snow-bridges (Scenario 2), the risk amounts to approx. 500,000 CHF/a, which increases slightly under Scenario 3 (approx. 560,000 CHF/a). In contrast the risk increases considerably under Scenario 4. The extension of the unforested area of Scenario 3 into upper parts of the slope more than doubles the risk (nearly 1.4 million CHF/a). Without any protection measures, the annual collective risk in Andermatt would increase up to more than 3 million CHF/a. Potential fatalities were far more important than damage to buildings as they made up 75% (Scenario 1) to 89% (Scenario 5) of the total collective risk (Fig. 3.6).
3.3.3 Sensitivity analysis

Alternating values of friction parameters $\mu$ and $\xi$ for the forest area clearly affected the simulated avalanche runout areas and the resulting collective risk (Table 3.2). A decrease in $\xi$ had a vital impact on the simulation results, which show an increase of the runout area ranging between 0.31 and 2.12% of the simulated runout area using the current $\mu$-$\xi$-combination. Furthermore, the three model runs using the maximum assigned $\xi$ of 800 m/s$^2$ resulted in highest increases in avalanche runout area (1.79 to 2.12%).

The collective risk is controlled by the runout area and the location of the damage potential. The variation in the runout area causes the total collective risk in Andermatt to reach a maximum of up to approx. 722,000 CHF/a, compared to the risk calculated for runout area using the current $\mu$-$\xi$-combination (approx. 500,000 CHF/a). Another effect on the collective risk is caused by the shift between red and blue hazard zones as a result of changes in simulated avalanche pressure. While blue zones decrease by a maximum of 12.46%, the area of red zones increases by up to 5.85%. Only one combination of friction parameters resulted in an increase of both the blue and the red zones ($\mu = 0.6$ m/s$^2$; $\xi = 400$ m/s$^2$), resulting in an increase in risk of approx. 19% compared to the current $\mu$-$\xi$-combination. This is relatively
small compared to the highest increase in risk of approx. 44%, which was determined by four different $\mu$-$\xi$-combinations.

**Table 3.2.** Variation of avalanche runout area in AVAL-2D using different friction parameter combinations for forested area and the resulting changes in collective risk in Andermatt. Runout areas calculated by the process-model AVAL-2D for a 300-year avalanche event using eight different combinations of the friction parameter $\mu$ (dry-Coulomb type friction) and $\xi$ (velocity squared friction) for forested area in % of the runout area of the currently used $\mu$-$\xi$-combination*. The forest-cover of Scenario 2 was employed for the simulation, describing the current forest-cover without existing snow-bridges. Shown for the total runout and as defined in BFF/SLF (1984) for red zones (pressures $>30$ kN/m$^2$) and blue zones (pressures $<30$ kN/m$^2$).

<table>
<thead>
<tr>
<th>Combinations of friction parameter</th>
<th>Variation of runout area in % on the current $\mu$-$\xi$-combination for forested areas</th>
<th>Annual collective risk [CHF/a]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\mu$ [m/s$^2$]</td>
<td>$\xi$ [m/s$^2$]</td>
<td>Total runout</td>
</tr>
<tr>
<td>-----------------</td>
<td>-----------------</td>
<td>-------------</td>
</tr>
<tr>
<td>0.2*</td>
<td>400*</td>
<td>0.00*</td>
</tr>
<tr>
<td>0.2</td>
<td>600</td>
<td>1.54</td>
</tr>
<tr>
<td>0.2</td>
<td>800</td>
<td>2.00</td>
</tr>
<tr>
<td>0.4</td>
<td>400</td>
<td>0.31</td>
</tr>
<tr>
<td>0.4</td>
<td>600</td>
<td>0.92</td>
</tr>
<tr>
<td>0.4</td>
<td>800</td>
<td>2.12</td>
</tr>
<tr>
<td>0.6</td>
<td>400</td>
<td>0.81</td>
</tr>
<tr>
<td>0.6</td>
<td>600</td>
<td>1.37</td>
</tr>
<tr>
<td>0.6</td>
<td>800</td>
<td>1.79</td>
</tr>
</tbody>
</table>

**3.4 Discussion**

The methodological framework of risk-based evaluation was applied to the case study ‘Bannwald of Andermatt’ (Switzerland) focusing on the forest as an effective biological protection against snow avalanches. This revealed benefits and limitations of risk-based approaches for managing protection forests, as well as potentials for improvement.

The comparison of risks associated with changing forest cover indicates the importance of spatially explicit evaluation approaches supporting forest management decisions to optimize the protection function of mountain forests. The wide range of the annual collective risk in Andermatt, i.e. between 72,000 CHF/a under current conditions (Scenario 1) and 3 million CHF/a without any protection measures (Scenario 5), highlights the forests crucial role for the protection against snow avalanches, which is the most important natural hazard in this area. Furthermore, this substantial variation in risk reflects the spatially explicit effect of the protection function, controlled by the spatial distribution of forest cover, slope inclination and
the arrangement of damage potential and their interactions. In our case study, this is especially true for the upper parts of the forest. Comparing the effect of the unforested area on risk in the lower part of the slope (Scenario 3: \( R = \text{approx. 560,000 CHF/a} \)) with an enlarged disturbed area in upper parts of the slope showed more than a doubling of the annual collective risk (Scenario 4: \( R = \text{approx. 1.4 million CHF/a} \)). In both cases, it is crucial that the protection function is rapidly restored. Since this will probably not be the case by natural regeneration only, given the harsh climatic conditions above Andermatt, additional engineering defense structures have to be considered, in particular in the upper part of the anticipated unforested area.

As demonstrated, risk analyses allow the protection function to be translated into an economic value, since risk is also controlled by the monetary value of potentially endangered objects. In the district of Andermatt, there is a high damage potential in the valley directly below the forest. Therefore, a large number of people, buildings and infrastructure are potentially at risk. As a consequence of the high damage potential, the forest itself provides benefits of approx. 2.5 million CHF annually, as can be shown by the difference in collective risk between the current forest cover without existing snow-bridges (Scenario 2) and no forest cover (Scenario 5). In other words, one hectare of intact protection forest above the town of Andermatt has on average a value of approx. 184,000 CHF/a in reducing the risk of avalanches. This calculated risk-reducing effect is much higher than results from similar studies, where risk-reducing effects of forests are smaller by a factor of 460 for scarcely populated areas or of 19 for study regions with denser population (Bebi et al., 2004; Grêt-Regamey et al., 2008a). It is also considerably higher than values calculated based on replacement costs, which assume costs of approx. 24,000 CHF/ha annually for the replacement of forest by snow-bridges (Frey and Leuenberger, 1998; Wilhelm, 1999). In contrast to our risk-based approach, replacement cost approaches do not account for spatial variations in damage potential, forest cover and terrain characteristics. Therefore, these methods may underestimate the value of the forest in cases with a high damage potential, but overestimate it in most places, where the damage potential is low. The spatial arrangement of objects in the area exposed to a potential avalanche event has thus a vital influence on the annual collective risk. This is a crucial factor when evaluating protection measures such as engineering defense structures and the protective effect of forest (e.g. Fuchs et al., 2004, 2005).

In Switzerland, standardized input parameters to estimate the damage potential are increasingly becoming available (PLANAT, 2005). This improves the comparability of the
results of risk analyses, at least on the national level, and makes the proposed procedure feasible for the management of protection forests in the future. However, while absolute values as presented here should always be interpreted with caution, the magnitudes of these values still provide valuable information for managing protection forest, e.g. for prioritizing between different management interventions or for deciding on which slope to invest money to maintain or improve the protective effect of the forest. Applied to one single slope, as performed in this study, risk-based evaluation methods reveal also on a smaller scale strong variations between different forest stands in their importance for the protection against snow avalanches.

The case study 'Bannwald of Andermatt' focused on the protection function of one single forest complex, without considering possible changes of other ecosystem goods and services caused by changes in forest cover. The relatively small spatial extent of the study area of only 24 ha was enough to demonstrate variations in risk controlled by spatial variations within this forest complex. However, this extent is usually not adequate to support decision-making for management interventions on a regional scale, where logistic issues of forest, resource and risk management have to be taken into account (BAFU, 2000) and where priorities and conflicts between different ecosystem goods and services have to be considered (Grêt-Regamey et al., 2008a). Furthermore, to optimally allocate resources between different silvicultural interventions and to better prioritize the management of protection forests, their long-term development including potential disturbance interactions needs to be taken better into account (Wehrli et al., 2006). Linking a spatially explicit risk-based approach with additional modeling components of ecosystem valuation and forest dynamics would thus be very valuable for evaluating different management strategies and their impact on the protection function on a regional scale.

Generating the avalanche runout distances with AVAL-2D requires only few input data, which makes the model potentially applicable for many regions of the world. Keeping in mind that uncertainties are involved in the whole modeling process (see Gruber and Bartelt, 2007), the approach can be implemented easily in other observation areas. The development of user-friendly software packages for several process models will facilitate the implementation of risk-based approaches for future protection forest management (WSL/SLF, 2008). The performed sensitivity analysis has shown that alternating friction parameters for the forest area can have a vital impact on the calculated risk with an increase of up to 44% compared to the risk calculated using the current $\mu-\xi$-combination. In contrast to the slight
increase in total runout area (approx. 2.12%), this resulting increase in risk is very high. In particular, a decrease in $\xi$ to 800 m/s$^2$, which lays between the $\xi$-value currently used for forest (400 m/s$^2$) and $\xi$ used to model different track characteristics such as elevation, roughness and channel geometry (1200-4000 m/s$^2$), affected the simulation results significantly. This emphasizes the importance of considering different forest characteristics within the avalanche simulations, particularly if used in risk analysis, where small changes in runout area can have a vital influence on the calculated risk. The importance of increased terrain roughness by standing and lying stems and snags for avalanche control has already been emphasized in previous research (Frey and Thee, 2002; Kupferschmid Albisetti et al., 2003; Schönenberger et al., 2005; Rammig et al., 2007). At this stage, however, values of the friction parameter for forest areas were only rarely verified with real avalanche events in forest areas (e.g. Casteller et al., 2008). There is only little quantitative information available which would help to quantify the effect of differences in forest structure and terrain roughness on avalanche runout distances. While large avalanches released far above forested terrain are not stopped by the forest (Bartelt and Stöckli, 2001), small avalanches triggered close to the treeline can potentially be decelerated by forests (Margreth, 2004). Therefore, it is reasonable to assume that different forest structures have an impact on the simulated runout distances for small avalanches. However, more research is needed to calibrate these relationships with the help of observations of avalanche events in forest areas and to parameterize the model to simulate avalanche events taking the impact of different forest structures into account.

Our risk-based approach could profit from progress in modeling forest dynamics, avalanche dynamics and valued ecosystem services and from a combination of such models. While some of these shortcomings can potentially be improved in the near future, some uncertainties will always remain. Practical interest in probabilistic assessment and techniques to address uncertainties has grown rapidly in recent decades (ADB, 1990), and different techniques have been developed for dealing with such information (Pearl, 1988). One of these techniques is the Bayesian-networks approach, which has the advantages (1) to support a structured approach to the interdisciplinary task requiring information from different specialist fields, (2) to explicitly include uncertainties at all levels of the procedure, (3) to identify the major sources of uncertainty in the decision-making process and (4) to potentially improve the model dynamically with newly observed data or expert opinion (Grêt-Regamey et al., 2008b). Bayesian-network approaches have been applied in the field of natural hazards (Aspinall,
1992; Stassopoulou et al., 1998; Straub and Grêt-Regamey, 2006) and could be used for risk-based approaches in mountain forest management.

The approach presented in this paper may serve as a valuable method to support decision-making in a future protection forest management. Moreover, risk-based evaluation strategies allow to compare costs and effects of silvicultural interventions and/or alternative investments in engineering defense structures and may, if applied on a larger scale, provide useful information for a consistent allocation of public funds.

3.5 Conclusions

Risk-based approaches to evaluate the protective effect of mountain forests against natural hazards in a spatially explicit manner are potentially valuable for decision-making in the management of mountain forests. The main advantages compared to conventional planning methods are (1) in better accounting for spatial differences in the location of the damage potential as well as of topographical and forest structural characteristics and (2) in a better comparability of the benefits of specific management interventions and their costs, and with alternative risk reducing measures.

There are, however, several points which can be improved in the future. The three major points the approach would profit from are (1) more realistic scenarios of forest cover changes, which could be achieved by linking existing spatially explicit forest structure information with a model of forest dynamics, (2) a quantification of additional ecosystem goods and services with a relevance for a specific region, and (3) a quantification of the uncertainties on the different modeling levels and a consideration of these uncertainties in the risk-based approach.

Acknowledgements

We would like to thank Urs Gruber for his continuous support with AVAL-2D and the Amt für Forst und Jagd, Canton Uri for providing data of the case study area Andermatt. Finally, we would like to thank Silvia Dingwall and Alec van Herwijnen for proof reading this work and three anonymous reviewers for valuable comments on an earlier version of the manuscript.
Snow avalanches in forested terrain: Influence of forest parameters, topography and avalanche characteristics on runout distance

Received 28 October 2011
Accepted July 2012

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Abstract

Mountain forests are recognized as an effective biological protection measure against snow avalanches. To investigate how forests decelerate snow avalanches, we analyzed two data sets from the European Alps. The first data set contained 43 small to medium avalanches which released in forests and either stopped in forested terrain within 50 to 400 m or ran through forests and stopped in unforested terrain with a maximum runout distance of 700 m. The second data set consisted of 44 medium to large avalanches (360 to 1800 m in runout distance) which all stopped within forests, but started above treeline. Statistical dependencies between predictor variables on forest conditions, terrain features and avalanche characteristics (60 in total), and the response variable avalanche runout distance were investigated. Clear differences between avalanches that released in forests and avalanches that released above forests were observed. Forest structural parameters, in particular the starting zone stem density of trees with small diameters (1–15 cm), had a significant effect on runout distances of small to medium avalanches, which released in evergreen coniferous and mixed forests ($r_S = -0.3; p = 0.015$). Beyond a threshold of 200 m this effect was negligible for runout distances of avalanches which were still in motion. In contrast, forest structure did not affect runout distances of medium to large avalanches, which started above treeline, but forests in general were still able to slow avalanche speeds and limit avalanche runout. Furthermore, runout distance was significantly affected by avalanche size characteristics for medium to large avalanches, while avalanche size was less important in determining the runout distance of small avalanches, which released in forest openings. These results emphasize that it is important to treat these two cases differently in protection forest as well as natural hazard management.

4.1 Introduction

Mountain forests play an important role in avalanche protection (Brang et al., 2006). Especially in populated areas in which the risk of avalanches limits habitability (Grêt-Regamey and Straub, 2006), there is considerable interest in understanding how forest structure affects the frequency and magnitude of avalanches (Gruber and Bartelt, 2007; Bebi et al., 2009). In addition, avalanches in forested terrain are a threat to recreationists, who often access forests while out-of-bounds (off-piste) skiing. Avalanches released in forests are usually small; however, depending on ecological, meteorological, and topographical
conditions, they may develop into larger avalanches which can pose hazard to settlements and infrastructure below the forest (SLF, 2000).

Forest structure in terms of crown closure, tree density, and size and distribution of forest gaps in combination with topography directly influences the probability of avalanche releases in forests and, therefore, is the determining factor that controls the protective capacity of mountain forests (e.g. Bebi et al., 2001; Schneebeli and Bebi, 2004; Viglietti et al., 2010). While the protective effect of forests on avalanche formation in potential starting zones is relatively well understood (for a review see Bebi et al., 2009), much less is known about the secondary protective effect of forests on avalanche runout. Previous studies have shown that this effect is limited to decelerating small to medium avalanches (Salm, 1978; Gubler and Rychetnik, 1991; Schneebeli and Bebi, 2004), while speed reduction of avalanches by forests seems to be negligible for large destructive avalanches (de Quervain, 1979; Margreth, 2004). According to field observations and estimates based on physical arguments, snow avalanche events released more than approximately 150 m above treeline are sufficiently strong to break or uproot trees (Schneebeli and Bebi, 2004; Bebi et al., 2009). Since tree fracture consumes relatively little of the avalanche energy, large avalanches released high above the treeline are able to destroy forests without significant deceleration (Bartelt and Stöckli, 2001). However, the decelerating effect of different forest structures on small avalanches released in forests or directly above the treeline has not yet been quantified (Bebi et al., 2009). In addition, recent observations from the European Alps emphasize the importance of studying also potential decelerating effects of forests on larger avalanches (LfU, 2010). It has been shown that medium to large avalanches released high above treeline destroyed large areas of mountain forests, but, surprisingly, stopped in forests before reaching the valley bottom (LfU, 2010). These observations again emphasize the intimate relationship between avalanche size and the protective capacity of forests.

Due to their sporadic occurrence and a non-continuous monitoring, observation data on avalanches in forested areas are rare. Avalanches in forested terrain are often not recognized or documented as they are not of primary importance compared to large destructive avalanches in open terrain endangering settlements, infrastructure, and human lives. However, they do play an important role in protection forest management. Decisions on silvicultural interventions need to consider the effect of different forest structures in potential starting zones, the avalanche track, and runout zones so that forests can fulfill the protective function effectively (Teich and Bebi, 2009, see Chapter 3). Furthermore, when it comes to decisions
about the size and extent of avalanche defense structures in potential starting zones within forested areas or directly above the treeline, forest and civil engineers need to know if forests with a certain structure or extent are capable of hindering avalanches that would endanger settlements and infrastructure.

In particular, we hypothesize that mountain forests growing in the avalanche path are capable of significantly influencing avalanche runout distances by deceleration, due to increasing friction and decreasing mass. This hypothesis is based on avalanche experiments at the Swiss Vallée de la Sionne site, which show that avalanche size controls flow regimes and, therefore, avalanche stopping behavior (Bartelt et al., 2012a). While for small to medium avalanches this effect strongly depends on forest structure, we expect that forest structure is negligible for large destructive avalanches.

In this paper, we present an analysis of the influence of forest parameters, terrain features, and avalanche characteristics on avalanche runout distances in forested terrain. Among 60 collected variables we identify the most important ones, which affect avalanche runout distances of small to medium avalanches, which started in forests, as well as for medium to large avalanches released above the treeline. Compared to the present study, previous analyses of forest-avalanche interactions with focus on the avalanche path did not contain such a large set of variables, especially on forest parameters (e.g. McClung, 2003; Takeuchi et al., 2011). Furthermore, based on the analysis of a small subset on wet snow avalanches, we draw and discuss general assumptions of differences between wet and dry snow avalanches in forested terrain.

4.2 Methods

4.2.1 Avalanche data sets

We analyzed two existing data sets from Europe containing 87 avalanches of different size. For avalanche size definitions we refer to typical path lengths where “small” < 100 m avalanche length, “medium” < 1000 m, and “large” < 2000 m (McClung and Scherer, 2006; EAWS, 2012). The first data set consists of 43 small to medium wet and dry snow avalanches from the Swiss Alps ranging between 50 and 700 m in runout distance, which were observed during the winters 1986–1990. All these avalanches started in forests and detailed data on avalanche characteristics and forest parameters in the avalanche starting zone were collected in the field close to the events (Tables 4.1 and 4.2; for more details see Schneebeli and
Meyer-Grass, 1993). We refer to this data set as ‘forest avalanches’ since we define a forest avalanche in general as an avalanche that released in forests. The avalanche starting points of forest avalanches were specified as $x,y$-coordinates and runout distances were recorded from the starting point in 5 m steps as the horizontal projection. To reconstruct and project the actual avalanche runout distances, we determined a representative avalanche flow line following the stream network identified by a GIS software.

The second data set on 44 dry snow avalanches is from Germany, mostly observed during one big avalanche cycle in February 2009 in the Bavarian Alps. In contrast to the Swiss data set, these avalanches are larger with runout distances from 360 to 1800 m measured in horizontal projection along a GIS-identified stream network. They started mainly above the treeline, but stopped in forests. Therefore, we refer to this data set as ‘avalanches released into forest’.

Probability densities show that avalanche runout distance is not normally distributed, at least for forest avalanches (Fig. 4.1). Runout distance of avalanches released into forest may be approximated as a normal distribution. The forest avalanches data set contains 57 continuous and categorical variables describing forest parameters, terrain features, and avalanche characteristics compared to avalanches released into forest with 36 variables (Tables 4.1 and 4.2). The availability of detailed forest data was reduced for avalanches released into forest to a few parameters, which were obtained from orthophotographs.
Table 4.1. Descriptive statistics for continuous variables for the data sets on ‘forest avalanches’ ($n = 43$) and ‘avalanches released into forest’ ($n = 44$), NA = no data.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Forest avalanches</th>
<th>A. released into forest</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Avalanche characteristics</strong></td>
<td>Mean</td>
<td>STD</td>
</tr>
<tr>
<td>Runout distance [m]</td>
<td>235</td>
<td>173</td>
</tr>
<tr>
<td>Fracture height [cm]</td>
<td>55</td>
<td>40</td>
</tr>
<tr>
<td>Release width [m]</td>
<td>15</td>
<td>12</td>
</tr>
<tr>
<td>Snow height at release [cm]</td>
<td>86</td>
<td>46</td>
</tr>
<tr>
<td>Estimated height of new snow at release [cm]</td>
<td>9</td>
<td>17</td>
</tr>
<tr>
<td>Width of runout zone [m]</td>
<td>NA</td>
<td>NA</td>
</tr>
</tbody>
</table>

| **Terrain Features**                          | Mean  | STD | Range   | Mean  | STD | Range   |
| Mean slope angle$^a$ in the starting zone [$^\circ$] | 39    | 5   | 30-50   | 39    | 4   | 28-46   |
| Mean slope angle in the avalanche track [$^\circ$] | 35    | 5   | 24-43   | 36    | 5   | 26-47   |
| Mean slope angle in the runout zone [$^\circ$] | 33    | 5   | 19-39   | 26    | 6   | 15-38   |
| Mean slope angle (overall) [$^\circ$]          | 36    | 4   | 29-43   | 34    | 3   | 27-41   |
| Starting point elevation [m asl]               | 1584  | 543 | 800-2215| 1523  | 149 | 940-1840|
| Runout zone elevation [m asl]                  | 1421  | 526 | 695-2140| 907   | 133 | 600-1240|
| Vertical drop [m]                              | 163   | 109 | 35-415  | 616   | 180 | 220-1100|

<p>| <strong>Forest$^b$ parameters</strong>                     | Mean  | STD | Range   | Mean  | STD | Range   |
| Length of forest gap at release$^c$ [m]        | 28    | 22  | 0-90    | NA    | NA  | NA      |
| Distance to first trees$^d$ [m]                | NA    | NA  | NA      | 274   | 234 | 0-955   |
| Distance to forest [m]                         | NA    | NA  | NA      | 515   | 360 | 0-1200  |
| Distance through forest [m]                    | 146   | 93  | 30-400  | 521   | 271 | 100-1300|
| Number of stems per hectare DBH$^e$ 1-15 cm [No/ha] | 371   | 584 | 0-3251  | NA    | NA  | NA      |
| Number of stems per hectare DBH &gt; 6 cm [No/ha] | 450   | 370 | 0-2083  | NA    | NA  | NA      |
| Number of stems per hectare DBH &gt; 16 cm [No/ha] | 230   | 161 | 0-840   | NA    | NA  | NA      |
| Mean diameter at breast height DBH &gt; 1 cm [cm] | 22    | 12  | 2-61    | NA    | NA  | NA      |
| Mean diameter at breast height DBH &gt; 16 cm [cm]| 34    | 11  | 0-61    | NA    | NA  | NA      |
| Dominant height$^f$ [m]                        | 19    | 6   | 0-28    | NA    | NA  | NA      |
| First branches above ground [m]                | 3.6   | 2.3 | 0-10    | NA    | NA  | NA      |
| Total canopy density$^g$ [%]                   | 40    | 22  | 0-82    | NA    | NA  | NA      |
| Norway spruce (Picea abies (L.) H. Karst.) canopy density [%] | 27    | 34  | 0-100   | NA    | NA  | NA      |
| European larch (Larix decidua Mill.) canopy density [%] | 33    | 38  | 0-100   | NA    | NA  | NA      |</p>
<table>
<thead>
<tr>
<th>Species</th>
<th>Canopy Density [%]</th>
<th>Basal Area DBH 1-15 cm [m²/ha]</th>
<th>Basal Area DBH &gt; 16 cm [m²/ha]</th>
<th>Basal Area on Total Area [%]</th>
<th>Regeneration (height 1-130 cm) [No/ha]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Swiss stone pine (Pinus cembra L.)</td>
<td>7 14 0-55 NA NA NA</td>
<td>1 2 0-9 NA NA NA</td>
<td>24 16 0-83 NA NA NA</td>
<td>45 27 0-90 NA NA NA</td>
<td>718 1505 0-7200 NA NA NA</td>
</tr>
<tr>
<td>Other conifers canopy density [%]</td>
<td>1 6 0-30 NA NA NA</td>
<td>5 8 0-23 NA NA NA</td>
<td>23 35 0-90 NA NA NA</td>
<td>2 11 0-56 NA NA NA</td>
<td>26 40 0-100 NA NA NA</td>
</tr>
<tr>
<td>European beech (Fagus sylvatica L.)</td>
<td>23 35 0-90 NA NA NA</td>
<td>1 2 0-9 NA NA NA</td>
<td>24 16 0-83 NA NA NA</td>
<td>45 27 0-90 NA NA NA</td>
<td>718 1505 0-7200 NA NA NA</td>
</tr>
<tr>
<td>Other broadleaf trees canopy density [%]</td>
<td>5 8 0-23 NA NA NA</td>
<td>23 35 0-90 NA NA NA</td>
<td>24 16 0-83 NA NA NA</td>
<td>45 27 0-90 NA NA NA</td>
<td>718 1505 0-7200 NA NA NA</td>
</tr>
<tr>
<td>Basal area [DBH 1-15 cm [m²/ha]]</td>
<td>1 2 0-9 NA NA NA</td>
<td>24 16 0-83 NA NA NA</td>
<td>45 27 0-90 NA NA NA</td>
<td>718 1505 0-7200 NA NA NA</td>
<td>718 1505 0-7200 NA NA NA</td>
</tr>
<tr>
<td>Other broadleaf trees basal area [%]</td>
<td>3 6 0-23 NA NA NA</td>
<td>24 16 0-83 NA NA NA</td>
<td>45 27 0-90 NA NA NA</td>
<td>718 1505 0-7200 NA NA NA</td>
<td>718 1505 0-7200 NA NA NA</td>
</tr>
<tr>
<td>Basal area [DBH &gt; 16 cm [m²/ha]]</td>
<td>24 16 0-83 NA NA NA</td>
<td>45 27 0-90 NA NA NA</td>
<td>718 1505 0-7200 NA NA NA</td>
<td>718 1505 0-7200 NA NA NA</td>
<td>718 1505 0-7200 NA NA NA</td>
</tr>
<tr>
<td>Basal area on total area [%]</td>
<td>22 34 0-100 NA NA NA</td>
<td>35 40 0-100 NA NA NA</td>
<td>26 40 0-100 NA NA NA</td>
<td>3 6 0-23 NA NA NA</td>
<td>718 1505 0-7200 NA NA NA</td>
</tr>
<tr>
<td>Norwegian spruce (Picea abies (L.) H. Karst.)</td>
<td>22 34 0-100 NA NA NA</td>
<td>35 40 0-100 NA NA NA</td>
<td>26 40 0-100 NA NA NA</td>
<td>3 6 0-23 NA NA NA</td>
<td>718 1505 0-7200 NA NA NA</td>
</tr>
<tr>
<td>European larch (Larix decidua Mill.)</td>
<td>22 34 0-100 NA NA NA</td>
<td>35 40 0-100 NA NA NA</td>
<td>26 40 0-100 NA NA NA</td>
<td>3 6 0-23 NA NA NA</td>
<td>718 1505 0-7200 NA NA NA</td>
</tr>
<tr>
<td>Swiss stone pine (Pinus cembra L.) basal area [%]</td>
<td>9 19 0-85 NA NA NA</td>
<td>22 34 0-100 NA NA NA</td>
<td>26 40 0-100 NA NA NA</td>
<td>3 6 0-23 NA NA NA</td>
<td>718 1505 0-7200 NA NA NA</td>
</tr>
<tr>
<td>Other conifers basal area [%]</td>
<td>2 11 0-56 NA NA NA</td>
<td>22 34 0-100 NA NA NA</td>
<td>26 40 0-100 NA NA NA</td>
<td>3 6 0-23 NA NA NA</td>
<td>718 1505 0-7200 NA NA NA</td>
</tr>
<tr>
<td>European beech (Fagus sylvatica L.) basal area [%]</td>
<td>26 40 0-100 NA NA NA</td>
<td>22 34 0-100 NA NA NA</td>
<td>26 40 0-100 NA NA NA</td>
<td>3 6 0-23 NA NA NA</td>
<td>718 1505 0-7200 NA NA NA</td>
</tr>
<tr>
<td>Other broadleaf trees basal area [%]</td>
<td>3 6 0-23 NA NA NA</td>
<td>22 34 0-100 NA NA NA</td>
<td>26 40 0-100 NA NA NA</td>
<td>3 6 0-23 NA NA NA</td>
<td>718 1505 0-7200 NA NA NA</td>
</tr>
</tbody>
</table>

*See text for further description of variable.

1. Forests are characterized by a maximum distance between trees of 25 m, a minimum canopy density of 20% and a dominant height above 3 m.
2. Downslope measured maximum extent of a forest opening.
3. Distance from the starting point to single trees or group of trees which are not defined as forests.
4. Outside bark diameter at breast height measured 1.37 m above the forest floor on the uphill side of the tree.
5. Mean height of the 100 biggest trees per ha.
6. Percentage of the ground covered by a vertical projection of the tree crown.
7. Cross section area of a tree stem in m² measured at breast height.
Table 4.2. Categorical predictor variables and description of categories.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description and categories</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Avalanche characteristics</strong></td>
<td></td>
</tr>
<tr>
<td>Avalanche type</td>
<td>Form of the avalanche release: Avalanche started from (1) loose snow which slipped out from</td>
</tr>
<tr>
<td></td>
<td>the snow surface and forms a triangle shaped release area; (2) a cohesive snow slab or;</td>
</tr>
<tr>
<td></td>
<td>(3) gliding snow often triggered by an increasing water amount in the snow cover</td>
</tr>
<tr>
<td>Wet or dry snow avalanche</td>
<td>Liquid water in the release (wet) or not (dry)</td>
</tr>
<tr>
<td>Position of sliding surface&lt;sup&gt;a&lt;/sup&gt;</td>
<td>Within snow cover (1); New snow fracture (2); Old snow fracture (3); On the ground (4)</td>
</tr>
<tr>
<td><strong>Terrain Features</strong></td>
<td></td>
</tr>
<tr>
<td>Aspect</td>
<td>Divided compass aspect (8 sectors): 1 = N; 2 = NE; 3 = E; 4 = SE; 5 = S; 6 = SW; 7 = W;</td>
</tr>
<tr>
<td></td>
<td>8 = NW</td>
</tr>
<tr>
<td>Cross-slope curvature in starting zone,</td>
<td>Concave or gullied slope (+1); Convex slope or ridge (-1); Almost no curvature or open slope</td>
</tr>
<tr>
<td>avalanche track and runout zone&lt;sup&gt;b&lt;/sup&gt;</td>
<td>(0)</td>
</tr>
<tr>
<td>Downslope curvature in starting zone,</td>
<td>Concave (+1); Convex (-1); Flat (0)</td>
</tr>
<tr>
<td>avalanche track and runout zone&lt;sup&gt;b&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td>Surface roughness in starting zone,</td>
<td>Low (1); Medium (2); High (3)</td>
</tr>
<tr>
<td>avalanche track and runout zone&lt;sup&gt;b&lt;/sup&gt;</td>
<td></td>
</tr>
<tr>
<td><strong>Forest parameters</strong></td>
<td></td>
</tr>
<tr>
<td>Stop or no-stop in forest</td>
<td>Avalanche stopped within forest (1); Avalanche ran through forest and stopped in unforested</td>
</tr>
<tr>
<td></td>
<td>areas (0)</td>
</tr>
<tr>
<td>Release in forest</td>
<td>Avalanche started within forest (1); Avalanche started above forest (0)</td>
</tr>
<tr>
<td>Forest type</td>
<td>(1) “Mixed forests” contain deciduous forest, mostly dominated by European beech (Fagus</td>
</tr>
<tr>
<td></td>
<td>silvatica L.) and mixed alpine forests; (2) Norway spruce (Picea abies (L.) H. Karst.)</td>
</tr>
<tr>
<td></td>
<td>dominated “Evergreen coniferous forest”; (3) “Deciduous coniferous forest” formed by</td>
</tr>
<tr>
<td></td>
<td>European larch (Larix decidua Mill.) at the upper treeline</td>
</tr>
<tr>
<td>Crown closure</td>
<td>(1) Dense forest (Crown coverage &gt;90%); (2) Loose (Crown coverage 70-90%); (3) Scattered</td>
</tr>
<tr>
<td></td>
<td>(Crown coverage 40-70%); (4) Scattered to open (Crown coverage 20-40%) and; (5) Open</td>
</tr>
<tr>
<td></td>
<td>(Crown coverage &lt;20%); Based on the classification system of Bebi et al. (2001), crown</td>
</tr>
<tr>
<td></td>
<td>closure was delineated and digitized in GIS by orthophotographs analyses.</td>
</tr>
<tr>
<td>Vertical structure</td>
<td>(1) Non; (2) One layer; (3) Two layers; (4) &gt;Two layer; (5) Clumped or grouped</td>
</tr>
<tr>
<td>Stage of development</td>
<td>(1) Non; (2) Seedlings; (3) Pole stage forest (8 &lt; DBH &lt; 30 cm); (4) Young timber trees</td>
</tr>
<tr>
<td></td>
<td>(31 &lt; DBH &lt; 40 cm); (5) Middle-aged timber trees (41 &lt; DBH &lt; 50 cm); (6) Old timber trees</td>
</tr>
<tr>
<td></td>
<td>(DBH &gt; 51 cm)</td>
</tr>
</tbody>
</table>

<sup>a</sup>Variable is not available for avalanches released into forest

<sup>b</sup>See text for further description of these variables.
Fig. 4.1. Probability densities and probability distributions of avalanche runout distances for the data sets ‘forest avalanches’ and ‘avalanches released into forest’.

4.2.2 Description of selected terrain variables

Selected variables on terrain features were determined for both data sets from digital elevation models (DEMs) as described below. The analyses were mainly based on high-resolution DEMs, which are gained from airborne Lidar (Light detection and ranging) data with a spatial resolution of 2 m and a vertical accuracy of approximately 0.5 m. This was done separately for the avalanche starting zone, the avalanche track, and the runout zone. Each zone is defined as one-third in length of the total runout area. In contrast to the forest avalanches data set, runout areas of avalanches released into forest were mapped close to the event from helicopter flights or site visits. To estimate the potential runout areas of forest avalanches, we applied the two-dimensional numerical avalanche dynamics program RAMMS (Christen et al., 2010a) and back-calculated all avalanches. The simulation results were verified with photographs taken shortly after most events.

Selected Terrain Variables:

- Mean slope angle: Average slope angles in the starting zone, the avalanche track, and the runout zone as well as an overall mean slope angle were determined from DEMs by GIS zonal statistics.
• Cross-slope curvature: Plan curvature was calculated using the ArcGIS (ESRI, 2011) tool “Curvature,” which determines the relative position of a cell to its surrounding pixels in a 3 × 3 pixel moving-window. Positive values indicate a concave or gullied slope (+1), negative values denote a convex slope or ridge (-1), and values around 0 mean almost no curvature, respectively, flat terrain (0). The mean value of the curvature raster was taken for each zone to assign the corresponding category.

• Downslope curvature: The profile curvature was calculated similar to the cross-slope curvature. Positive values indicate a downwards decrease in slope angle (concave, +1), negative values describe a downwardly increasing slope angle (convex, -1), and values around 0 characterize an almost plain slope (0).

• Surface roughness: Local surface roughness is expressed as the standard deviation of the terrain height undulations (differences in elevation) within a 3 × 3 pixel moving-window and averaged within the starting zone, the avalanche track, and the runout zone. Before that, we calculated a continuously inclining trend raster for each zone of the avalanche area and subtracted it from the DEM to obtain a flattened raster containing local height differences only. Categories are low (1), medium (2), and high (3) surface roughness. Thresholds for the categories were defined by comparing the results of the DEM analysis with sporadic field samples.

4.2.3 Statistical analysis

Since many of the studied variables are categorical rather than continuous and the dependent response variable avalanche runout distance is not normally distributed (Fig. 4.1), we calculated Spearman’s rank correlation coefficient ($r_S$) to determine statistical dependencies between independent predictor variables describing forest parameters, terrain features and avalanche characteristics, and avalanche runout distance. In contrast to other correlation coefficients, $r_S$ is known as non-parametric and does not assume a linear relationship between response and predictor variables. A significant Spearman correlation can result when response and predictor variables are related by any monotonic function (Kendall, 1990). We defined a correlation statistically significant if the respective $p$-value is $0.01 < p \leq 0.05$ and highly significant for $p \leq 0.01$. We tested all available variables against the avalanche runout distance separately for the forest avalanches and the avalanches released into forest data sets and for two subsets on wet and dry snow forest avalanches within the data set forest avalanches.
Furthermore, we calculated regression trees to test the relative importance of the variables that most influence changes in avalanche runout distance, i.e. to identify parameters which classify our data set significantly and to find thresholds for this classification. Regression trees analyze nonlinear relationships in a robust way and split the data iteratively into increasingly more homogenous partitions by constructing a set of decision rules on the predictor variables by an exhaustive search procedure (Breiman et al., 1998). The selected split is the one that maximizes the homogeneity of the two resulting groups with respect to the response variable (Prasad et al., 2006). The regression tree model of the “party” add-on package to the “R” system for statistical computing was used to model conditional inference trees (Hothorn et al., 2006; R Development Core Team, 2011). This non-parametric class of regression trees is applicable to all kinds of regression problems by embedding tree-structured regression models into a well-defined theory of conditional inference. To avoid overfitting, predefinitions were set as a significance level of 95% (respectively $p \leq 0.05$), which must be exceeded in order to implement a split, and a minimum of 20% of the number of observations should result in a terminal node.

4.3 Results

4.3.1 Forest avalanches

Several forest variables show significant or highly significant correlations with avalanche runout distance of forest avalanches (Table 4.3). Avalanches that stopped in forests had significantly smaller runout distances compared to avalanches that ran through forests and stopped in unforested terrain (Fig. 4.2), which supports our initial hypothesis. The regression tree model (vertical drop excluded) identified ‘stop or no-stop in forest’ as the most important variable among the predictor variables influencing avalanche runout (Fig. 4.3), i.e. avalanches stopped in forests within a mean runout distance of approximately 150 m. The distance through forest was of secondary importance, with a threshold of 100 m. Therefore, the general existence of forests in the avalanche path seems to play an important role on the first 100–200 m for the decelerating effect of forests.
Table 4.3. Highly significant** ($p \leq 0.01$) and significant* ($0.01 < p \leq 0.05$) Spearman rank correlation coefficients ($r_s$) for avalanche runout distance of ‘forest avalanches’.

<table>
<thead>
<tr>
<th>Predictor variable</th>
<th>$r_s$</th>
<th>$p$-value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Avalanche characteristics</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Avalanche type</td>
<td>-0.39</td>
<td>0.011*</td>
</tr>
<tr>
<td><strong>Terrain Features</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cross-slope curvature in the avalanche track</td>
<td>-0.33</td>
<td>0.030*</td>
</tr>
<tr>
<td>Cross-slope curvature in the runout zone</td>
<td>-0.36</td>
<td>0.019*</td>
</tr>
<tr>
<td>Surface roughness in the starting zone</td>
<td>0.37</td>
<td>0.013*</td>
</tr>
<tr>
<td>Vertical drop</td>
<td>0.97</td>
<td>&lt;.0001**</td>
</tr>
<tr>
<td><strong>Forest parameters</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stop or no-stop in forest</td>
<td>-0.67</td>
<td>&lt;.0001**</td>
</tr>
<tr>
<td>Distance through forest</td>
<td>0.35</td>
<td>0.021*</td>
</tr>
<tr>
<td>Forest type</td>
<td>0.33</td>
<td>0.033*</td>
</tr>
<tr>
<td>Number of stems per hectare DBH 1-15 cm</td>
<td>-0.30</td>
<td>0.015*</td>
</tr>
<tr>
<td>Mean diameter at breast height DBH &gt; 1 cm</td>
<td>0.36</td>
<td>0.017*</td>
</tr>
</tbody>
</table>

Correlations between parameters characterizing forest structure and runout distance were found for the type of forest, the number of stems per hectare, and the mean diameter at breast height (DBH). Avalanches traveling through deciduous coniferous forests formed by European larch (*Larix decidua* Mill.) have significantly longer runout distances compared to evergreen coniferous and mixed forests, in that order. Forest density characterized by the number of stems per hectare has a significant impact on avalanche runout for the class of trees with a DBH ranging between 1 and 15 cm. Mean diameter at breast height shows a positive correlation, i.e. avalanches released in forests containing stems of larger mean DBHs have longer runout distances. Compared to large trees where these relationships are not that strong, small trees seems to be especially important in the starting zone and on the first 200 m of the avalanche path for limiting avalanche runout.
**Fig. 4.2.** Differences in avalanche runout distance for avalanches which stopped or did not stop in forest for the data set on *‘forest avalanches’*. Boxplots show minimum, the lower quartile (Q 0.25), the median (Q 0.5), the upper quartile (Q 0.75), and maximum values for each category. Point is relative position of extreme value.

**Fig. 4.3.** Regression tree model of avalanche runout distances based on predictor variables with significant or highly significant correlations excluding vertical drop for the data set on *‘forest avalanches’* ($n = 43$). The response variable avalanche runout distance [m] is displayed in the boxplots at the bottom of the tree showing minimum, the lower quartile (Q 0.25), the median (Q 0.5), the upper quartile (Q 0.75), and maximum values. The $n$-value exhibits the number of avalanches which are explained by the corresponding variable. STOP = Stop [1] or no-stop [0] in forest, LENGTH.FOREST = Distance through forest [m].
Terrain had a strong influence on runout distance in terms of cross-slope curvature in the avalanche track and the runout zone (Fig. 4.4). Small to medium avalanches, which started in forests, were significantly longer in concave gullied terrain compared to flat terrain or convex slopes, emphasizing that more channelized terrain generally delivers larger avalanches to the runout zone. Surface roughness in the starting zone shows a positive correlation with runout distance, i.e. higher local height differences lead to larger avalanches. Steepness in the starting zone, the avalanche track, and the runout zone as well as the overall mean slope angle did not correlate with runout distances of forest avalanches.

![Boxplot showing differences in avalanche runout distance for concave, flat, and convex cross-slope curvature in the avalanche track and the runout zone of the data set on 'forest avalanches'. Boxplots show minimum values, the lower quartile (Q 0.25), the median (Q 0.5), the upper quartile (Q 0.75), and maximum values for each category of cross-slope curvature. Points are relative positions of extreme values.](image)

**Fig. 4.4.** Differences in avalanche runout distance for concave, flat, and convex cross-slope curvature in the avalanche track and the runout zone of the data set on 'forest avalanches'. Boxplots show minimum values, the lower quartile (Q 0.25), the median (Q 0.5), the upper quartile (Q 0.75), and maximum values for each category of cross-slope curvature. Points are relative positions of extreme values.

There is no general relationship between parameters characterizing avalanche size, like fracture height and release width, and runout distance. The only variable on avalanche characteristics that appeared as statistically significant was the avalanche type, where glide avalanches have smaller runout distances than loose snow and slab avalanches, in that order.

### 4.3.2 Subsets on wet and dry snow forest avalanches

In addition to the statistical analyses of the whole data set on forest avalanches, we calculated Spearman rank correlations for the two subsets on wet ($n = 28$) and dry snow avalanches ($n = 16$) and retained only variables with significant and highly significant correlations as
summarized in Table 4.4. The runout distances of the subsets on wet and dry snow avalanches range between 50–700 m and 60–600 m, respectively, but on average dry snow forest avalanches tend to have longer runout distances (mean = 306 m) than wet snow forest avalanches (mean = 193 m).

Table 4.4. Highly significant** ($p \leq 0.01$) and significant* ($0.01 < p \leq 0.05$) Spearman rank correlation coefficients ($r_S$) for avalanche runout distance of the subsets on wet and dry snow avalanches within the data set on ‘forest avalanches’.

<table>
<thead>
<tr>
<th>Predictor variable</th>
<th>Dry</th>
<th>Wet</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$r_S$</td>
<td>$p$-value</td>
</tr>
<tr>
<td><strong>Avalanche characteristics</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Avalanche type</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td><strong>Terrain Features</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean slope angle in the starting zone</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Mean slope angle in the avalanche track</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Mean slope angle in the runout zone</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Mean slope angle (overall)</td>
<td>0.55</td>
<td>0.027*</td>
</tr>
<tr>
<td>Cross-slope curvature in the avalanche track</td>
<td>-0.58</td>
<td>0.018*</td>
</tr>
<tr>
<td>Cross-slope curvature in the runout zone</td>
<td>-0.73</td>
<td>0.001**</td>
</tr>
<tr>
<td>Surface roughness in the starting zone</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Runout zone elevation</td>
<td>-0.647</td>
<td>0.007**</td>
</tr>
<tr>
<td>Vertical drop</td>
<td>0.96</td>
<td>&lt;.0001**</td>
</tr>
<tr>
<td><strong>Forest parameters</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Stop or no-stop in forest</td>
<td>-0.83</td>
<td>&lt;.0001**</td>
</tr>
<tr>
<td>Distance through forest</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>First branches above ground</td>
<td>-0.56</td>
<td>0.024*</td>
</tr>
<tr>
<td>European beech basal area percentage</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

For wet snow avalanches, the distance an avalanche runs through the forest correlates strongly with avalanche runout distance in a negative direction, indicating that a long traveling distance through forests leads to short runout distances. When analyzing wet and dry snow forest avalanches separately, the height of first branches above ground and the European beech (*Fagus silvatica* L.) basal area percentage appeared as new variables correlating significantly with avalanche runout distance. The variable first branches above ground characterize the mean crown length of the respective forest. A small distance to first branches...
means that tree crowns almost reach the forest floor and vice versa. For wet snow forest avalanches this relationship is positive in contrast to dry snow forest avalanches with a negative correlation coefficient, i.e. long tree crowns are linked to shorter runout distances of wet snow avalanches. In contrast, shorter runout distances of dry snow avalanches are correlated with shorter tree crowns which could indicate a higher forest density. The percentage of beech on basal area influences runout distances of wet snow forest avalanches in the way that a higher percentage causes shorter runout distances.

In contrast to the results for the whole data set on forest avalanches where terrain steepness had no influence on avalanche runout distance, overall terrain steepness shows positive correlations with runout distance for dry snow forest avalanches (mean = 32°), while a decrease in slope angle (mean = 38°) is correlated with increasing runout distances of wet snow forest avalanches. Cross-slope curvature affects dry snow forest avalanches the most, i.e. more channelized terrain leads to longer runout distances compared to flat or convex terrain. Avalanche size characteristics had no influence on runout distances of both wet and dry snow avalanches.

4.3.3 Avalanches released into forest

Spearman rank correlations for the data set on avalanches released into forest show different statistical dependencies between predictor variables and avalanche runout distance compared to forest avalanches (Tables 4.3 and 4.5); forest structural parameters did not correlate with avalanche runout distance of avalanches released into forest.

Highly significant positive correlations were calculated for the distance to forest, the distance to first trees, and the distance an avalanche ran through forest. Avalanches which started high above treeline had longer runout distances than avalanches with short distances to first trees or forest. An increase in distance through forest is correlated with increasing runout distances. The distance to forest is correlated with the distance through forest ($r_S = -0.32$), highlighting that avalanche parameters characterizing avalanche size are much more important for this set of avalanches compared to forest avalanches.
Table 4.5. Highly significant** \((p \leq 0.01)\) and significant* \((0.01 < p \leq 0.05)\) Spearman rank correlation coefficients \((r_s)\) for avalanche runout distance of the data set on ‘avalanches released into forest’.

<table>
<thead>
<tr>
<th>Predictor variable</th>
<th>(r_s)</th>
<th>(p)-value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Avalanche characteristics</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Release width</td>
<td>0.38</td>
<td>0.028*</td>
</tr>
<tr>
<td><strong>Terrain Features</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Surface roughness in the avalanche track</td>
<td>0.64</td>
<td>0.0002**</td>
</tr>
<tr>
<td>Starting point elevation</td>
<td>0.39</td>
<td>0.002**</td>
</tr>
<tr>
<td>Runout zone elevation</td>
<td>-0.49</td>
<td>0.0003**</td>
</tr>
<tr>
<td>Vertical drop</td>
<td>0.79</td>
<td>&lt;.0001**</td>
</tr>
<tr>
<td><strong>Forest parameters</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Distance through forest</td>
<td>0.41</td>
<td>0.005**</td>
</tr>
<tr>
<td>Distance to first trees</td>
<td>0.77</td>
<td>&lt;.0001**</td>
</tr>
<tr>
<td>Distance to forest</td>
<td>0.57</td>
<td>&lt;.0001**</td>
</tr>
</tbody>
</table>

Regression tree models emphasize these findings: Parameters characterizing avalanche size split the data set significantly into four groups of varying mean runout distances (Fig. 4.5). Vertical drop is the most important variable as well as of secondary importance especially for larger avalanches of this data set. In addition, release width splits the smaller avalanches at a threshold of 130 m into two groups of different mean runout distances. If vertical drop is excluded from the regression tree model, the distance to forest is the most important variable followed by the distance through forest of secondary importance and again distance to forest of third importance (Fig. 4.6). For example, an avalanche stops at a mean runout distance of 1000 m if the distance to forest ranges between 500 and 725 m and the distance through forest does not exceed a threshold of 500 m.
Fig. 4.5. Regression tree model of avalanche runout distances based on predictor variables with significant or highly significant correlations for the data set on ‘avalanches released into forest’ \( (n = 44) \). The response variable avalanche runout distance \[ \text{[m]} \] is displayed in the boxplots at the bottom of the tree showing minimum, the lower quartile (Q 0.25), the median (Q 0.5), the upper quartile (Q 0.75), and maximum values. The \( n \)-value exhibits the number of avalanches which are explained by the corresponding variable. VERT.DROP = Vertical drop \[ \text{[m]} \], ANRBREI = Release width \[ \text{[m]} \].

Fig. 4.6. Regression tree model of avalanche runout distances based on predictor variables with significant or highly significant correlations excluding vertical drop for the data set on ‘avalanches released into forest’ \( (n = 44) \). The response variable avalanche runout distance \[ \text{[m]} \] is displayed in the boxplots at the bottom of the tree showing minimum, the lower quartile (Q 0.25), the median (Q 0.5), the upper quartile (Q 0.75), and maximum values. The \( n \)-value exhibits the number of avalanches which are explained by the corresponding variable. LENGTH.TO.FOREST = Distance to forest \[ \text{[m]} \], LENGTH.FOREST = Distance through forest \[ \text{[m]} \].
4.4 Discussion

The present study contains statistical analyses of 60 variables on forest parameters, terrain features, and avalanche characteristics, and their effects on the avalanche runout distances of small to medium avalanches released in forests as well as on medium to large avalanches released above the treeline. In particular, the large number of predictor variables characterizing forest structure is much more comprehensive than in previous studies on the influence of forests in the avalanche path on avalanche magnitude, frequency, or runout distance (e.g. Frey et al., 1987; Butler and Malanson, 1992; McClung, 2003; Takeuchi et al., 2011).

4.4.1 Avalanches starting in forests

Our results highlight the importance of forests within the first 100–200 m of the avalanche path, since avalanches which stopped in forests were significantly smaller in runout distance compared to avalanches which ran through forests and stopped in unforested terrain. Cross-correlations emphasize the general effect of forest growing in avalanche starting zones since ‘stop or no-stop in forest’ is neither related to avalanche size characteristics nor to the distance through forest or other forest parameters. Forests of a certain structure are capable of stopping small avalanches within a critical distance of 200–400 m. Field surveys undertaken in British Columbia forests already pointed to a relationship between length of slope and susceptibility of the downslope forests to avalanche damage; slope lengths greater than 200 m are considered to pose moderate risk, while slope lengths greater than 400 m are considered to pose high risk, in combination with other factors (Weir, 2002). The significant decelerating effect of older forests on smaller avalanches by overturning trees and entraining the heavy root cluster was already highlighted by Bartelt and Stöckli (2001). However, we could also verify the positive effect of forests containing smaller stem diameters (1 < DBH < 15 cm); such forests are generally more dense compared to forests dominated by stems of larger diameters (DBH > 16 cm), where the number of stems in the starting zone did not influence runout distance significantly. We assume that, due to crowns starting higher above ground, there is less biomass in the zone where avalanches accelerate, so that they might turn into far-reaching avalanches; a high density of small diameter stems limits the avalanche mass. In addition, smaller bending stresses and the complete deflection of such trees consume avalanche energy resulting in a significant deceleration of small avalanches (Johnson, 1987). Thresholds for mean diameters of breakage of different coniferous species in several
Avalanche paths in the Swiss Alps were determined as approximately 10–20 cm, which lies within our class of small-diameter stems (Tiri, 2009). Small trees which are not broken or uprooted during an avalanche event can still fulfill their protective function afterwards.

The influence of the forest type on runout distance reveals the characteristics of these mountain forest ecosystems. Avalanches that traveled through deciduous coniferous forests were significantly longer than avalanches that ran through evergreen coniferous and mixed forests. Larch stands near timberline have an open, less dense structure supported by cross-correlation results where the forest type does correlate significantly with the number of stems per hectare for all DBH classes (-0.71 < rS < -0.50). A positive correlation was found between forest type and mean DBH of trees larger than 1 cm in diameter (rS = 0.41). In contrast to deciduous coniferous forests, the growth of small avalanches is prevented in evergreen coniferous and mixed forests, also containing a high number of small diameter stems, because of an increased crown biomass, higher interception effects, and, therefore, less snow entrainment in the avalanche path.

Terrain had a significant influence on avalanche runout distance in terms of cross-slope curvature in the avalanche track and runout zone, surface roughness in the starting zone, and the vertical drop. A higher vertical drop is related to path scale and may imply higher snow erosion in the avalanche path followed by greater destructive effects and longer runout distances (McClung, 2003; McClung and Schaerer, 2006). However, due to a limited range of slope angles of our data set, such high correlations between runout distances and vertical drop could be expected. Surface roughness in the starting zone shows positive correlations with runout distance that indicates that a larger snow supply is needed for potential avalanche releases in areas with high surface roughness.

In the present study, surface roughness was a predictor variable in terms of local terrain height differences without regard to ground vegetation or dead wood. However, concerning effective protection forest management, especially after storm events, the possible influence of dead wood on avalanche magnitude needs to be discussed briefly. Fallen logs, remnant stumps and root plates of upturned trees can prevent the formation of small avalanches (Schneebeli and Bebi, 2004). If an avalanche is already moving, tree entrainment in the debris enlarges the avalanche in mass and volume (Bartelt and Stöckli, 2001). Therefore, it could be highly valuable to keep tree debris in place, if a storm damages a protection forest (Bartelt and Stöckli, 2001). At least over the first 10 to 20 years after a storm event, dead wood still
increases surface roughness in the starting zone and can prevent small avalanche releases (Putallaz, 2010).

Correlations of cross-slope curvature in the avalanche track and the runout zone with runout distance could be related to snow entrainment with more mass added in channelized terrain delivering larger avalanches to the runout zone compared to flat terrain or convex slopes (McClung, 2003; McClung and Schaerer, 2006). This corresponds to the longer runout distances found for avalanches released in deciduous coniferous forests. The starting point elevations in this type of forest are higher compared to those in evergreen coniferous and mixed forest and, therefore, avalanches starting in larch forests are more prone to gullied terrain. In our study, slope angle had no significant influence on runout distances of forest avalanches. However, avalanches start in forests generally on steeper slopes compared to avalanches in open terrain (Schneebeli and Bebi, 2004). Another study has also shown that no terrain variable including slope angle accounted for over 20% of variations in runout distance of avalanches in forested terrain (Butler, 1979). They concluded that this depends strongly on the region where avalanches were observed.

The influence of the avalanche type (glide snow avalanches are shorter compared to slab or loose snow avalanches, in that order) could possibly be explained by the amount of wet snow avalanches in our data set. This avalanche type starts from a slow gliding surface often triggered by an increasing water amount in the snowpack (Clarke and McClung, 1999) and, since wet snow in motion has a much higher friction on the sliding surface compared to dry snow, leads to shorter runout distances (McClung and Schaerer, 2006).

**4.4.2 Wet and dry snow avalanches in forested terrain**

Separate analyses of the two subsets on wet and dry snow avalanches show similar correlations as the whole data set, but also reveal specific characteristics of the two categories. In general, the type of snow condition (wet or dry snow) and the type of forest correlates significantly \( r_s = -0.53 \), i.e. wet snow avalanches do occur more often at lower elevations in mixed forests in contrast to dry snow avalanches which release more frequently in evergreen and deciduous coniferous forests at high elevations. Beech is a typical tree species of low altitude areas. A higher beech basal area percentage was negatively correlated with avalanche runout distance of wet snow forest avalanches. This could be related to a general increase in forest density, which reduces the speed of small wet snow avalanches in deciduous and mixed forests. Observations of wet snow avalanches in forested terrain are rare, but the few
examples verify our findings, e.g. the speed of three wet snow avalanches in very steep terrain (45° mean slope angle) was reduced by dense beech forests without damaging any trees and even small regeneration was not affected by the events (Imbeck and Meyer-Grass, 1988).

Crown length expressed in height of first branches above ground appeared as correlating significantly with runout distances for both subsets, for dry snow forest avalanches in a negative direction and for wet snow forest avalanches in a positive direction, i.e. the lower the crown the longer the runout distances of dry snow avalanches and the opposite for wet snow avalanches. Branch lopping is often linked to tree fracture and low energy consumption which increases avalanche mass and, therefore, flow energy (Bartelt and Stöckli, 2001). Dry snow avalanches occur more frequently in less dense coniferous forests near timberline, with triangle-shaped crowns starting close to the ground, and are more prone to avalanche destructive forces. Wet snow avalanches release more often in deciduous forests with crowns starting higher above the ground. Trees are less vulnerable and have a positive decelerating effect on wet snow avalanche runout as discussed before.

In contrast to forest avalanches, where slope angle had no significant influence on runout distance, terrain steepness shows positive correlations for dry snow forest avalanches, while a decrease in slope angle is correlated with increasing runout distances of wet snow forest avalanches. In general, terrain steepness restricts the amount of snow because of given shear strength, which leads to higher fracture depths, higher snow erosion in the avalanche path, and longer runout distances, and wet snow in motion has much higher friction at the sliding surface, which distinguishes it from dry snow (McClung and Schaerer, 2006). These relationships could explain both cases. First, increasing slope angles of the subset on dry snow avalanches and less friction at the sliding surface lead to generally longer runout distances compared to wet snow avalanches. And second, decreasing slope angles along the avalanche path lead to increased snow erosions and increasing runout distances of wet snow avalanches. Furthermore, conditions on ground vegetation in the avalanche path as well as an increasing amount of liquid water at the sliding surface can preclude significant energy dissipation along the lateral margins of the flow (Butler and Malanson, 1992). Resulting continued high energy levels can favor a more excessive travel of wet snow avalanches in the runout zone with decreasing slope angles in contrast to dry snow avalanches (Butler and Malanson, 1992). However, similar observations were made before where an inclining runout zone showed a positive correlation with mean avalanche size without a clear physical explanation (McClung, 2003).
Keeping in mind that the number of observations within the two subsets was limited, we draw first assumptions on the behavior of wet snow avalanches in forested terrain, since studies on this topic are especially rare. Few documented events on larger wet snow avalanches, which occurred in forests, have shown their destructive potential (SLF, 1952). Future research should focus on wet snow avalanches in forested terrain; as with increasing winter temperatures under future climate conditions (Laternser and Schneebeli, 2003), the occurrence of destructive wet snow avalanches in forests might increase and raises the risk to settlements and infrastructure (Martin et al., 2001).

4.4.3 Avalanches released above treeline

Compared to forest avalanches, forest structure does not play such an important role for avalanche runout distances of avalanches released into forest. Forests in general affect runout distance in terms of distance to forest (including distance to first trees) and distance through forest. While the distance to forest limits avalanche runout distance, the distance an avalanche travelled through forest seems to increase avalanche mass through entrainment of stems in the avalanche debris (Bartelt and Stöckli, 2001). A threshold for the distance to forest appeared within the second regression tree model (vertical drop excluded). Thus, forests in general may be able to limit runout distances of larger avalanches even if the avalanches are released high above treeline, i.e. with a maximum distance to forest of approximately 700 m. Takeuchi et al. (2011) came to similar conclusions by studying a large-scale dry slab avalanche that stopped shortly after penetrating a cedar forest. Forests in combination with topography are able to decelerate large avalanches (Anderson and McClung, 2012).

Release width as a parameter characterizing avalanche size shows significant positive correlations with runout distance, which distinguishes avalanches released into forest from forest avalanches. Surface roughness in the avalanche track shows highly significantly positive correlations with runout distance indicating that higher local terrain undulations determine larger snow supplies and snow entrainment leading to longer runout distances.

The differences between the two data sets on forest avalanches and avalanches released into forest emphasize that it is important to treat these two cases differently in protection forest as well as natural hazard management. Especially for small to medium avalanches released in forests or directly above the treeline, the protective power of forests depends sensitively on the density of the forest stand by preventing avalanche releases (Schneebeli and Meyer-Grass, 1993; Bebi et al., 2001) as well as by decelerating and stopping already moving avalanches as
seen in the present study. However, our data set on 87 observed avalanches in total is still limited. To strengthen our findings on the effect of forest structure in the avalanche path on runout distance, future studies should focus on collecting more reliable data on avalanches in forested terrain. This topic is especially important, since recurrence periods of avalanches that damage forests and might endanger settlements and infrastructure are short; between 20 and 30 years as observed in Switzerland (Föhn, 1979).

4.5 Conclusions

According to our hypotheses, we could demonstrate that forest structure has a significant influence on runout distances of small to medium avalanches released in forest openings. Especially on the first 100–200 m from the starting point, evergreen coniferous and mixed forests also containing small-diameter stems (1–15 cm) limited avalanche mass such that runout distances did not exceed 200–400 m. Beyond this threshold, this effect is negligible for runout distances of avalanches that are still in motion.

For larger avalanches released high above treeline, the effect of different forest structures along the avalanche path is negligible, but forests in general are still able to slow avalanche speeds and limit runout distances. In contrast to avalanches released in forests, avalanche size in terms of release width and fracture height controls runout distances significantly as these avalanches behave similar to avalanches in open unforested terrain.

Therefore, an effective protection forest management helps to form forest stands that decelerate and stop small to medium avalanches released in forests. Furthermore, forest and civil engineers should take this effect of forests and its limitations into account when establishing the dimensions of avalanche defense structures in potential starting zones within forested areas or directly above treeline.

Our findings reveal necessary research needs on forest-avalanche interactions along the avalanche path in order to define thresholds of avalanche size where forests have a decelerating effect on avalanches. Future research should include a better quantification of thresholds between small and large avalanches according to existing size classification systems for avalanches in unforested areas, since an improved knowledge and understanding of interactions between avalanches and forests in the avalanche path is necessary to support optimized and regionally adapted decision making in protection forest as well as natural hazard management.
Acknowledgements

We thank Thomas Feistl, Armin Fischer, and Christian Ginzler for their assistance collecting the data as well as the Bavarian avalanche warning service for providing the data set on avalanches released into forest. We also thank Natalie Zurbriggen and two anonymous reviewers for valuable comments on earlier versions of the manuscript. This study was funded by the CCES (Competence Center Environment and Sustainability of the ETH Domain) within the project MOUNTLAND.
Chapter 5

Paper III

Observations and modeling of the braking effect of forests on small and medium avalanches

Received 20 March 2013

Accepted 13 October 2013

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Abstract

A long-standing problem in avalanche science is to understand how forests stop avalanches. In this paper we quantify the effect of forests on small and medium avalanches, crucial for road and ski-run safety. We performed field studies on seven avalanches where trees affected the runout. We gathered information concerning the release zone location and dimension, deposition patterns and heights, runout distance and forest structure. In these studies the trees were not destroyed, but acted as rigid obstacles. Wedge-like depositions formed behind (1) individual tree stems, (2) dense tree groups and (3) young trees with low-lying branches. Using the observations as a guide, we developed a one-parameter function to extract momentum corresponding to the stopped mass from the avalanche. The function was implemented in a depth-averaged avalanche dynamics model and used to predict the observed runout distances and mean deposition heights for the seven case studies. The approach differs from existing forest interaction models, which modify avalanche friction to account for tree breakage and debris entrainment. Our results underscore the importance of forests in mitigating the danger from small-to-medium avalanches.

Keywords: avalanches, forest, snow

5.1 Introduction

Traditionally the protective capacity of mountain forests has been quantified assuming that avalanches do not start in dense forest stands (De Quervain, 1978; Gubler and Rychetnik, 1991; Neweseley et al., 2000; Gruber and Bartelt, 2007). Forests act to stabilize the snow cover and prevent destructive avalanches from releasing. They serve as a natural defense against avalanches where meteorological conditions and the terrain enable trees to grow.

The ability of forests to stop avalanches that start above the timberline is limited. Observations show that trees cannot withstand the dynamic forces of large, fast-moving avalanches (De Quervain, 1978; Margreth, 2004) (Fig. 5.1). The energy required to break and uproot trees and entrain the woody debris is small in comparison to the overall flow energy of the avalanche (Bartelt and Stöckli, 2001). The braking effect of forests is small for extreme avalanches. Avalanche experts therefore often neglect forests, assuming either extremely large avalanches (that easily destroy the forest) or that the forest has been removed by previous events (Christen et al., 2010b). Consequently, avalanche dynamics calculations
typically ignore forests completely or prescribe only minor changes to the flow friction (Gruber and Bartelt, 2007).

Fig. 5.1. Uprooted trees in Val Prada, Switzerland, in winter 2009. The avalanche destroyed the whole forest and does not seem to be stopped or even decelerated by the forest. (Photo: S. Margreth, SLF)

Modeling how mountain forests stop small-to-medium avalanches has recently become a critical question in avalanche hazard mitigation (Casteller et al., 2008; Anderson and McClung, 2012). (According to the European avalanche classification scale, release volumes are defined to be <1000 m$^3$ for small avalanches and between 1000 and 10,000 m$^3$ for medium avalanches (EAWS, 2012).) Frequent (not extreme) avalanches are often the primary hazard for roads, railways and ski-runs, particularly in climates where wet snow avalanches are common (Gruber and Bartelt, 2007). Local authorities must deal with the risk of small-to-medium avalanches hitting infrastructure, and therefore people, numerous times during a winter season. Forests can stop these avalanches and are an important protective measure (Teich et al., 2012a, see Chapter 4).

There is thus an urgent need to quantify the braking effect of forests on small-to-medium avalanches (Bebi et al., 2009; Teich and Bebi, 2009, see Chapter 3; Takeuchi et al., 2011; Teich et al., 2012a, see Chapter 4). In this case, trees remain standing after avalanche impact. They withstand dynamic forces and thus work as effective obstacles to decelerate the flow. The effect is similar to avalanche dams (Faug et al., 2003, 2008, 2010; Naaim et al., 2003, 2004); however, the working mechanism differs because the forest is not a single, rigid man-made defense structure, but a natural and inhomogeneous array of slender obstacles (trees, tree groups). If the trees are not broken or uprooted, forest structure (stem density, gaps, crown coverage, age and low-lying vegetation) is of crucial importance.
The existing forest avalanche data contain much material with valuable observational content, especially regarding the effect of different forest structures in hindering avalanche formation (Schneebeli and Meyer-Grass, 1993; Viglietti et al., 2010). However, information on forest structure and avalanche flow (e.g. velocity, flow heights and deposition patterns) is limited and concentrated on the extreme avalanche case (Bartelt and Stöckli, 2001; Casteller et al., 2008; Christen et al., 2010b; Takeuchi et al., 2011). A first step to model avalanche flow in forests is to understand how forests stop avalanche snow. To this end, we recorded data from five forest avalanches near Davos, Switzerland, and one within the Bavarian Prealps, Germany (Section 5.2), in winter 2011/12. One other Bavarian case study during winter 2008/09 completes our dataset. In these events, the avalanche paths were partially or completely covered by forest. The focus of this data collection was to document release areas and fracture depths, snow conditions, forest structure, flow perimeter and deposition patterns. The events were special, in that we collected data on forests that were not destroyed by avalanches. Of particular importance was to quantify the mass deposition behind trees.

Based on the observations, we develop an avalanche/forest interaction function (detrainment function) to be used within the framework of a depth-averaged avalanche dynamics model (Christen et al., 2010a). Our goal is to simulate the observed events. We assume that the trees stop the granular snow flow by a combination of processes: impact followed by jamming, resulting in a sudden and local dissipation of flow energy behind trees or tree groups. We address avalanche/forest interactions by specifying snow detrainment rates, rather than using higher friction values to represent the highly nonlinear braking effect of trees. The friction approach has been applied by several authors for extreme avalanches within the framework of Voellmy-type models (Voellmy, 1955; Bartelt and Stöckli, 2001; Christen et al., 2010b). This approach is justifiable for extreme avalanches, where the braking effects are small and occur over longer flow distances. For the small-avalanche case, Voellmy-type relations represent the avalanche/forest interaction poorly (Teich et al., 2012c, see Appendix B). The detrainment function is parameterized by a single coefficient representing forest structure. This coefficient determines the braking power of the forest. Both the friction and detrainment approaches have the same goal: to explain the deceleration and quantify the amount of mass stopped by the forest. The detrainment approach, however, is more direct, in the sense that we extract mass from the avalanche volume, removing momentum directly from the flow, rather than indirectly by friction coefficients. Furthermore, it is easier to calibrate, as the detrainment function provides users with the total mass per unit area stopped in the forest. Therefore we
are able to compare calculated deposition volumes with observations and measurements of the seven case studies and to demonstrate the potential and limitations of the detrainment approach.

5.2 Observations

5.2.1. Documented avalanches

Field campaigns in the Swiss and German Alps were performed to investigate how avalanche mass is stopped by forests. The stopped mass can be estimated by calculating the difference between the volume of the initial release area and the deposition zone, and by determining the volume of deposited snow behind trees. As we assume forest structure has a crucial impact on the mass balance and the runout distance, we also gathered information on stem density and vegetation cover. Although single small trees and low branches were sometimes destroyed when hit by the avalanches, we focused on small-to-medium avalanches flowing through the forest where the trees acted as obstacles. This was the main selection criterion for the observation of an event. Such events are rarely documented by forest managers. Field studies have to be conducted before changing weather conditions (snowfall or melting) affect the deposits. Spotting such avalanches and reaching the tracks quickly, when they are accessible, is generally challenging.

In the 2008/09 and 2011/12 winters, data on seven avalanche events were collected: five in the region of Davos (ID-I to ID-V) and two in the region of Spitzingsee, Germany (ID-VI and ID-VII). The observed avalanche sites cover a wide range of terrain, snow and forest characteristics (Table 5.1), with altitude levels ranging between 1000 m asl (runout, Hagenberg, ID-VII) and 2100 m asl (release area, Dischma, ID-IV). The differences in altitude from release to runout vary from 50 m (Junkerboden, ID-I) to 450 m (Dischma, ID-IV). The smallest release volume was calculated to be ~320 m$^3$ (Junkerboden, ID-I), whereas the largest release area covers ~7400 m$^2$, with a release volume of 5190 m$^3$ (Monstein, ID-V). Different terrain features in the avalanche track, such as gullies and flat slopes, could be distinguished. Slope angles vary from 50° steep release areas to flat runout zones. As the avalanche deposits could generally not be reached before the weather conditions changed, we classified snow characteristics according to qualitative criteria, such as dry, moist and wet, based on meteorological data from the nearest weather station. The meteorological conditions prior to the event, and therefore the causes of the avalanches, differed, resulting in wet snow avalanches (e.g. Filisur, ID-I) as well as dry snow avalanches (e.g. Brecherspitz, ID-VII).
Forests penetrated by the avalanches we studied consist mainly of conifers with varying stand densities and age. For modeling we distinguished between a canopy density of >50% for dense forests and <50% for open forests. Canopy density was determined by analyzing orthoimages (from 2011 with 25 cm grid resolution) of each event (Bebi et al., 2001).

Table 5.1. Characteristics of forest avalanches documented during the 2008/09 and 2011/12 winters.

<table>
<thead>
<tr>
<th>Switzerland</th>
<th>Germany</th>
</tr>
</thead>
<tbody>
<tr>
<td>Junker-boden</td>
<td>Hagenberg</td>
</tr>
<tr>
<td>Filisur south</td>
<td>Brecherspitz</td>
</tr>
<tr>
<td>Filisur north</td>
<td></td>
</tr>
<tr>
<td>Dischma</td>
<td></td>
</tr>
<tr>
<td>Monstein</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Internal ID</th>
<th>Date</th>
<th>Temperature (dry, moist, wet)</th>
<th>Terrain features (upper part/track/runout)</th>
<th>Forest structure (upper part/track/runout)</th>
<th>Tree age</th>
<th>GPS measurements of deposits</th>
<th>GPS measurements of release area</th>
<th>Image of release</th>
<th>Altitude [m asl]</th>
<th>Slope angle, release to runout [°]</th>
<th>Release volume [m³]</th>
</tr>
</thead>
<tbody>
<tr>
<td>ID-I</td>
<td>1 Jan. 2012</td>
<td>moist</td>
<td>unchanneled flat</td>
<td>dense/open/no forest</td>
<td>mixed</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>1540-1500</td>
<td>39-0</td>
<td>320</td>
</tr>
<tr>
<td>ID-II</td>
<td>~23 Feb. 2012</td>
<td>wet</td>
<td>unchanneled unchanneled</td>
<td>open/no forest/open/dense</td>
<td>mixed</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>1320-1080</td>
<td>50-25</td>
<td>1080</td>
</tr>
<tr>
<td>ID-III</td>
<td>~23 Feb. 2012</td>
<td>wet</td>
<td>unchanneled unchanneled</td>
<td>open/no forest/dense</td>
<td>mixed</td>
<td>no</td>
<td>no</td>
<td>no</td>
<td>1360-1058</td>
<td>50-20</td>
<td>1390</td>
</tr>
<tr>
<td>ID-IV</td>
<td>~27 Feb. 2012</td>
<td>wet</td>
<td>unchanneled unchanneled</td>
<td>open/no forest/dense</td>
<td>mixed</td>
<td>no</td>
<td>no</td>
<td>yes</td>
<td>2093-1642</td>
<td>42-15</td>
<td>3690</td>
</tr>
<tr>
<td>ID-V</td>
<td>1 Mar. 2012</td>
<td>wet</td>
<td>unchanneled unchanneled</td>
<td>open/no forest/dense</td>
<td>mixed</td>
<td>no</td>
<td>no</td>
<td>yes</td>
<td>2070-1640</td>
<td>50-10</td>
<td>5190</td>
</tr>
<tr>
<td>ID-VI</td>
<td>24 Feb. 2009</td>
<td>dry</td>
<td>unchanneled unchanneled</td>
<td>open/dense/unchanneled</td>
<td>mixed</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>1419-1027</td>
<td>45-23</td>
<td>3460</td>
</tr>
<tr>
<td>ID-VII</td>
<td>14 Feb. 2012</td>
<td>dry</td>
<td>unchanneled unchanneled</td>
<td>open/dense/unchanneled</td>
<td>mixed</td>
<td>yes</td>
<td>yes</td>
<td>yes</td>
<td>1472-1327</td>
<td>50-25</td>
<td>690</td>
</tr>
</tbody>
</table>

It was essential to document the exact shapes of the release and deposition areas, to allow comparison with simulation results (Section 5.3). We used a handheld differential global navigation satellite system (dGNSS) device whenever possible, so we could map the runout areas precisely. Sometimes, due to safety reasons or lack of accessibility, the release area could not be reached. In these cases we used images of the release area from the opposite
slope or from a helicopter, and matched these with maps of the area. For the two events near Filisur, Switzerland, we performed a terrain analysis with a spatial resolution of 2 m.

Terrain features, such as gullies, ridges and slope angle, were taken into account to identify probable release areas. The GIS analysis is only accurate up to a scale of several meters, whereas the error of measurements with the dGNSS device is in the range of a few centimeters.

We collected information about the deposition patterns of avalanche snow within the forest, which allowed us to quantify the stopped mass. Photographs were taken, which document the significant amount of avalanche snow that remained behind the trees. Not only are considerable amounts of avalanche snow stopped by tree trunks, but also by root plates of upturned trees, low-lying branches and dead woody debris. Depositions in forests were mainly concentrated at the outer edges of the avalanche tracks, where the flow velocities were small (Fig. 5.2). We observed differences in deposited snow amounts due to slope angle, snow temperature (wet, moist or dry), stand density and age of trees (Section 5.2.2).

![Avalanche track near Filisur, Switzerland (ID-III). Note the main avalanche channel in the foreground with little snow on the ground, in comparison with the dense forest in the background.](image)

### 5.2.2. Deposition volume behind trees

In all the case studies (ID-I to ID-VII) we observed wedge-like depositions behind single trees, as well as tree groups (Fig. 5.3). Wedge-shaped depositions have been observed behind obstacles in chute experiments with granular materials (Gray et al., 2003). Deposition wedges have also been observed behind pressure-measurement pylons at the Swiss Vallée de la Sionne (Sovilla et al., 2010) and Italian Seehore (Bovet et al., 2011) avalanche test sites. Although the deposition wedges had different dimensions, depending on the snow properties
and tree-stand characteristics, a general geometry could be determined (Fig. 5.3). Typically, the upper and lower width of the wedge at the base (ground), $d_u$ and $d_l$, are the same, $d_u = d_l = d$. The base width, $d$, is determined by the base width of the obstacle: (1) the stem diameter (Fig. 5.3a) or (2) the total width of a dense group of trees (Fig. 5.3b). Small trees with low-lying branches have base widths much greater than the stem diameter (Fig. 5.3c), because additional snow can be stopped by the branches. For single-tree impacts, the width of the upper wedge surface at the tree was sometimes smaller than the stem diameter, resulting in a pyramid-shaped wedge (Fig. 5.3a). The angle $\delta$ defines the top wedge angle of the pyramid (Fig. 5.3a). In general, the exterior side planes were parallel to the primary flow direction of the avalanche; the planes are nearly vertical, especially close to the tree. For large stem diameters, the trees’ sides are often rubbed clean of snow, indicating snow is stopped behind the tree, while the avalanche continues to move forward. This suggests that strong velocity gradients can develop when the avalanche flows within the forest. Shear planes, similar to those found in levee formation in runout zones (Bartelt et al., 2012b), were observed in case studies ID-II, ID-III and ID-V (Fig. 5.2). For most cases, the upper surface of the wedges was close to horizontal, i.e. angle $\gamma$ was equal to the slope angle of the terrain (Fig. 5.3a). The wedges were sometimes tilted towards the slope, especially if the snow was wet (Fig. 5.3b and c). Settling and melting affected the depositions while we were getting to the tracks.

The observations allow us to quantify the volume, $W$, of snow captured behind one tree or group of trees. The wedge volume for the single-stem case (Fig. 5.3a) is

$$W = \frac{d^3}{12 \tan(\gamma) \tan^3\left(\frac{\delta}{2}\right)}, \quad (5.1)$$

and for the tree-group case (Fig. 5.3b) it is

$$W = \frac{d h_w l}{2} = \frac{d h_w^2}{2 \tan \gamma}, \quad (5.2)$$

where $h_w$ is the wedge height and $l$ is the horizontal wedge length.
Fig. 5.3. Typical deposition structure of avalanche snow behind trees. The second column depicts the deposition pattern from above; in the third column the approximated deposition volume is illustrated. (a) Deposited snow behind a single trunk of ~100 cm diameter in relatively flat terrain (20°). (b) Deposited snow behind a group of trees. (c) Deposited snow behind a small tree (~4 m high) in steep terrain (34°); note the effect of branches close to the ground. The horizontal wedge length, $l$, and the slope-parallel wedge length, $a$, depend on the wedge height, $h_w$, and on angle $\gamma$.

Equation (5.2) can also be used for a single tree with low-lying branches (Fig. 5.3c). We provide calculated volumes of the wedges depicted in Figure 5.3. The dimensions of the wedges are provided in Table 5.2. Note that for cases b (tree groups) and c (low-lying branches) the detrained volumes are much larger than for the single-tree case.

Table 5.2. Observed wedge dimensions and calculated volumes of the depositions in Figure 5.3. Cases b and c (group of trees and small trees with underlying branches) catch more mass than case a (single trunk).

<table>
<thead>
<tr>
<th>Observation</th>
<th>Slope angle [°]</th>
<th>Width $d$ [m]</th>
<th>Wedge height $h_w$ [m]</th>
<th>Top wedge angle $\delta$ [°]</th>
<th>Volume $W$ [m$^3$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>23</td>
<td>1</td>
<td>0.8</td>
<td>68</td>
<td>0.43</td>
</tr>
<tr>
<td>b</td>
<td>33</td>
<td>4</td>
<td>2</td>
<td>-</td>
<td>12.3</td>
</tr>
<tr>
<td>c</td>
<td>34</td>
<td>2</td>
<td>2</td>
<td>-</td>
<td>5.9</td>
</tr>
</tbody>
</table>

The volume equations (Eqs. 5.1 and 5.2) allow us to derive a first approximation of the mean deposition height for different stem densities (Fig. 5.4). The mean deposition height, $h_d$, depends strongly on the deposition widths and therefore on the forest structure (Table 5.3).
Assuming a dense forest (400 trees per hectare), with average stem diameters of $d = 1$ m (for simplicity) on a slope of 30° with a top wedge angle of $\delta = 60°$ (from measurements), we find a rather small mean deposition height: only 2 cm averaged over the entire forest area struck by the avalanche. We emphasize that the stem diameter is measured at the ground, according to our observations. The snow that can be stopped by the forest can increase by a factor of >10 when wide, wedge-shaped deposits are created behind groups of trees. For example, when $d = 4$ m for a forest with the same stem density but trees grouped together, the mean deposition height is 18 cm. Here we assume that a tree group contains three trees (Fig. 5.3b). This result reveals the importance not only of the stem diameter, but also the forest structure.

![Fig. 5.4.](image)

**Fig. 5.4.** The goal of the forest model is to calculate the mean deposition height, $h_d$. Wedge formation behind isolated tree stands is not predicted. The total deposited mass, $M_d$, should, however, be equal to the observations. $W$ is the volume of snow captured behind a single tree or tree group.

Generally, we assume mean deposition heights of a few to 50 cm as reasonable amounts of snow being stopped by forests, $1 \text{ cm} < h_d < 50 \text{ cm}$.

**Table 5.3.** Deposited snow and corresponding mean deposition height, $h_d$, for angle $\gamma = 30°$ (approximately equal to the slope angle of the terrain), wedge height $h_w = 2$ m, top wedge angle, $\delta = 60°$. The tree diameter, $d$, is 1 m for a single tree, 2 m for a tree with branches reaching to the ground and 4 m for a group of three trees. For single trees we used Eq. (5.1) to calculate the volume, and for trees with branches and groups of trees we used Eq. (5.2). We assume a snow density of $\rho = 300$ kg m$^{-3}$, an avalanche length of 50 m and a velocity of 10 m s$^{-1}$ to calculate $K$ according to Eq. (5.14).

<table>
<thead>
<tr>
<th>Forest structure</th>
<th>Stem density [ha$^{-1}$]</th>
<th>Deposition volume [m$^3$]</th>
<th>$h_d$ [m]</th>
<th>$K$-value [Pa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single trees</td>
<td>400</td>
<td>173</td>
<td>0.02</td>
<td>10</td>
</tr>
<tr>
<td>Group of trees</td>
<td>400</td>
<td>1842</td>
<td>0.18</td>
<td>110</td>
</tr>
<tr>
<td>Trees with branches</td>
<td>400</td>
<td>2771</td>
<td>0.28</td>
<td>166</td>
</tr>
<tr>
<td>Single trees</td>
<td>200</td>
<td>87</td>
<td>0.01</td>
<td>5</td>
</tr>
<tr>
<td>Group of trees</td>
<td>200</td>
<td>921</td>
<td>0.09</td>
<td>55</td>
</tr>
<tr>
<td>Trees with branches</td>
<td>200</td>
<td>1386</td>
<td>0.14</td>
<td>83</td>
</tr>
</tbody>
</table>
5.3 Modeling

5.3.1 Avalanche modeling

We applied the numerical avalanche dynamics program, RAMMS (Rapid Mass Movements), to simulate the observed avalanche events and to perform simulations on an ideal parabola-shaped avalanche track (Christen et al., 2010a). We describe the mountain profile in a horizontal $X,Y$ coordinate system. The elevation of the mountain profile, $Z(X,Y)$, is defined for each coordinate pair $(X,Y)$. The geographic coordinates are used to construct a local surface-based coordinate system $(x,y,z)$. The unknown field variables are the avalanche flow height, $h(x,y,t)$, and the mean avalanche velocities, $U(x,y,t)$ and $V(x,y,t)$, in the $x$- and $y$-directions, $\mathbf{V} = (U,V)^T$ (Fig. 5.5). Avalanche flow is modeled using depth-averaged mass- and momentum balance equations (Christen et al., 2010a):

\[
\frac{\partial h}{\partial t} + (\mathbf{V} \cdot \nabla) h = \dot{Q}
\]

(5.3)

\[
\frac{\partial (h \mathbf{V})}{\partial t} + (\mathbf{V} \cdot \nabla)(h \mathbf{V}) = \mathbf{G} - \frac{1}{2} \nabla (g_z h^2).
\]

(5.4)

The force components associated with the gravitational acceleration, $g$, in the $x$- and $y$-directions are denoted $\mathbf{G} = (G_x, G_y)^T$ and are given by

\[
G_x = g_x h \quad \text{and} \quad G_y = g_y h,
\]

(5.5)

with

\[
g = g_x \mathbf{i} + g_y \mathbf{j} + g_z \mathbf{k}.
\]

(5.6)

The corresponding resistances in the $x$- and $y$-directions are denoted $S_x$ and $S_y$, $\mathbf{S} = (S_x, S_y)^T$.

Let $A_r(x,y)$ be the location of the avalanche release zone; this can be a forest opening or a region located above the timberline. The region $A_f$ defines the forest. There can be multiple forest areas (Fig. 5.5). Mass uptake from the snow cover and snow detrainment from the avalanche (stopped mass) is specified by the volumetric mass flux, $\dot{Q}(x,y,t)$ defined per unit area. However, as we assume no mass uptake in forested areas, we did not account for entrainment in this study. We therefore define $\dot{Q} = -\dot{h}_d$ as the detrainment rate. This provides the mean deposition height, $h_d$, of stopped snow mass in the forested area, $A_f$. 


Fig. 5.5. The model domain and definition of primary variables: $A_r$ is the release area and $A_f$ the forest area. $U$ and $V$ are the velocities in $x$- and $y$-direction, respectively. The gravitational acceleration in the $x$-, $y$- and $z$-directions is denoted $g_x$, $g_y$ and $g_z$, respectively. $S$ is the resistance acting in the opposite direction to the velocity, $V$.

An additional depth-averaged energy equation accounting for the kinetic energy, $R(x,y,t)$, associated with particle velocity fluctuations, is included in the RAMMS model (Bartelt et al., 2012a):

$$\frac{\partial (hR)}{\partial t} + V \cdot \nabla (hR) = \alpha (S \cdot V) - \beta (hR).$$ 

(5.7)

Parameter $\alpha$ controls the production of random fluctuation energy, $R$, from the frictional work rate of the mean flow, $\dot{W}_f = S \cdot V$. Therefore, for $\alpha > 0$, we have more collisional, disperse flows; $\alpha S$ corresponds to the granular stresses caused by fluctuating particle motion that is not transformed into heat, which could be considered as a turbulent Reynolds stress, by analogy with conventional fluids. Parameter $\beta$ determines the dissipation of fluctuation energy by different mechanisms (collisions, plastic deformation, abrasion, fragmentation). The inclusion of the random kinetic energy in the model formulation is helpful when calculating the
distribution of cold, dry avalanche deposits in the runout zone, as well as the motion of small avalanches, which can stop on steep slopes (Bartelt et al., 2012a).

We use the well-known Voellmy Ansatz (Voellmy, 1955; Salm, 1993) to model flow resistance. The Voellmy approach splits the total basal friction into a velocity-independent dry-Coulomb term, which is proportional to the normal stress (friction coefficient, \( \mu \)) and a velocity-dependent ‘viscous’ or ‘turbulent’ friction (friction coefficient, \( \xi \)).

\[
S_x = \frac{U}{|V|} \left[ \mu(R) g' \dot{h} + \frac{g |V|^2}{\xi(R)} \right] \tag{5.8}
\]

and

\[
S_y = \frac{V}{|V|} \left[ \mu(R) g' \dot{h} + \frac{g |V|^2}{\xi(R)} \right]. \tag{5.9}
\]

However, the constitutive parameters, \( \mu \) and \( \xi \), are functions of the mean fluctuation energy, \( R h \) [J m\(^{-2}\)] (Bartelt et al., 2012a).

We use

\[
\mu = \mu_0 \exp\left( -\frac{R h}{R_0} \right), \tag{5.10}
\]

\[
\xi = \xi_0 \exp\left( \frac{R h}{R_0} \right), \tag{5.11}
\]

where \( R_0 \) is the activation energy per unit area [J m\(^{-2}\)] controlling the onset of the fluidized regime (Bartelt et al., 2012a). The activation energy depends on the avalanche size (more activation energy is required to overcome the overburden pressures of thick dense avalanche cores) and cohesive properties of the flowing snow (more energy is required to break the bonds of cohesive snow). An estimate for the activation energy, \( R_0 \), is the sum of the mean overburden pressure and the cohesion. Parameter \( \mu_0 \) is the static Coulomb friction parameter and \( \xi_0 \) the speed-dependent friction parameter before fluidization. When \( \alpha = 0 \), we have the standard Voellmy–Salm (VS) model with constant friction parameters, \( \mu \) and \( \xi \). For more information concerning the numerical implementation, see Christen et al. (2010a), and for the role of fluctuations in avalanche flow see Bartelt et al. (2012a).
5.3.2 Modeling avalanche flow in forests

The region $A_f(x,y)$ defines the location of the forest in the model domain. The elements in this domain are assigned forest properties, depending on forest density, age and undergrowth. It is not possible to calculate each wedge-shaped deposition pattern behind individual trees or tree stands, as we assume average forest values per computational element (e.g. tree density) (Fig. 5.6). Therefore, no information is needed on the position of individual trees. The forest model simulates the mean deposition height, $h_d$, which, when multiplied by the element area, should accurately represent the total deposited volume observed at that location in the case studies (Fig. 5.4). Isolated trees are not considered to be part of $A_f$ when they stop too little snow to have an effect on the overall flow behavior of the avalanche.

Fig. 5.6. Schematic illustration of the mass flux before and after the interaction with forests of different densities. Snow gets deposited behind trees most effectively if groups of trees enable jamming. Higher $K$-values are applied for the denser forest.

In general, there are two possible ways to model the braking effect of forests: (1) the friction approach and (2) the detrainment approach (Fig. 5.7).
Fig. 5.7. Two approaches can be used to model tree interaction with avalanches. The friction approach attempts to find values for $S$ to stop the mass. The detrainment approach determines $M_d$ and extracts the corresponding momentum from the flow.

**Friction approach**

In the friction approach, modified friction parameters, $\mu_f$ and $\xi_f$, are assigned to the forest domain, $A_f$, to model the enhanced braking effect. For example, in the current version of RAMMS, coefficient $\xi_f$ is assumed to be 400 m s$^{-2}$ (significantly smaller than the open-terrain value of 2000 m s$^{-2}$); coefficient $\mu$ is only slightly increased (Gruber and Bartelt, 2007). These values are based on energy arguments in which different failure modes (tree overturning, trunk fracture, entrainment of woody debris) extract flow energy from the avalanche (Bartelt and Stöckli, 2001). The fundamental assumption in this approach is that the avalanche is both large enough and fast enough to induce tree failure. This approach is presently employed to model all avalanche flows in forests, independent of the avalanche size. The modified $\mu$ and $\xi$ values are based on mechanical processes, such as tree overturning or trunk fracturing. As we assume that the trees do not break, the friction parameters, $\mu_f$ and $\xi_f$, should be related to non-destructive processes, such as jamming.

**Detrainment approach**

Extracting mass that gets caught behind tree stands from the avalanche is an alternative way to model the forest/avalanche interaction. We term this method the detrainment approach, as we postulate that when mass is stopped behind dense tree stands it is instantly subtracted from
the flow. The stopping is sudden and caused primarily by material jamming, which is initiated behind dense group structures of trees. The momentum of the stopped mass is removed from the total momentum of the avalanche flow (Fig. 5.7) (see also Faug et al., 2004; Naaim et al., 2004). We assume that the trees do not break and that they act as obstacles causing mass to stop (Fig. 5.3). This process is difficult to model with Voellmy-type parameters, because the friction coefficients, especially $\xi$, are designed for avalanche flow in open terrain where the dissipative processes are slow and continual; they are not designed to model tree impact. Instead of attempting to define friction values that slow the avalanche, and therefore allow the avalanche to naturally detrain material (Naaim et al., 2003), we impose a stress, $K$ [Pa], which instantly detrains mass from the flow. This stress must be in balance with the change in momentum associated with the detrained mass per unit area, $M_d$:

$$\frac{dM_d}{dt} \|V\| = -K,$$  \hspace{1cm} (5.12)

where $V$ is the depth-averaged velocity of the avalanche. We emphasize that the mass, $M_d$, is the average mass per unit area, which might differ from the height of the deposits at the tree. The stress, $K$, is related to the forest structure and density, but also to properties of the flowing snow. Therefore,

$$\frac{dM_d}{dt} = -\frac{K}{\|V\|},$$  \hspace{1cm} (5.13)

or, in terms of the mean deposition height,

$$\rho \frac{dh_d}{dt} = \frac{K}{\|V\|},$$  \hspace{1cm} (5.14)

where $\rho$ is the flow density of the avalanche. Parameter $K$ is related to non-destructive processes, such as granular jamming behind tree stands. This assumption is only valid for small and medium avalanches.

### 5.4 Results

#### 5.4.1 Numerical experiment

To begin our analysis, we first carried out a numerical experiment to explore the differences between the friction and detrainment approaches. The numerical experiment enabled us to perform multiple simulations with equal initial conditions and varying forest
characterizations. We constructed an ideal, parabola-shaped avalanche track in order to avoid complex terrain features (Fig. 5.8). The average altitude difference between release area and runout is 380 m. The parabola is characterized by a 300 m long runout area. In width the parabola is flat and therefore the flow is unchanneled. We simulated avalanches with variable starting volumes and $\alpha = 0$ (standard Voellmy model). We computed the movement of the avalanche with forest ($A_f = 0$) and without forest ($A_f \neq 0$). We specified a calculation grid size of 1 m.

The release area, fracture depth, snow density and the two friction parameters, $\mu = \mu_0$ and $\zeta = \zeta_0$, had to be defined. To test the influence of forests on different sizes of avalanches, we specified three release volumes, all with different release areas, but a constant fracture depth of 1 m for all three cases. The resulting release volumes, $V_0$, were ~1000, 5000 and 20,000 m$^3$. The flowing snow density was set to $\rho = 300$ kg m$^{-3}$. We kept the friction parameters, except for simulations with the friction parameter approach, constant: $\mu = 0.26$ and $\zeta = 2000$ m $s^{-2}$. These parameters are valid for frequent avalanches (10 year return period) with release volumes between 5000 and 25,000 m$^3$ in unchanneled terrain $>1500$ m asl, according to the recommended guideline values (Buser and Frutiger, 1980; Salm et al., 1990).

![Fig. 5.8. Simulation of avalanche on parabola-shaped avalanche track. The maximum calculated velocity for a release volume of 20 000 m$^3$ is shown.](image)

In our numerical experiment, the forest area covered the whole avalanche path below the release area (Fig. 5.8). At first we applied the friction approach and employed the $\mu$ and $\zeta$ values that are used in the current RAMMS version (adding $\Delta \mu = 0.02$ to the basic $\mu$ value and...
setting $\xi = 400 \text{ m s}^{-2}$), independent of the forest structure (Gruber and Bartelt, 2007). Recall that these values are derived for extreme avalanches that destroy the forest. Next we applied the detrainment approach with five different values for parameter $K$: 10, 20, 50, 100 and 200 Pa. These are reasonable values and are comparable with the calculated $K$-values of the case studies (Table 5.3): a $K$-value of 10 Pa corresponds to an open forest, whereas a $K$-value of 200 Pa corresponds to a dense forest with tree clusters and low-lying vegetation. As a control, we simulated the avalanches without any forest cover. For these simulations and the detrainment simulations we specified the guideline friction parameters ($\mu = 0.26$ and $\xi = 2000 \text{ m s}^{-2}$) for frequent avalanches.

Profiles of deposition height, velocity and momentum along longitudinal and transverse sections of the avalanche track were analyzed, in order to explore differences in runout length, deposition patterns, velocity distribution and the development of the total momentum of the model avalanches. Although both approaches (friction and detrainment) have the same goal – to stop flowing mass – our findings reveal crucial differences.

Runout shortening was observed in the forest case for both the friction and detrainment approaches in comparison with the simulations without forest (Fig. 5.9). We display the maximum flow height along the avalanche path for the three different flow volumes. The distance ($x$-axis of the plots) is measured from the starting zone ($x = 0$). Simulation results of (1) the detrainment approach for different $K$-values between $K = 10 \text{ Pa (K10)}$ and $K = 200 \text{ Pa (K200)}$, (2) the friction approach ($\mu, \xi$ approach) and (3) the case without forest are shown in Figure 5.9. The numerical results reveal that the runout of small avalanches (1000 m$^3$; Fig. 5.9c) is barely influenced by changing the friction parameters. Conversely the detrainment approach leads to a significant runout shortening, dependent on the magnitude of parameter $K$. The runout of larger avalanches (20,000 m$^3$; Fig. 5.9a) is not significantly shortened when applying the detrainment approach, in contrast to the friction approach. This finding suggests that the immediate stopping and removal of flow mass because of trees has a greater influence on small avalanches than on larger avalanches.
Fig. 5.9. Profiles of maximum flow height for simulations of avalanches with different release volumes: (a) ~20,000 m$^3$; (b) ~5000 m$^3$; (c) ~1000 m$^3$. The simulations were conducted with the VS model of RAMMS on a parabolic slope using both the friction and detrainment approaches. Five different values for the detrainment coefficient, $K$ [Pa], were tested ($K_{10}$, $K_{20}$, $K_{50}$, $K_{100}$, $K_{200}$). Note the significant runout shortening for smaller avalanches using the detrainment approach, in contrast to the runout shortening for larger avalanches using the friction approach. The spikes in height at 400 m distance from release, when simulating with the friction approach and without forest for 5000 m$^3$ and 1000 m$^3$, originate from the pile-up of snow at the transition between sloped and flat (0°) terrain. This spike is missing when using the detrainment approach because the snow is already deposited on the track.

Figure 5.10 depicts different deposition patterns on the avalanche track with $V_0 \approx 20,000$ m$^3$ release volume. Most of the avalanche mass reached the flat part of the avalanche track when using either the friction approach or the detrainment approach. The results are similar for the case with no forest area. We investigated deposition heights at profile elevations $Z = 30$ and 60 m above zero (Fig. 5.8). At these altitude levels the slope angles of the track are 27° and 36°, respectively. Generally higher deposition heights were observed when applying the detrainment approach than for simulations with the friction approach. In fact, the friction
approach even resulted in smaller deposition heights than for simulations without forest (because of the longer simulation times). Note the steep increase of the deposition heights at the edges of the avalanche when applying the detrainment approach, indicating that more mass is deposited at the slower-moving sides of the avalanche, as observed in the field studies. The removal of snow at the slow-moving avalanche edges results in a narrower track width, especially at lower elevations.

**Fig. 5.10.** Cross section of the deposition heights of avalanches with friction and detrainment approaches for the parabola experiment. The release volume $V_0 \approx 20,000$ m$^3$; profiles are taken 30 and 60 m above zero. Note the slow, continual increase of the deposition heights at the avalanche edges when using the friction approach, in comparison with the detrainment approach. The detrainment removes mass faster at the edges, leading to smaller avalanche flow widths at lower elevations. This agrees with the field observations.

The development of the total momentum of the avalanche over time is illustrated in Figure 5.11. For all approaches (friction, detrainment and no forest) we observe an increase in momentum until the avalanche reaches the forest, i.e. the avalanche accelerates. After it penetrates the forest the momentum decreases. With the friction approach the decrease of momentum starts earlier (4 s) than for the detrainment approach (6-7 s) or without forest on the avalanche track (7 s). The momentum of all avalanches will decrease because the avalanche track is flattening. Although the highest decrease in momentum is reached only after 5 s with the friction approach, the detrainment approach is more effective at lower slope angles. Furthermore, more mass is removed at the tail and the avalanche edges, where the
velocities are small. Thus, although the maximum decrease in momentum is reached later (10-11 s) with the detrainment approach, more mass is stopped. From 7 s onwards, the decrease in momentum is higher with the detrainment approach, leading to earlier stopping of the avalanche. The detrainment approach exploits the velocity distribution between the head and tail (and sides) of the avalanche.

**Fig. 5.11.** Development of the total momentum in time of a small avalanche ($V_0 \approx 1000 \text{ m}^3$). The plot depicts the change in momentum illustrating the braking process. Detrainment (K10, K20, K50, K100, K200) and friction ($\mu, \zeta$) approaches are compared with the case with no forest.

### 5.4.2 Simulations of documented avalanches with $\alpha = 0$

We back-calculated the seven forest avalanche events described in Section 5.2 with the VS model ($\alpha = 0$). As in the numerical experiment, the forested region, $A_f$, was characterized by either differing friction parameters or by extracting mass with the detrainment function.

For each particular case study, the input parameters (release area, $A_r$, forest area, $A_f$, fracture height, $h_0$, and the $\mu$ and $\zeta$ values for non-forested regions) were identical for all simulations. We varied only the forest friction parameters or detrainment coefficients, $K$. Release areas and fracture heights were specified according to the observations of the field studies or, when it was impossible to enter the release zone, by applying a terrain analysis (Section 5.2). The open-terrain $\mu$ and $\zeta$ values were defined by the automatic procedure within RAMMS. This feature accounts for terrain features (e.g. gullies and flat slopes) as well as altitude level, return period and avalanche size, based on calibrations (Buser and Frutiger, 1980; Gruber and Bartelt, 2007).
Accurate, high-precision digital elevation models were necessary to simulate the observed avalanches. Resolutions of 1 m grid size were available for the avalanches released in Germany (ID-VI, ID-VII) and a resolution of 2 m for Switzerland (ID-I, ID-II, ID-III, ID-IV, ID-V).

The forest areas, $A_f$, were specified using orthophotographs taken from fixed-wing, airborne flyovers. For the friction approach we set $\xi = 400 \text{ m s}^{-2}$ and added $\Delta \mu = 0.02$ to the previously defined values; for the detrainment approach we did not change the friction parameters, but removed mass according to the detrainment function. Forest structure and densities were not accounted for when simulating avalanches with the friction approach; we defined dense and open forest structures by varying parameter $K$ when using the detrainment approach (Section 5.3.2). We selected the following values, according to the field observations:

- $K = 30 \text{ Pa (K30)}$ for dense forest stands with some group structures of trees and few low-lying branches that induce jamming;
- $K = 10 \text{ Pa (K10)}$ for open-forest structures or older forests, characterized by few branches, root plates or dead wood, which serve as low-lying obstacles.

The avalanches were simulated until the final deposition patterns were reached. They were considered stopped when they flowed with $<5\%$ of the maximum momentum reached by the avalanches (Christen et al., 2010a).

We focused our analysis on the runout distance and deposition structure of the avalanches. Both these characteristics differed significantly between simulations with the detrainment and the friction approach, as illustrated in Figure 5.12. The spatial distribution of deposition heights is presented for the seven avalanches (ID-I to ID-VII), for both approaches (a - friction, b - detrainment).
Fig. 5.12. Comparison of the simulation results of the seven observed avalanches (ID-I to ID-VII). Deposition heights (up to 50 cm) are shown for (a) the $\mu, \zeta$ approach and (b) the detrainment approach. The observed runout areas measured with differential GPS (ID-IV and ID-VII) and photographs (ID-VI) are outlined in red. The runout for all case studies is overestimated when using the friction approach. The detrainment approach overestimates two cases significantly (ID-I, ID-V), overestimates two cases slightly (ID-II, ID-IV), matches the runout length in two cases (ID-III, ID-VII) and slightly underestimates one case (ID-VI).

Three findings are valid for the seven simulated avalanches:

The runout of simulations with the friction approach always exceeded the runout of the detrainment approach. Many times the avalanches reached the valley bottom when using the friction approach, unhindered by the forests.

The friction approach always overestimated the runout compared with the observations. This is plausible, because the friction parameters are valid for extreme avalanches, but highlights the difficulties of calibrating forest friction parameters for all avalanche sizes.

More snow was deposited on the avalanche tracks when applying the detrainment approach, which caused avalanches to stop on steep slopes in several cases (ID-II, ID-III, ID-VI, ID-VII).
Furthermore, three characteristic deposition patterns could be distinguished for calculations with the detrainment approach:

Avalanche runout distances and areas were considerably overestimated in two cases (ID-I, ID-V). For avalanche ID-I at Junkerboden the very small release volume ($V_0 = 318 \text{ m}^3$) might serve as an explanation. Runouts of small avalanches tend to be overestimated when using the standard VS model (Maggioni et al., 2012). However, the very small release volume can only partly explain the difference, because the avalanche near Monstein (ID-V) had the largest release volume of the documented cases (Table 5.1). In the Monstein case study, we had no direct measurements of the release zone dimensions (we used photographs), and therefore we might have overestimated the release zone volume. We subsequently reduced the release zone volume and obtained the correct runout distance. This result highlights the problem of selecting the release zone dimensions correctly.

The calculation result of the avalanche at Hagenberg (IDVI) was unique: the detrainment approach underestimated the runout distance. This simulation result is different from that for the other avalanches, which provided reasonable approximations to the observed runout distances. The avalanche released during cold weather conditions with dry, cohesionless snow flowing around the trees and therefore reaching the road. The under-prediction can be attributed to the lack of jamming of snow granules between tree stands. Therefore, we specifically simulated this avalanche assuming $\alpha \neq 0$, accounting for the fluidization of the flow, and obtained better results (Section 5.4.3).

Simulations of the other four avalanches (ID-II, ID-III, ID-IV, ID-VII) produced reasonable deposition patterns (the friction approach greatly overestimated the runout distances and areas). In all of these case studies, wedge-shaped depositions were observed behind the vegetation (Table 5.4). Jammed snow mass behind tree groups appears to be the dominant stopping mechanism in all of these cases. An interesting feature of the deposition structure observed in the field campaign of avalanche ID-III could be simulated: the main depositions are concentrated on both sides of the primary flow channel, with almost no snow in the channel itself, which resembles the observations (Fig. 5.2). The main avalanche channel was unforest ed and mass was stopped at the forest edges.
Table 5.4. Calculated avalanche characteristics of the seven case studies: mean velocity, mean flow height, detrained volume and mean deposition height, $h_d$. Possible range of deposition widths, $d$, calculated according to Eqs. (5.1) and (5.2). From the observations we found the wedge height, $h_w$, to be approximately three times as high as the flow depths. The stem densities are taken from observations; however, we assume tree-stand clusters consisting of three trees. Note the calculated widths, $d$, are in the range of observed widths. The photographs show typical deposition structures of the six avalanches documented in winter 2011/12.

<table>
<thead>
<tr>
<th>Avalanche ID</th>
<th>ID-I</th>
<th>ID-II</th>
<th>ID-III</th>
<th>ID-IV</th>
<th>ID-V</th>
<th>ID-VI</th>
<th>ID-VII</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calculated mean velocity [m s$^{-1}$]</td>
<td>10</td>
<td>17</td>
<td>14</td>
<td>15</td>
<td>12</td>
<td>20</td>
<td>16</td>
</tr>
<tr>
<td>Calculated mean flow height [m]</td>
<td>0.4</td>
<td>0.8</td>
<td>0.5</td>
<td>1.3</td>
<td>1</td>
<td>0.8</td>
<td>0.6</td>
</tr>
<tr>
<td>Observed forest characteristics</td>
<td>trees with branches, 400 stems ha$^{-1}$</td>
<td>groups of trees, 300 stems ha$^{-1}$</td>
<td>groups of trees, 500 stems ha$^{-1}$</td>
<td>groups of trees, 300 stems ha$^{-1}$</td>
<td>groups of trees, 300 stems ha$^{-1}$</td>
<td>groups of trees, 400 stems ha$^{-1}$</td>
<td>groups of trees, 400 stems ha$^{-1}$</td>
</tr>
<tr>
<td>Calculated detrained volume [m$^3$]</td>
<td>110</td>
<td>880</td>
<td>1160</td>
<td>2750</td>
<td>3180</td>
<td>2980</td>
<td>590</td>
</tr>
<tr>
<td>Calculated $h_d$ [m]</td>
<td>0.06</td>
<td>0.09</td>
<td>0.09</td>
<td>0.21</td>
<td>0.25</td>
<td>0.11</td>
<td>0.05</td>
</tr>
<tr>
<td>Calculated range for $d$ [m]</td>
<td>1.1-1.5</td>
<td>0.6-1.7</td>
<td>1.1-2.7</td>
<td>0.4-2.1</td>
<td>0.9-2.8</td>
<td>0.5-1.5</td>
<td>0.5-1.3</td>
</tr>
<tr>
<td>Observed $d$ [m]</td>
<td>&lt;2.0</td>
<td>&lt;3.0</td>
<td>&lt;3.2</td>
<td>&lt;5</td>
<td>&lt;3.0</td>
<td>&lt;1.5</td>
<td>&lt;1.5</td>
</tr>
<tr>
<td>Picture</td>
<td><img src="image1.png" alt="Image" /> <img src="image2.png" alt="Image" /> <img src="image3.png" alt="Image" /> <img src="image4.png" alt="Image" /> <img src="image5.png" alt="Image" /> <img src="image6.png" alt="Image" /> <img src="image7.png" alt="Image" /></td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

5.4.3 Simulations with $\alpha \neq 0$

We simulated case study ID-VI (Hagenberg) accounting for particle velocity fluctuations ($\alpha \neq 0$). The advantage of this model extension is the simplified selection of the friction parameters. They are initially constant over the whole avalanche path and change according to the generation and decay of the energy associated with particle velocity fluctuations. Therefore, defining different pairs of $\mu$ and $\zeta$ values for different terrain features, altitude levels and return periods is unnecessary. The flow parameters should only account for snow characteristics, and not depend on avalanche size or altitude levels.

For $\mu_0$ we chose a value of 0.55. This value can be approximated as the tangent of the angle of repose of avalanche deposits (measurable at the sides and front of avalanche depositions;
Platzer et al., 2007). In addition this value corresponds to the steepest slope angle at which snow avalanche deposits are found. It matches the tangent of 29°, the approximate minimum angle which allows slab avalanches to release (McClung and Schäerer, 2006). The value also corresponds to the initial Coulomb friction values measured when a fracture slab begins to release before fragmentation (Van Herwijnen and Heierli, 2009). The value of ζ was set constant to 500 m s⁻² (Voellmy, 1955). Therefore it is between 300 and 700 m s⁻², the possible range calculated by Bartelt et al. (2012a), who ascertained this value using measured velocities at the avalanche tail when \( R = 0 \).

We determined the activation energy, \( R_0 \) [kPa], by summing the mean normal stress, \( N \), and cohesion, \( c \):

\[
R_0 \approx N + c = \rho gh + c \approx 2.0, \quad (5.15)
\]

using a flow density of 250 kg m⁻³ and a mean flow height of \( h = 0.8 \) m (Table 5.4). As the flow was dry and cold, we assumed the flow to be cohesionless and \( c \approx 0 \).

We took a value of \( \alpha = 0.05 \) for the generation of random kinetic energy, less than Bartelt et al. (2012a) used for their calculations, as we assume soft snow. The decay, \( \beta \), was defined according to snow characteristics, \( \beta = 0.7 \) (Buser and Bartelt, 2009). We defined the forested regions, \( A_f \), identical to simulations with the VS model (\( \alpha = 0 \)) with \( K \)-values of 10 and 30 Pa, depending on the forest structure.

We show the results of the simulations of avalanche ID-VI to highlight the differences and similarities of modeling avalanches in forested terrain with \( \alpha = 0 \) and \( \alpha \neq 0 \) with the detrainment approach. This avalanche was unique in the way that the runout distance was underestimated when choosing \( \alpha = 0 \). Figure 5.13 depicts the calculation results of deposition heights and velocities for the friction and the detrainment approaches with \( \alpha = 0 \) and \( \alpha \neq 0 \). Generally, the deposition areas of the detrainment approach (Fig. 5.13b1, c1) are comparable, whereas the friction approach provides the user with an avalanche reaching the valley floor (Fig. 5.13a1). With the detrainment approach and \( \alpha = 0 \), snow is lost on the steep slope, stopping the avalanche before reaching the road. For \( \alpha \neq 0 \), the avalanche overflows the road, in agreement with the observations. These significant differences can be illustrated using the calculated velocity profiles (Fig. 5.13b2, c2). The fluctuation energy for dry snow (characterized by \( \beta = 0.7 \)) causes higher velocities for \( \alpha \neq 0 \) and therefore less snow is deposited, leading to a longer runout.
Fig. 5.13. Comparison of the modeling results of the avalanche at Hagenberg (ID-VI). The results of the friction approach are shown in the first column (a1, a2); the detrainment approach with VS ($\alpha = 0$) in the second column (b1, b2). The detrainment approach with $\alpha \neq 0$ is shown in the third column (c1, c2). The deposition heights are presented in the upper row; the maximum velocities are presented in the lower row. Note the similar shape of the deposition areas calculated with the detrainment approach. The real avalanche reached the road and covered it with several meters of snow, but did not flow further into the forest below.

### 5.5 Discussion and conclusion

The inclusion of forest effects in avalanche dynamics simulations is an important feature for avalanche hazard analysis, especially for frequent, small-to-medium avalanches. Forests play a crucial protective role by shortening the runout distance of such avalanches. In this paper we have compared two different approaches to quantify this role. The first is to increase the friction parameters (Bartelt and Stöckli, 2001; Gruber and Bartelt, 2007); the second is to directly extract mass and its momentum from the flow that has been stopped by the trees. The rate of mass extraction is parameterized by a single coefficient, $K$, which depends on forest structure. The extraction is the result of higher friction, so the methods are equivalent, but they lead to different parameterizations of the braking process. However, the detrainment approach is more direct and appears to account for physical processes, such as snow jamming between trees, that are not embodied in the Voellmy friction model.

We systematically tested both approaches on an ideal, parabola-shaped slope to gauge the model performance. We found that runout shortening due to detrainment depends on release volume: the smaller the release volume, the larger the decrease in runout length. This result implies that the stopping of equal mass will have a greater effect on smaller avalanches,
which qualitatively agrees with observations. There is almost no effect of detrainment on larger avalanches, which also agrees with observations. Additionally we investigated the deposition patterns across the avalanche track and their dependence on velocity. More snow is deposited in steep terrain when applying the detrainment approach. This result also corresponds to the field observations: avalanches did not reach the valley floor because of snow being continuously detrained in the forest, even on steep slopes. Interestingly, our analysis of the development of the total momentum of the avalanche revealed that the deceleration and stopping of the flow is triggered later but more efficiently.

To demonstrate the applicability of the detrainment approach to real avalanche events we simulated seven case studies. We found that the simulated mean deposition heights correspond to the observed wedge heights. This calculation requires knowing the forest structure, as it involves averaging spatially inhomogeneous deposition patterns behind trees. This, coupled with a comparison of the observed runouts and lateral extension of the avalanches, is presently the only method we can apply to ascertain model performance. However, it also indicates that the parameter, $K$, can be calibrated by performing more mass-balance studies in forests. These studies must involve documenting the overall mass balance of an event and relating these data to the observed deposition patterns and forest structure. The values of $K$ can therefore be improved with future fieldwork, but data from past events can also be employed for this purpose (Teich et al., 2012a, see Chapter 4). Forest type, stem density, surface roughness and vertical structure of the forest seem to be crucial parameters to be considered (Teich et al., 2013, see Chapter 6).

Runout shortening was reproduced in the simulations, and a good agreement with the observed flow widths was found in four of the seven case studies. Three cases could not be reproduced with $K$-values of 10 and 30 Pa that we assume to correspond to the observed forest structure. In one case (ID-I), the starting volume was $<500 \text{ m}^3$ and the avalanche consisted of large, moist snow granules. The simulated avalanche ran too far for $K < 200 \text{ Pa}$. This could be an indication that the model scale is not fine enough to represent forest features, terrain roughness or snow characteristics in this particular case. The size limits of depth-averaged models must clearly be established in future work (Maggioni et al., 2012). A second simulation (ID-V) also ran too far for $K < 100 \text{ Pa}$, but could be accurately simulated if the release volume was decreased. In this case, the release volume and location were determined by photographs taken from the counter-slope, 1 km distant. Our conclusion is that accurate release zone measurements, as always, are required. Again, we are confronted with
documenting small release areas in inaccessible terrain. The third avalanche that could not be simulated adequately (ID-VI) could, however, be reproduced using the Voellmy extension ($\alpha > 0$). This suggests that the fluidization of the avalanche in dry/cold conditions is important, stressing the idea that jamming effects cannot develop easily in low-density flows with large granular fluctuations.

The detrainment approach, based on momentum extraction, always performed better than the friction approach, based on modified friction coefficients. Nonetheless, the application of the detrainment approach has two fundamental difficulties that must be addressed in future investigations.

First, the detrainment approach is only valid for small-to-medium avalanches where the forest is not destroyed and the trees act as obstacles. This is not always the case and, ideally, the model should determine when the trees in the forest break. This is not an easy task, as the breaking mode can vary from tree fracture to root upheaval and tree overturning. Furthermore, when the trees and other woody debris are entrained in the flow, they can become entangled in tree stands, leading to a complex flow state that is difficult, if not impossible, to model. Whether the entangled mass is stopped or gains more momentum, destroying still more forest, remains an open question. The application of the model is therefore restricted to a specific flow case.

Second, the model results are sensitive to the selection of the starting mass and snow characteristics. Although it is possible to back-calculate documented avalanches, the predictive capacity of the model remains limited. This is a general problem in the simulation of small and medium avalanches, which depends strongly on the size and location of the release zone, entrainment processes, snow properties and terrain features (which might be modified by avalanche deposits). Because of the strong variability of the initial and boundary conditions, as well as material properties, avalanche simulations that include forest effects should only be applied to selected problems (e.g. to determine the general cost effectiveness of silvicultural measures or to determine the vulnerability of specific objects for well-defined starting and boundary conditions).

Our results are, however, promising and will be strengthened by collecting more and specific data during future field studies. We plan to map the entire deposition area, quantifying mass piles behind individual tree clusters. The exact structure of each tree group (location in forest, relative tree composition, tree diameter, branch density, tree spacing, low-lying vegetation)
will be documented and correlated with the stopped mass. This will help to calibrate the $K$ parameter, by linking structural features of the forest to mean deposition heights. Granulometry studies are needed in the deposition wedges to relate the jamming process to snow properties. To underpin the fieldwork, small-scale granular chute experiments will be conducted to investigate how detrainment in forest-like structures modifies momentum and energy fluxes of avalanches.

**Acknowledgements**

We thank Armin Fischer, Jochen Veitinger and Irene Vassella for help with data collection and evaluation. We also thank Bernhard Zenke, who made the close cooperation with the Bavarian Avalanche Service possible. This research was funded by the Bavarian Environment Agency.
Chapter 6

Paper IV

Computational snow avalanche simulation in forested terrain

Received 23 July 2013
Accepted 13 September 2013

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Natural Hazards and Earth System Sciences Discussions 1, 2013, 5561–5601.

Under review for the journal Natural Hazards and Earth System Sciences.
Abstract

Two-dimensional avalanche simulation software operating in three-dimensional terrain is widely used for hazard zoning and engineering to predict runout distances and impact pressures of snow avalanche events. Mountain forests are an effective biological protection measure; however, the protective capacity of forests to decelerate or even to stop avalanches that start within forested areas or directly above the treeline is seldom considered in this context. In particular, runout distances of small- to medium-scale avalanches are strongly influenced by the structural conditions of forests in the avalanche path. We present an evaluation and improvement of a novel forest detrainment function implemented in the avalanche simulation software RAMMS for avalanche simulation in forested terrain. The new approach accounts for the effect of forests in the avalanche path by detraining mass, which leads to a deceleration and runout shortening of avalanches. The relationship is parameterized by the detrainment coefficient $K$ [Pa] accounting for differing forest characteristics. We varied $K$ when simulating 40 well-documented small- to medium-scale avalanches which released in and ran through forests of the Swiss Alps. Analyzing and comparing observed and simulated runout distances statistically revealed values for $K$ suitable to simulate the combined influence of four forest characteristics on avalanche runout: forest type, crown closure, vertical structure and surface roughness, e.g. values for $K$ were higher for dense spruce and mixed spruce-beech forests compared to open larch forests at the upper treeline. Considering forest structural conditions within avalanche simulation will improve current applications for avalanche simulation tools in mountain forest and natural hazard management.

6.1 Introduction

Avalanche dynamics models are widely used for hazard zoning and engineering to predict runout distances and impact pressures of snow avalanche events (Gruber and Margreth, 2001; Ancey et al., 2003; Gruber and Bartelt, 2007). The effect of mountain forests as an effective biological protection measure against avalanches has been rarely addressed in this context (Berger and Rey, 2004; Gruber and Bartelt, 2007; Teich and Bebi, 2009, see Chapter 3). Large destructive avalanches which often destroy the forest without a significant deceleration are of major interest in hazard zoning (e.g. Gruber and Häfner, 1995; Fuchs et al., 2005). Yet,
small- to medium-scale frequent avalanches are also often a threat to roads, railways and ski-runs below the forest (Techel et al., 2013). Especially when it comes to decisions about the size and extent of avalanche defense measures (including afforestation) in potential starting zones in forested areas, e.g. in newly created forest openings due to wind disturbance, or directly above the treeline, forest and civil engineers could benefit from reliable avalanche simulation in forested terrain (e.g. Weir, 2002; Schönenberger et al., 2005; Bebi et al., 2009).

The avalanche flow is not only influenced by terrain characteristics, but also by vegetation in the avalanche path (McClung, 2003). A recent study showed that forest structural parameters, e.g. the type of forest and the stem density in avalanche starting zones, have a significant influence on runout distances of small- to medium-scale avalanches starting in forested areas (Teich et al., 2012a, see Chapter 4). For large avalanches released high above the treeline, this effect is however negligible (de Quervain, 1979; Bartelt and Stöckli, 2001; Margreth, 2004; Schneebeli and Bebi, 2004; Christen et al., 2010b). The decreasing speeds and runout distances of large-scale avalanches depend mainly on the topography and the distance an avalanche travels through open terrain before penetrating into forests (McClung, 2003; Takeuchi et al., 2011; Anderson and McClung, 2012; Teich et al., 2012a, see Chapter 4). Both cases have only rarely been implemented in avalanche models (Anderson and McClung, 2012).

Flow models used for avalanche simulation often employ Voellmy-type relations splitting the total basal friction into a velocity independent dry-Coulomb term and a velocity dependent “viscous” or “turbulent” friction (Voellmy, 1955). The friction approach has been applied by several authors to model the effect of forest on avalanche runout by increasing friction in forested areas compared to open unforested terrain (Gubler and Rychetnik, 1991; Bartelt and Stöckli, 2001; Gruber and Bartelt, 2007; Teich and Bebi, 2009, see Chapter 3), and has been verified for few real large-scale avalanche events (Casteller et al., 2008; Takeuchi et al., 2011). Avalanche-forest interactions may however be only poorly represented within the framework of this model (Teich et al., 2012c, see Appendix B). Especially for small-scale avalanches physical processes within the avalanche flow such as snow entrainment (mass uptake) and detrainment (mass extraction) along the avalanche path are important and are not included in the calibrated Voellmy friction coefficients (Maggioni et al., 2012; Bovet et al., in

---

4 For avalanche size definitions we refer to typical path lengths where “small” $< 100$ m (volume $< 1000$ m$^3$), “medium” $< 1000$ m (volume $< 10,000$ m$^3$) and “large” $< 2000$ m (volume $< 100,000$ m$^3$) avalanche length (EAWS, 2012).
The local braking effect of forests on avalanche flow seems to be difficult to model with a frictional relationship at the grid scale (Feistl et al., 2014, see Chapter 5).

Instead of using higher friction values, Feistl et al. (2012, 2014, see Chapter 5) propose an additional detrainment function to account for avalanche-forest interactions. Based on field observations, they assume that trees stop fractions of the granular snow flow by a combination of impact, rubbing dissipation, deflection, cohesion and jamming. The stopped snow deposits behind trees, groups of trees or remnant stumps and, therefore, mass is directly extracted from the avalanche flow and the corresponding momentum is removed from the total momentum of the moving snow. This detrainment function accounts for the braking effect of forests on avalanche flow, and can be implemented in numerical avalanche dynamics models. The relationship is parameterized by the detrainment coefficient $K$, representing forest characteristics such as forest stand density or mean stem diameters. Currently, values of $K$ for forested areas have only roughly been estimated and tested for few real avalanche events (Feistl et al., 2014, see Chapter 5).

Detailed analyses of two-dimensional avalanche simulation software working in three-dimensional terrain objectively require a suitable data selection and a comprehensive and standardized way of processing multiple simulation results (Fischer, 2013). Processing and analyzing large quantities of one-dimensional avalanche model outputs automatically have been conducted in several studies (e.g. Ancey, 2005; Gauer et al., 2009; Eckert et al., 2009). In contrast, multidimensional simulation data has mainly been evaluated manually along predefined cross sections within the avalanche path (e.g. Christen et al., 2010b; Bühler et al., 2011). Comparing two-dimensional simulation results with field observations for a high number of avalanche events manually is however time consuming and rather subjective. To overcome this weakness, a standardized evaluation and comparison method for models operating in three-dimensional terrain has been suggested by Fischer (2013). This approach is employed here to analyze avalanche simulation results automatically and objectively.

In this study, we apply a novel detrainment modeling approach in order to investigate the effect of different forest characteristics on small- to medium-scale avalanches. We compare simulation results of the avalanche simulation software RAMMS (Christen et al., 2010a) with runout observations of avalanches released in forests of the Swiss Alps in order to improve the forest detrainment function. The avalanche dataset consists of 40 avalanches which started in forests and either stopped in forested terrain within 50–400 m or ran through forests and stopped in unforested areas with a maximum runout distance of 700 m. We evaluate our
model by systematically analyzing parameters characterizing forest structural conditions and their effects on simulated compared to observed runout distances. The overall aim is to define combinations of forest characteristics corresponding to a specific value of the detrainment coefficient $K$ to be applicable in practice.

6.2 Theory

6.2.1 Avalanche flow model

In this contribution, avalanche flow is modeled using depth-averaged mass and momentum equations; for a detailed mathematical description see Christen et al. (2010a). To briefly summarize: avalanche flow is characterized by unsteady and uniform motion with varying flow depth and velocity. Therefore, avalanche flow depth $H(x,y,t)$ and mean avalanche velocity $U(x,y,t)$ are the unknown field variables. The depth-averaged field variables are a function of time ($t$) and space ($x,y$) and, thus, the equations to model avalanche flow, i.e. mass balance and momentum equations, are solved from avalanche release ($t = 0$) to avalanche deposition.

The mass balance in terms of the avalanche flow depth ($H$) is given by

$$
\partial_t H + \partial_x (H U_x) + \partial_y (H U_y) = \hat{Q}(x,y,t)
$$

(6.1)

where $\hat{Q}(x,y,t)$ denotes the mass production source term with $\hat{Q} = \hat{Q}_e + \hat{Q}_d$, the sum of the volumetric entrainment $\hat{Q}_e$ and detrainment $\hat{Q}_d$ rates. The mass production source term specifies the mass uptake (entrainment) with $\hat{Q} > 0$ (i.e. $\hat{Q}_e > 0$ and $\hat{Q}_d = 0$) or mass extraction (detrainment) $\hat{Q} \leq 0$ (i.e. $\hat{Q}_e = 0$ and $\hat{Q}_d < 0$) from the snow cover per unit area as a function of time $t$; $U$ is the velocity in $x$ and $y$ direction.

The component wise depth-averaged momentum balance is given by

$$
\partial_t (H U_x) + \partial_x \left( c_x H U_x^2 + g_x k_{w/p} \frac{H^2}{2} \right) + \partial_y (H U_x U_y) = S_g - S_f
$$

(6.2)

and

$$
\partial_t (H U_y) + \partial_y \left( c_y H U_y^2 + g_y k_{w/p} \frac{H^2}{2} \right) + \partial_x (H U_x U_y) = S_g - S_f
$$

(6.3)
where $c_x$ and $c_y$ are the velocity profile shape factors, $k_{ap}$ is the earth pressure coefficient and $S_f = (S_{fx}, S_{fy})^T$ is the total friction (for details on $c$ and $k_{ap}$ we refer to Christen et al., 2010a).

The right-hand side terms of Eqs. (6.2) and (6.3) add up to the driving, gravitational acceleration $g$ in $x$ and $y$ direction. That is, avalanche flow resistance is implemented by a “Voellmy-fluid” friction relation assuming small shear strains in the flow body (Salm et al., 1990; Bartelt et al., 1999):

$$S_{gx} = g_x H \quad \text{and} \quad S_{gy} = g_y H .$$ (6.4)

The model splits the total basal friction $S_f$ into a velocity independent dry-Coulomb term which is proportional to the normal stress at the flow bottom (friction coefficient $\mu$) and a velocity dependent “viscous” or “turbulent” friction (friction coefficient $\xi$) (Salm, 1993):

$$S_{fx} = \frac{U_x}{\|U\|} \left[ \mu g_n H + \frac{g \|U\|^2}{\xi} \right] \quad \text{and} \quad S_{fy} = \frac{U_y}{\|U\|} \left[ \mu g_n H + \frac{g \|U\|^2}{\xi} \right] .$$ (6.5)

where $g_n$ is the surface normal component of the vector of gravitational acceleration $g = (g_x, g_y)$ (see Fig. 6.1). $\|U\|$ is the magnitude and direction of the mean flow velocity given by $\|U\| = \sqrt{U_x^2 + U_y^2}$. Therefore, snow characteristics and topographical conditions such as slope angle are presented via the inverse velocity.
Fig. 6.1. Schematic illustration of avalanche modeling in forested terrain. The release area \( (A_r) \) as well as forested areas \( (A_f) \) have to be defined by the avalanche expert and assigned an appropriate \( K \)-value dependent on specific forest characteristics which determine the detrainment rate \( \dot{Q}_d \). Avalanche flow in general is modeled by the velocities in \( x \) and \( y \) direction \( (U_x \) and \( U_y) \) and by the friction \( S \) acting in the opposite direction than \( \|U\| \) and the gravitational acceleration \( g \).

6.2.2 Improved avalanche modeling in forested terrain

The approach proposed by Feistl et al. (2012, 2014, see Chapter 5) to model the braking effect of forests on avalanches is based on extracting the mass of snow which is caught behind trees leading to a deceleration and significant runout shortening of avalanches (Eq. 6.6). When modeling avalanche flow in forested terrain, we assume that potential snow entrainment (mass uptake) is negligible for small- to medium-scale avalanches that started in forests. In fact, we hypothesize that snow detrainment, i.e. mass removal by trees, remnant stumps or dead wood, is predominant in forests and, thus, the mass production source term (see Eq. 6.1) corresponds to \( \dot{Q} \leq 0 \) (as the sum of the volumetric entrainment rate \( \dot{Q}_e = 0 \) and the volumetric detrainment rate \( \dot{Q}_d < 0 \)). This assumption is based on observations where trees in the path of small- to medium-scale avalanches did not break and, therefore, act like obstacles and “detrain” respectively extract avalanche mass (Faug et al., 2004). The extracted mass stops promptly and, thus, is instantly subtracted from the flow (Eq. 6.1) and the momentum of
the stopped mass is removed from the total momentum of the avalanche flow (Eqs. 6.2 and 6.3). The stopping process is immediate and can be associated with infinite friction. To account for the effect of differing forest conditions on avalanche flow, this relationship is now parameterized with the forest detrainment coefficient \( K \) [Pa] according to

\[
\dot{M}_d = -\frac{K}{\| \dot{U} \|} \quad \text{where } \dot{M}_d = \rho \cdot \dot{Q}_d
\]

(6.6)

with \( \dot{M}_d \) as the mass lost by the avalanche in front of tree-stands. The density of the avalanche snow is denoted with \( \rho \).

This relationship indicates that the higher the velocity the less snow is removed from the flow. Parameter \( K \) accounts for the braking power of different forest types per square meter and, therefore, depends on forest characteristics such as stand density or mean stem diameter (Fig. 6.1).

6.3 Materials and methods

6.3.1 Avalanche data

Our evaluation and operationalization of the forest detrainment function were based on 40 small- to medium-scale avalanches released in forests with runout distances ranging between 50 and 700 m. Within this dataset, 38 wet and dry snow avalanches were observed during the winters 1986-1990 in the Swiss Alps (avalanches #1 to #38; Table 6.F1). For these avalanches, the starting points were specified as \( x, y \) coordinates and runout distances were recorded from the starting point in 5 m steps as the horizontal projection. Detailed data on avalanche characteristics and forest parameters in the avalanche starting zone were collected in the field close to the events (Schneebeli and Meyer-Grass, 1993). Since adequately detailed maps of release areas existed only for 26 of these avalanches, we reconstructed the release areas of the remaining 12 avalanches based on given avalanche starting points, maximum release widths, field notes and photos taken shortly after the avalanche events combined with digital elevation model (DEM) and orthophotograph analyses (Vassella, 2012). In addition, two avalanches (#39 and #40; Table 6.F1) which released in forests near Davos, Switzerland in the winter 2011/12 were mapped using a hand-held differential GPS device (for details see Feistl et al., 2014, see Chapter 5). Forest structural parameters (Table 6.1), terrain variables and avalanche characteristics such as the type of snow (dry or wet snow avalanche) or the distance an avalanche ran through forest were assigned to all 40 avalanche events based on
collected field data, orthophotographs and DEM analyses (Table 6.F1). Avalanche release volumes ($V_r$) were calculated corresponding to mapped and reconstructed release areas and given release heights mainly measured in the field or estimated based on measurements of nearby snow and weather stations.

We chose forest and terrain variables due to pretests of potentially relevant variables and their compatibility with existing assessment methods. Forests were classified in three types dependent on the main tree species: “beech forests” containing beech as well as mixed beech-spruce forests with the main tree species European beech (*Fagus sylvatica* L.), “spruce forests”, i.e. evergreen coniferous forests dominated by Norway spruce (*Picea abies* (L.) H. Karst.), and “larch forests” as deciduous coniferous forests formed by European larch (*Larix decidua* Mill.) at the upper treeline. Forest density was characterized by the variable crown closure describing the intensity of the crown coverage in three aggregated classes (see Table 6.1). The crown coverage was delineated and digitized in GIS by orthophotographs analyses based on the classification system of Bebi et al. (2001). The stage of development indicates the mean stem diameter distribution as well as the age of the forest which are also represented somewhat by the vertical structure (Tables 6.1 and 6.F2). The terrain variables overall mean slope angle, the cross-slope curvature and terrain roughness were determined from a high-resolution DEM, which was gained from airborne lidar (light detection and ranging) data with a spatial resolution of 2 m and a vertical accuracy of approximately 0.5 m. Cross-slope curvature was defined by the relative position of a cell to its surrounding pixels in a 3 pixel x 3 pixel moving-window. The mean value of the curvature raster was taken for the avalanche track to assign the corresponding category “gully” or concave slope, and “flat” terrain, i.e. almost no curvature. Terrain roughness was expressed as the standard deviation of the terrain height undulations (differences in elevation) within a 3 pixel x 3 pixel moving-window with corresponding categories “low” and “high”. For a detailed methodological description we refer to Teich et al. (2012a, see Chapter 4). In addition to the terrain roughness gained from the DEM, the small-scale surface roughness was also assigned to each avalanche. This variable was mapped in the field and describes the nature of the surface cover. Categories are “smooth”, “knobby”, “scree” and “stumps/shrubs/saplings” (Table 6.1).
Table 6.1. Forest parameters and corresponding categories assigned to each avalanche.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Description and categories</th>
</tr>
</thead>
</table>
| Forest type               | (1) “Beech forests” contain deciduous and coniferous forests, but mostly dominated by European beech (*Fagus sylvatica* L.)  
|                           | (2) Norway spruce (*Picea abies* (L.) H. Karst.) dominated “spruce forests”          
|                           | (3) “Larch forests” formed by European larch (*Larix decidua* Mill.) at the upper tree line |
| Crown closure             | (1) Dense to loose (Crown coverage >70%)                                                   
|                           | (2) Scattered (Crown coverage 40-70%)                                                     
|                           | (3) Open (Crown coverage <40%)                                                           |
| Vertical structure        | (1) One layer                                                                             
|                           | (2) Two layers                                                                            
|                           | (3) >Two layers                                                                           
|                           | (4) Clumped or grouped                                                                     |
| Stage of development      | (1) Pole stage forest and young timber trees (8 < DBH ≤ 40 cm)                             
|                           | (2) Middle-aged timber trees and old timber trees DBH > 40 cm                             
|                           | (3) Mixed                                                                                 |
| Surface roughness         | (1) Smooth                                                                                
|                           | (2) Knobby                                                                               
|                           | (3) Scree                                                                                 
|                           | (4) Stumps/shrubs/saplings                                                              |

*Mean diameter at breast height: Outside bark diameter measured 1.37 m above the forest floor on the uphill side of the tree.

6.3.2 Simulation software and set-up

The forest detrainment function (Eq. 6.6) was implemented in the current version of the avalanche simulation software RAMMS (RApid Mass Movement System). Based on a two-dimensional depth-averaged flow model (Eqs. 6.1-6.4), RAMMS calculates the development of avalanche flow depth $H(x,y,t)$ and depth-averaged avalanche velocities $U(x,y,t)$ as a function of time $t$ (see Section 6.2.1); the system of partial differential equations is solved numerically using first and second order finite volume techniques (Christen et al., 2010a). The depth-averaged field variables $H$ and $U$ are used to predict avalanche runout distances or impact pressures in complex three-dimensional terrain. Three spatially explicit quantities are required to perform the numerical calculation: (1) a DEM, (2) release areas ($A_r$), and (3) model friction parameters ($\mu$ and $\xi$, Eq. 6.5). In addition, to run RAMMS including the forest detrainment function, forested areas ($A_f$) have to be defined in the model domain and assigned a $K$-value theoretically corresponding to specific forest characteristics such as forest density, age or undergrowth.
We determined forested areas based on existing forest maps and orthophotograph analyses. In order to focus the evaluation and operationalization on the detrainment function only, snow density was set to $\rho = 300$ kg m$^{-3}$ and we kept the friction parameters constant at $\mu = 0.29$ m s$^{-2}$ and $\xi = 1500$ m s$^{-2}$ throughout this study. We chose this combination since the estimated release volumes of our avalanche dataset range between 19 and 3398 m$^{3}$ which corresponds to the avalanche size class “tiny” (<5000 m$^{3}$), and is applied in practice to simulate frequent avalanches (10 yr return period), in unchanneled terrain above 1500 m asl (Buser and Frutiger, 1980; Salm et al., 1990). The simulations are based on a DEM with a spatial resolution of 2 m and a vertical accuracy of approximately 0.5 m. The mapped release areas and measured release heights were used to specify the initial conditions for each simulation run. All simulations were accomplished without any pre-defined stopping criteria.

For each observed avalanche a reference simulation was computed by running RAMMS without accounting for any forest influence in the avalanche path ($K = 0$). In order to find optimal values for $K$ dependent on different forest characteristics, we then simulated each observed avalanche with varying values for $K$ of 5, 10, 20, 30, 40, 60, 80, 100, 130, 160, 190 and 220 Pa. These $K$-values were chosen based on results of a computational experiment performed by Feistl et al. (2014, see Chapter 5).

The main simulation results are maximums over time $t$ of the flow depth $H(x,y,t)$ and the two dimensional slope parallel velocities $U(x,y,t)$ at a constant density $\rho$. As usually applied in hazard assessment (Eckert et al., 2010), the according peak pressure field can then be derived as

$$P(x,y) = \rho U_{\text{peak}}^2(x,y)$$  \hspace{1cm} (6.7)

where $x,y$ denote the two dimensional Cartesian coordinates. Here $U_{\text{peak}}$ corresponds to its maximum $U$ value over the entire simulation time $t$:

$$U_{\text{peak}}(x,y) = \max_{t} U(x,y,t)$$  \hspace{1cm} (6.8)

For our analyses, we exported the spatially explicit maximum pressure output.

### 6.3.3 Analyzing simulation results

To compare the two-dimensional model output with the one-dimensionally recorded avalanche runout distances, we applied the analysis method AIMEC (Automated Indicator based Model Evaluation and Comparison) presented by Fischer (2013).
The AIMEC-approach allows for a standardized and objective evaluation of two-dimensional simulation results. The simulation results are transformed from Cartesian coordinates \((x, y)\) to a coordinate system dependent on the specific avalanche path \((s, l)\) (Fig. 6.2), here applied for the peak pressure:

\[
P(x, y) \rightarrow \tilde{P}(s, l)
\]  

(6.9)

As a scalar metric, the runout indicator is defined based on the peak pressure (Eq. 6.7), and evaluated for each simulation run. This runout indicator corresponds to the horizontal projection of length measured along the avalanche path coordinate \(s\) where the cross sectional maximum peak pressure value:

\[
\tilde{P}_{\text{max}}^{\text{cross}}(s) = \max_{\tau} \tilde{P}(s, l)
\]  

(6.10)

falls below a certain pressure limit \(\tilde{P}_{\text{max}}^{\text{cross}}(s) < P_{\text{limit}}\) (Fig. 6.2).

The choice of the pressure threshold \((P_{\text{limit}})\) is of great importance for reliable runout indicators and further analyses. Since we ran the simulations without any pre-defined stopping criteria such as for the flow momentum or flow depth, no realistic stopping may be modeled in flat natural terrain. Defining runout distance based on thresholds for the maximum flow momentum or the minimum flow depth on the contrary could also lead to a misinterpretation of simulation results, especially for small-scale avalanches, which would influence further analyses considerably. These problems were avoided by applying a pressure based runout indicator to determine simulated runout distances (Fischer, 2013).

We ran AIMEC with pressure thresholds \(P_{\text{limit}}\) of 1, 3, 5 and 10 kPa as well as 0.5 kPa for very small avalanches with release volumes \(V_r < 100 \text{ m}^3\); however, differences between corresponding runout indicators were low. In particular, for very small avalanches \((V_r < 100 \text{ m}^3)\) the differences between runout indicators determined with \(P_{\text{limit}} = 3 \text{ kPa}\) and \(P_{\text{limit}} = 1 \text{ kPa}\) for the reference simulations with \(K = 0\) ranged between 1 and 66% (mean = 22%). When calculating the difference between both runout indicators for all avalanches of our data set, the mean difference was rather low with only 14% (ranges between 0 and 67%). For simulations performed with the forest detrainment \((K > 0)\), mean differences between the two runout indicators \((P_{\text{limit}} = 3 \text{ kPa} \text{ and } P_{\text{limit}} = 1 \text{ kPa})\) decreased for very small avalanches \((V_r < 100 \text{ m}^3)\) to 2% and for all avalanches to 7%. Due to such small differences, we applied a pressure threshold of \(P_{\text{limit}} = 3 \text{ kPa}\) throughout this study which corresponds to a pressure threshold used for hazard zone mapping in Switzerland (BFF/SLF,
1984). That is, for avalanches with return periods \( \leq 30 \text{ yr} \) an impact pressure \( >3 \text{ kPa} \) is assigned to have consequences regarding land-use planning (Jóhannesson et al., 2009).

![Schematic avalanche simulation result](image)

**Fig. 6.2.** Schematic avalanche simulation result (see Fig. 6.1; red areas correspond to forests with specific forest characteristics, e.g. tree density illustrated by green dots), e.g. the outline of the peak pressure field with a new coordinate system along the central flow line \( z(x,y) \) in bold.

In order to measure the differences of simulated runout indicators \( \text{runout}_{\text{sim}} \) to observed runout distances \( \text{runout}_{\text{obs}} \), the relative runout difference (\( \Delta \text{runout} \) in \%) is introduced

\[
\Delta \text{runout} = \left( \frac{\text{runout}_{\text{sim}} - \text{runout}_{\text{obs}}}{\text{runout}_{\text{obs}}} \right) \cdot 100
\]

where positive values indicate overestimated runout distances respectively negative values for \( \Delta \text{runout} \) reveal that runout distances were underestimated by the avalanche simulation software compared to the recorded ones.

### 6.3.4 Statistical analysis

For an evaluation of general dependencies between variables describing forest structure, topography and avalanche characteristics, and the response variable \( \Delta \text{runout} \), we calculated Spearman’s rank correlation coefficient \( (r_s) \) for categorical and continuous predictor variables.
since it is known as non-parametric and does not assume a linear relationship. In addition, Pearson’s correlation coefficient ($r$) was calculated for all continuous variables and $\Delta \text{runout}$ to reveal potential linear dependencies and to measure their strengths. A correlation was assumed to be statistically significant if the respective $p$-value was $0.01 < p \leq 0.05$ and highly significant for $p \leq 0.01$.

The evaluation and operationalization of the avalanche model included four steps:

1) We tested all variables against $\Delta \text{runout}$ (further referred to as $\Delta \text{runout}_{\text{ref}}$) for the reference simulations without any influence of forest ($K = 0$).

2) Based on the simulations including the mass extracting effect of forests parameterized with the detrainment coefficient $K$, we determined an optimal $K$-value for each avalanche event ($K_{\text{opt}}$). That is, one value for $K$ was defined for each of the 40 avalanche events which resembled the observed runout distances “best”, i.e. where $K$ approaches zero of $\Delta \text{runout}$, on condition that $\Delta \text{runout} \geq 0$. A conservative evaluation of simulation results leading to overestimated rather than to underestimated runout distances is preferred to reveal optimal $K$-values which are applicable in practice.

3) We again calculated $r_S$ and $r$ respectively, and tested the forest parameters forest type, crown closure, vertical structure, stage of development and surface roughness as well as the release volume and the distance an avalanche ran through forest against the response variable $K_{\text{opt}}$.

4) We defined $K$-values based on specific forest characteristics and their combined effects to be applicable in practice for reliable avalanche simulation in forested terrain.

We evaluated our derived $K$-values by simulating two avalanche events additionally observed in 2012 in forested terrain in the Swiss and Bavarian Alps. These avalanches differed in forest conditions and the distance they ran through forest as well as in the snow type. To further test the practical applicability of the derived $K$-values we ran RAMMS using a default simulation set-up and compared simulation results manually.
6.4 Results

6.4.1 Avalanche simulation with $K = 0$

Runout distances were overestimated by RAMMS for 38 of 40 investigated avalanches in forested terrain when forests’ influence was not considered. The relative runout difference $\Delta \text{runout}$ (Eq. 6.11), further referred to as $\Delta \text{runout}_{ref}$, revealed overestimations by RAMMS up to 700%. The two avalanches with negative values for $\Delta \text{runout}_{ref}$ (-34 and -48%) are of very small release volumes ($V_r < 50 \text{ m}^3$).

Variables which affected $\Delta \text{runout}_{ref}$ of our dataset significantly are the release height, the snow type, the absolute as well as the relative distance an avalanche ran through forest, and the small-scale surface roughness (Table 6.2). Dependencies between the continuous variables release height, and absolute and relative distance through forest are not linear since no significant correlations were found when calculating Pearson’s correlation coefficient ($r$). However, it could be assumed that increasing release heights, accompanied with increasing release volumes (see Table 6.F2), are related to an increase in $\Delta \text{runout}_{ref}$. That is, the bigger an avalanche, the larger the difference between observed and simulated runout distances. Both correlations imply, that a loss of avalanche volume modeled for forested areas may lead to a significant runout shortening and a more realistic avalanche simulation which would match the observations.

Differences between observations and simulations were significantly higher for dry snow avalanches compared to wet snow avalanches (Fig. 6.3). Thus, one can assume that the accompanying snow densities and thermal snow temperatures also determine the detraining effect of forests. Here, snow density was kept constant at $\rho = 300 \text{ kg m}^{-3}$ which is often applied for dry snow avalanches. The snow type was also correlated with release volume and release height (Table 6.F2) where the latter one also influenced $\Delta \text{runout}_{ref}$ significantly (Table 6.2). The nature of the surface cover, i.e. surface roughness, was correlated significantly with $\Delta \text{runout}_{ref}$. That is, a scree slope and higher small obstacles such as stumps and shrubs in the avalanche path were related to larger differences between observed and simulated runout distances and, therefore, also determine the amount of snow deposited in the avalanche track.
Table 6.2. Highly significant** ($p \leq 0.01$) and significant* ($0.01 < p \leq 0.05$) Spearman rank correlation coefficients ($r_S$) between predictor variables and $\Delta \text{runout}_{ref}$ calculated for the reference simulation runs with $K = 0$, and between predictor variables and the assigned optimal value for $K (K_{opt})$.

<table>
<thead>
<tr>
<th>Predictor variable</th>
<th>$\Delta \text{runout}_{ref} (K = 0)$</th>
<th>$K_{opt}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forest type</td>
<td>-</td>
<td>0.39 ($p = 0.014^*$)</td>
</tr>
<tr>
<td>Surface roughness</td>
<td>0.41 ($p = 0.011^*$)</td>
<td>-</td>
</tr>
<tr>
<td>Snow type</td>
<td>-0.37 ($p = 0.019^*$)</td>
<td>-</td>
</tr>
<tr>
<td>Release volume</td>
<td>-</td>
<td>0.58 ($p &lt; 0.001^{**}$)</td>
</tr>
<tr>
<td>Release height</td>
<td>0.36 ($p = 0.025^*$)</td>
<td>-</td>
</tr>
<tr>
<td>Absolute distance through forest</td>
<td>-0.53 ($p = 0.001^{**}$)</td>
<td>-0.51 ($p = 0.001^{**}$)</td>
</tr>
<tr>
<td>Relative distance through forest</td>
<td>0.34 ($p = 0.039^*$)</td>
<td>-</td>
</tr>
</tbody>
</table>

Besides surface roughness, distributions of $\Delta \text{runout}_{ref}$ suggest influences of other forest parameters on avalanche simulations (Fig. 6.3). In particular, runout indicators for avalanches that started in spruce forests were highly overestimated (median = 88%, mean = 154%), but less overestimated for avalanches which ran through beech forests (median = 52%, mean = 79%) or larch forests (median = 44%, mean = 49%). For simulations without any forest influence, $\Delta \text{runout}_{ref}$ was largest for avalanches which ran through evergreen, dense forests with a more than two-layered vertical structure, containing different age classes and varying stem diameters.

Mean slope angle, cross-slope curvature and terrain roughness in terms of local differences in elevation (in contrast to surface roughness describing the nature of the surface cover) did not influence $\Delta \text{runout}_{ref}$ significantly. This strengthens the theory that avalanche-forest interactions need to be implemented by a function dependent on forest characteristics in combination with snow conditions only.
Fig. 6.3. Difference between simulated and observed runout distances (Δrunout_{ref}) calculated for the reference simulation runs without any forests influence (K = 0) shown for the subsets of variables snow type and small-scale surface roughness which are statistically significant (first row) and for the subsets of four other forest structural parameters (no statistically significant relationships). Boxplots show minimum values, the lower quantile (Q 0.25), the median (Q 0.5), the upper quantile (Q 0.75) and maximum values of Δrunout_{ref}. Points are relative positions of extreme values.

6.4.2 Avalanche simulation with varying K-values

For the next step of our evaluation and further operationalization, we calculated Δrunout for each simulation run with varying values for K and analyzed relationships between forest characteristics and Δrunout. In general, increasing K-values corresponded to decreasing runout indicators where the strength of this effect seemed to decrease around K-values of 150 Pa and higher (Figs. 6.4 and 6.5). Very small avalanches with release volume V_r < 100 m^3 showed diverging simulation results. For such avalanches, values of Δrunout were often negative when applying the forest detrainment function; one avalanche simulation did not even start with the smallest chosen K-value of 5 Pa. However, differences between avalanche
simulations in terrain covered with different forest types are visible, especially between larch forests and the two other forest types, spruce and beech forests, when calculating mean values of Δrunout corresponding to each chosen K-value for the three categories separately (Fig. 6.4). In addition, differences in the vertical structure of a forest stand as well as in crown closure had a higher influence on the amount of snow extracted from the avalanche flow compared to a differing stage of development (Fig. 6.5). The latter forest variable is however relatively well represented by the vertical structure (Table 6.F2). The nature of the surface cover also influenced the amount of snow removed from the avalanche flow. The effect of differences in small-scale surface roughness could have been even underestimated since our simulation set-up allowed not to account for changes in surface roughness in unforested areas.

In terms of the operationalization, optimal values for \( K (K_{\text{opt}}) \) were assigned to each observed avalanche based on the election rule that Δrunout approaches zero on condition Δrunout \( \geq 0 \). A significant correlation was found between \( K_{\text{opt}} \) and the forest type (Fig. 6.6) as well as for the release volume and the absolute distance an avalanche ran through forest (Table 6.2); the latter two were even linear with \( r = 0.35 \) and \( p = 0.028^* \) for release volume respectively \( r = -0.44 \) and \( p = 0.005^{**} \) for the distance through forest. Thus, the larger the release volume the higher is \( K_{\text{opt}} \), respectively the longer the distance an avalanche runs through forest the lower the corresponding \( K_{\text{opt}} \). According to theory \( K \) however should only account for forest characteristics.

Thus, we propose to choose a “best” value of \( K \) to simulate avalanche runout in forested terrain dependent on the four forest characteristics forest type, crown closure, vertical structure and surface roughness. Based on Figures 6.5 and 6.6, possible values for \( K \) can be obtained to predict avalanche runout distances in forested terrain. According to this, \( K \)-values of 5 Pa may be assigned to areas covered with larch forests, 80 Pa to forests dominated by spruce and 100 Pa to beech and mixed beech-spruce forests. These values should be adapted with \( K \)-values corresponding to classes of the forest characteristics crown closure, vertical structure and surface roughness (see Fig. 6.5), e.g. the mean value of the respective \( K \)-values for these four forest characteristics were calculated for our case studies (see Section 6.4.3). The influence of \( K \)-values higher than approximately 150 Pa on Δrunout decreases (Fig. 6.5). Therefore, \( K \)-values \( >150 \) Pa seem to be not meaningful for modeling avalanche-forest interactions.
Fig. 6.4. Mean values of Δrunout for each applied $K$-value calculated separately for the three forest type categories. The dashed line corresponds to $Δrunout = 0$ indicating the potential mean optimal $K$-value for each category.

Fig. 6.5. Mean values of Δrunout for each applied $K$-value calculated separately for the corresponding categories of four forest variables. The dashed line corresponds to $Δrunout = 0$ indicating the potential mean optimal $K$-value for each category of the respective forest variable.
Fig. 6.6. Optimal $K$-values ($K_{\text{opt}}$) assigned to each observed avalanche based on simulations with varying values of $K$ shown for subsets of different forest types. Boxplots show minimum values, the lower quantile (Q 0.25), the median (Q 0.5), the upper quantile (Q 0.75) and maximum values of $K_{\text{opt}}$. Points are relative positions of extreme values.

6.4.3 Case studies

In order to test the practical application of our results, we simulated two additionally observed avalanches with RAMMS including the forest detrainment function (Table 6.3). Therefore, we assigned a “best” $K$-value to forested areas based on the four forest parameters forest type, crown closure, vertical structure and surface roughness, and the corresponding categories (see Table 6.1).

Table 6.3. Characteristics and $K$-values corresponding to selected forest parameters of two avalanches which were not included in previous analyses to verify the results of the operationalization.

<table>
<thead>
<tr>
<th>Location (Country)</th>
<th>Dischma valley (CH)</th>
<th>$K$ [Pa]</th>
<th>Brecherspitz (GER)</th>
<th>$K$ [Pa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Snow type</td>
<td>wet</td>
<td></td>
<td>dry</td>
<td></td>
</tr>
<tr>
<td>Release volume (m$^3$)</td>
<td>5043</td>
<td></td>
<td>1324</td>
<td></td>
</tr>
<tr>
<td>Forest parameters</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Forest type</td>
<td>mainly larch</td>
<td>5</td>
<td>beech</td>
<td>100</td>
</tr>
<tr>
<td>Crown closure</td>
<td>mainly open</td>
<td>50</td>
<td>scattered to dense</td>
<td>125</td>
</tr>
<tr>
<td>Vertical structure</td>
<td>one layer</td>
<td>75</td>
<td>one to two layers</td>
<td>75</td>
</tr>
<tr>
<td>Surface roughness</td>
<td>knobby</td>
<td>75</td>
<td>smooth</td>
<td>25</td>
</tr>
<tr>
<td>Assigned $K$-value</td>
<td>50</td>
<td></td>
<td></td>
<td>80</td>
</tr>
</tbody>
</table>
Values of $K$ were estimated based on Figures 6.4-6.6. For forest type, crown closure, vertical structure and surface roughness $K$-values close to $\Delta \text{runout} = 0$ were chosen and, then, the mean value of $K$ was calculated (Table 6.3). We ran RAMMS with a default simulation setup, i.e. values for friction parameters $\mu$ and $\zeta$ were not kept constant but defined by an automatic procedure of RAMMS depending on terrain features such as gullies or flat slopes, elevation, the return period (set to 10 yr) and the avalanche size class (“tiny”). The simulations were based on a 2 m grid for the avalanche observed in Switzerland respectively a 1 m grid for the one from Germany. Forested areas and forest characteristics were delineated based on pixel maps, orthophotographs, and photographs taken during field visits. Again, we ran the simulations until the final pressure patterns were reached. In practice a stopping criteria of 5% of the total momentum is often applied indicating that if the sum of all momenta of all grid cells is lower than 5% of the maximum momentum sum, the simulation is stopped (Christen et al., 2010a). However, test-simulation runs applying this threshold have shown that runout distances of our case studies and, therefore, such small-scale avalanches, were highly underestimated. In contrast, we ran our simulations without any stopping criteria and analyzed the simulation results by only displaying the grid-cells of the runout area which exceeded a pressure threshold of 3 kPa. This corresponds to our limit for the maximum peak pressure ($P_{\text{limit}}$) when defining runout distances by applying AIMEC (see Section 6.3.3) as well as to the impact pressure threshold with consequences for hazard zone mapping in Switzerland (BFF/SLF, 1984; Jóhannesson et al., 2009).

The simulation results showed a good agreement with the observed runout when applying the novel forest detrainment function with values for the detrainment coefficient $K$ dependent on four forest characteristics (Fig. 6.7). Even if the runout area did not match the observed ones exactly, runout distances were predicted relatively well by the model for both avalanche events; simulated runout distances stopped within -6 to 3 m compared to the observed ones.
Fig. 6.7. Simulation results gained with RAMMS including the forest detrainment function by applying the “best” value for the detrainment coefficient $K$ for forested areas in comparison to the observed runout distances of the two case studies “Dischma valley” (left) and “Brecherspitz” (right).

6.5 Discussion

In this study, we applied a novel detrainment modeling approach (Feistl et al., 2012, 2014, see Chapter 5) to account for avalanche-forest interactions within computational avalanche simulation. The aim was to evaluate and improve the forest detrainment function (Eq. 6.6) and, therefore, to quantify the detrainment coefficient $K$ which controls the amount of snow caught behind trees in the avalanche path.

In general, immediate stopping and removal of a certain amount of mass by trees has a greater influence on small- to medium-scale avalanches than on larger avalanches (Feistl et al., 2014, see Chapter 5). Large-scale avalanches are able to break and uproot trees linked to a low energy consumption which increases avalanche mass and, therefore, flow energy (Bartelt and Stöckli, 2001). When applying a Voellmy-type relation which is often employed by avalanche flow models, the effect of forests on such avalanches can be modeled by increasing friction compared to unfores ted terrain (Bartelt and Stöckli, 2001). This is not valid for modeling small-scale avalanches in forested terrain: Previous simulations of our dataset with RAMMS with alternating $\xi$-values for forested areas (100-1000 m s$^{-2}$) showed that runout distances of 31 out of the 40 avalanches were still overestimated when applying the smallest chosen $\xi$-value of 100 m s$^{-2}$ (Teich et al., 2012c, see Appendix B). Moreover, simulating small-scale avalanches with a model based on frictional relationships only is generally questionable.
(Sailer et al., 2008) and, therefore, including physical processes within the avalanche flow such as snow entrainment (mass uptake) and detrainment (mass extraction) is important (Bovet et al., in prep.). For example, mass extraction by forests as realized in this study leads to a significant deceleration and runout shortening of small- to medium-scale avalanches (see also Feistl et al., 2014, see Chapter 5).

The results gained from analyzing reference simulations accomplished without any forests’ influence ($K = 0$) highlight the importance of modeling local braking effects of forests on avalanche flow. Significant correlations between the predictor variables release height and the distance an avalanche ran through forest with the response variable $\Delta \text{runout}_{\text{ref}}$ suggest that a loss of avalanche volume modeled for forested areas will lead to shorter runout distances. In addition, local surface roughness due to stumps and shrubs or scree slopes also affected $\Delta \text{runout}_{\text{ref}}$ significantly. This effect should also be considered for small- to medium-scale avalanches’ simulation in unforested areas such as large forest openings caused by natural disturbances which are often interspersed with shrubs, fallen logs, remnant stumps and root plates of upturned trees (Fig. 6.8). Remained dead wood is able to increase the surface roughness at least over the first 10-20 yr after the die-back (Brown et al., 1998; Rammig et al., 2007). Indeed, the effective heights and interacting avalanche flow depths also determine the mass deposited behind obstacles (Faug et al., 2004; Naaim et al., 2004). Based on sporadic field samples we can assume effective heights of approximately 0-30 cm for “smooth” slopes, 30-50 cm for “knobby” terrain, and 30-150 cm for “scree” slopes as well as for terrain interspersed with stumps, shrubs and/or saplings. The significant correlation between the snow type and $\Delta \text{runout}_{\text{ref}}$ indicates that the effectiveness of the mass removal by forests is also determined by snow densities as well as thermal snow temperatures, e.g. as more wet and viscous the snow as slower the avalanche (Vera Valero et al., 2012).
In the next step, we simulated each avalanche with varying $K$-values (between 5 and 220 Pa) and assigned an optimal value for $K$ ($K_{\text{opt}}$) to each avalanche event. In general, runout distances decreased with increasing $K$-values while this effect decreased around $K = 150$ Pa. However, some of the 40 observed avalanches were still overestimated by RAMMS when simulating with the highest chosen $K$-value of 220 Pa. On the one hand, partially misinterpreting the orthophotographs and DEMs when reconstructing 12 release areas could have affected the simulation results (Vassella, 2012). On the other hand, other processes such as the influence of thermal snow temperature on the avalanche flow (see above) and the effect of different topographic features, usually modeled by varying friction parameters $\mu$ and $\zeta$, could have also influenced the simulations. In order to reduce uncertainties related to the avalanche modeling process and to account for effects of varying $K$-values on the simulations only, we used constant values for $\mu$ and $\zeta$ throughout this study (see Section 6.3.2). Although not all avalanches of our dataset ran through unchanneled terrain, constant values for $\mu$ and $\zeta$ were valid in our study since friction parameters are mainly relevant for larger avalanches (Gruber and Bartelt, 2007; Christen et al., 2010b). Alternatively, a physically based implementation of curvature effects may lead to an improved representation of topographical conditions (Fischer et al., 2012).

The statistical analyses between predictor variables and the response variable $K_{\text{opt}}$ revealed that the forest type in which an avalanche released and ran through had an influence on $\Delta$runout. Thus, the forest type mainly determines the $K$-value to be chosen for avalanche simulation in forested terrain in combination with crown closure, vertical structure, and surface roughness since:

**Fig 6.8.** Snow detrained by a stump highlighting the significant effect of surface roughness on small-scale avalanches which should be considered in avalanche simulations.
clear differences of mean Δrunout between the categories of these forest parameters are visible (Fig. 6.5),

these variables can be largely derived from remote sensing-based data (orthophotographs, lidar-data) possibly combined with sporadic field samples, but no extensive measurements are required,

other studies on the effect of forest structural parameters on observed runout distances emphasize the relevance of these forest characteristics (e.g. McClung, 2003; Teich et al., 2012a, see Chapter 4).

The case studies performed by simulating two additional avalanches verified this argumentation (Table 6.3 and Fig. 6.7): the good agreement of the simulated and observed runout distances when applying $K$-values based on the four suggested forest characteristics encourages the applicability of the forest detrainment function for hazard analyses and, therefore, for a practical natural hazard and protection forest management.

For these two avalanches we applied a default simulation set-up and analyzed the simulation results manually, but based on an avalanche pressure threshold of >3 kPa used for hazard mapping in Switzerland (BFF/SLF, 1984). Impact or peak pressure results are in general of high interest in snow avalanche modeling to estimate the avalanches’ destructive potential, and are utilized for hazard zoning and engineering affecting land-use planning in many countries (Jóhannesson et al., 2009).

We also chose the threshold of $P_{\text{limit}} = 3$ kPa when analyzing our simulation results automatically by applying AIMEC (Fischer, 2013). That is, a pressure based runout indicator was used to determine simulated runout distances. In the case of very small avalanches, the pressure threshold $P_{\text{limit}}$ has to be defined carefully since predefined pressure limits could be too high, i.e. never be exceeded. Defining too low pressure limits could however lead to a misinterpretation of the simulation results, e.g. when accounting for runout which is attributed to non-realistic stopping in flat natural terrain due to a diffusive runout behavior arising from the flow model (Fischer, 2013). The $P_{\text{limit}} = 3$ kPa yielded reliable runout indicators and differed not considerably from runout indicators determined with lower values. In contrast, a $P_{\text{limit}} > 3$ kPa is not appropriate to determine runout indicators of small-scale avalanches since tested values of 5 and 10 kPa were not exceeded for many simulated avalanches of our dataset. However, a verification of the results received with AIMEC is still necessary since
numerical solutions can include singularities, especially when simulating small-scale avalanches.

In this study, we could only compare observed and simulated avalanche runout distances. Reliable observations as well as measurements and experiments on the effect of forests on the avalanche flow which also contain more avalanche characteristics such as avalanche velocity and avalanche mass balance are rare. In addition, more well-documented avalanches in forested terrain have to be analyzed in the way we did to establish better grounded results on the role of forest type, crown closure, vertical structure and surface roughness in avalanche simulation to further improve the new forest detrainment function, in particular in forested areas with varying decelerating effects. The presented findings are however a valuable first step to simulate small- to medium-scale avalanches in forested terrain to be applicable in hazard analyses.

6.6 Conclusions and outlook

The applied forest detrainment function, which can be implemented in numerical avalanche dynamics models, will improve the simulation of small- to medium-scale avalanches in forested terrain considerably. A value for the detrainment coefficient $K$ can now be defined dependent on the four forest parameters forest type, crown closure, vertical structure and surface roughness. As the suggested forest characteristics can be largely derived from remote sensing-based data (orthophotographs, lidar-data), there is a high potential for practical implementations. In addition, we demonstrated that applying a standardized method to analyze a high number of two-dimensional avalanche simulation results automatically increases the reliability of an objective software evaluation; the employed method AIMEC provided accurate runout indicators as the basis for further analyses.

Implementing avalanche-forest interactions in avalanche simulation will facilitate current applications for such software, e.g. by better accounting for the protective effects of forests in natural hazard mapping (Berger and Rey, 2004; Gruber and Bartelt, 2007), for managing mountain forests efficiently (Weir, 2002; Brang et al., 2006; Teich and Bebi, 2009, see Chapter 3) or to value “avalanche protection by forests” as a key ecosystem service in mountainous regions (Grêt-Regamey et al., 2013). The forest detrainment function will be implemented in the next version of RAMMS and tested by practitioners based on the findings gained in this study.
Acknowledgements

We thank Irene Vassella for the careful data collection and Perry Bartelt for valuable discussions on the manuscript. This study was funded by the CCES (Competence Center Environment and Sustainability of the ETH Domain) within the project MOUNTLAND and partly financed by the Bavarian Environment Agency.
Chapter 7

Paper V

Snow and weather conditions associated with avalanche releases in forests: Rare situations with decreasing trends during the last 41 years

Received 1 March 2012
Accepted 12 June 2012

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Abstract

Mountain forests play a crucial role in avalanche control by modifying the snow's mechanical properties. However, snow avalanches do occur in forests due to unfavorable combinations of site, snow and weather conditions and these so-called ‘forest avalanches’ can pose hazard to human settlements and infrastructure. While the meteorological contributory factors of avalanche releases in open unforested terrain are relatively well understood, much less is known about snow and weather conditions associated with avalanche releases in forests. In order to identify such critical meteorological situations, we analyzed 21 snow and weather variables of 189 naturally released forest avalanches. By applying a hierarchical clustering method, we distinguished two forest avalanche types: (1) ‘new snow forest avalanches’ which release in periods of heavy snowfall and under stormy and permanently cold conditions and (2) ‘old snow forest avalanches’ which release after periods of high insolation and an increase in air temperature. Snow and weather conditions of new snow forest avalanches are rare and clearly distinguishable by classification trees from those of avalanches released in open unforested terrain at similar elevations. We tested for long-term trends in the occurrence of favorable meteorological conditions for forest avalanches during 41 winters (1970/71–2010/11) applying a logistic regression model. The number of potential forest avalanche days decreased at 11 of 14 snow and weather stations in the Swiss Alps for new snow forest avalanches and at 12 of 14 stations for old snow forest avalanches, independent from elevation and climatic region. These negative trends suggest a further decrease of snow and weather conditions associated with avalanche releases in forests under current climate change and, in combination with the currently observed increase in forest cover density in the Swiss Alps, it is thus likely that avalanche releases in forested terrain will become less frequent. However, such events will also occur in the future and the presented characterization of meteorological conditions could support avalanche warning and forest services in forecasting forest avalanches.

Keywords: Forest avalanches, Snow and weather conditions, Cluster analysis, Classification tree, Logistic trend analysis, Forecasting
7.1 Introduction

Snow avalanche formation is a complex interaction between terrain, snowpack and meteorological conditions (Schweizer et al., 2003). Statistical approaches can be applied to explore these relationships and are used by most avalanche-forecasting services. A forecast is made by empirically weighting the influence of the contributory factors in a specific situation and, thus, estimating the avalanche probability and characteristics (McClung, 2002; Schweizer et al., 2003). Contributory factors are relatively well known and have physical meanings that are related to the avalanche formation process (Perla, 1970; Schweizer et al., 2008). According to Schweizer et al. (2003) the essential factors are: terrain, precipitation (especially new snow), wind, temperature (including radiation effects), and snowpack stratigraphy. Most of the relevant meteorological parameters can be measured by automatic snow and weather stations (Gubler, 1993) and, therefore, avalanche forecasting is primarily based on analyses of measured snow and weather parameters which are linked to avalanche releases (Kronholm et al., 2006).

Research on these contributory factors focused mainly on avalanches in open unforested terrain, since the occurrence of avalanches in forests is not primarily a meteorological phenomena (Schneebeli et al., 1997). Furthermore, due to modified precipitation, wind, temperature, and snow properties in forests compared to those in unforested terrain, mountain forests play a crucial role in avalanche control by preventing avalanche formation (Schneebeli and Bebi, 2004). Forest structure in terms of crown closure, tree density and size and distribution of forest gaps in combination with topography directly influences the probability of forest avalanche releases (e.g. Bebi et al., 2001; Schneebeli and Bebi, 2004; Viglietti et al., 2010). The main effect of forests is the modification of the snow's mechanical properties and, therefore, the formation of continuous weak snowpack layers favoring slab avalanches is reduced. The relevant processes are (1) the interception of falling snow by trees, (2) the reduction of near-surface wind speeds, (3) the modification of the radiation and temperature regimes, and (4) the direct support of the snowpack by stems, remnant stumps and dead wood (Schneebeli and Bebi, 2004). Snow depth in forests is lower compared to open unforested areas, because interception by tree crowns reduces the amount of snow reaching the ground by 10 to 50% (McClung and Schaerer, 2006). The intercepted snow falls out irregularly and creates a more heterogeneous snowpack around the stems within a typical distance of about 1.5 times the crown projection. Moreover, the intercepted snow has a higher density compared to new snow which reaches the ground directly and is, therefore, less prone to
 avalanches (Bründl et al., 1999). Wind increases unloading of intercepted snow from the trees, but reduced wind speeds prevent extreme snow accumulation in gullies and depressions as they tend to occur in open areas (Schneebeli and Bebi, 2004). Maximum accumulation usually occurs in gaps width of 1 to 2 times the height of the surrounding trees (Imbeck and Ott, 1987). Due to shielding effects of the canopy, forests reduce the incoming shortwave and enhance the incoming longwave radiation, and fluctuations in snowpack surface temperatures are more moderate (Höller, 1998). Therefore, surface hoar as a major cause of slab avalanche formation is much smaller in forests, if any, and the spatial patterns are highly variable (Lutz and Birkeland, 2011; Shea and Jamieson, 2010).

However, due to the complex interactions between ecological conditions, topography and meteorological parameters the protective effect of forest may be reduced and, therefore, snow avalanches do occur in forests (Frey and Salm, 1990; Gubler and Rychetnik, 1991). These so-called ‘forest avalanches’ are important disturbances that affect mountain ecosystems and can pose substantial hazard to human settlements and infrastructures as well as to the forest cover itself (Bebi et al., 2009). While the effect of forests on avalanche formation in potential starting zones is addressed in several studies (for a review see Bebi et al., 2009), much less is known about the meteorological conditions which increase the probability of forest avalanche releases.

The assessment of avalanche activity under changing climate conditions is also an important issue with respect to risk management in the future (Martin et al., 2001); the effect of climate change on the avalanche activity is hardly understood, but is of great importance for inhabitants of alpine areas (Schneebeli et al., 1997; Jomelli et al., 2007). Current studies on its influence on avalanches in open unforested terrain suggest that climate change has had recently little impact on avalanche frequency (Laternser and Schneebeli, 2002), but a decrease in runout elevation was observed (Eckert et al., 2010a). A possible explanation could be that dry snow avalanches are replaced by wet snow avalanches because of climate warming (Martin et al., 2001). Furthermore, future changes in climate and land-use are likely to have considerable impacts on both avalanches and on forest cover and composition. Due to such potential changes, the frequency and magnitude of destructive forest avalanches could increase or decrease dependent on elevation and ecological shifts (Bebi et al., 2009).

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5 We define a ‘forest avalanche’ as a special type of avalanche which is released in forests. Forests are characterized by a maximum distance between trees of 25 m, a minimum canopy density of 20% and a dominant height above 3 m. Avalanches which are released directly above the treeline and run through forests are not forest avalanches in this context.
In this paper, we present a comprehensive analysis of 21 variables on snow and weather conditions of 189 forest avalanche events observed in the Swiss Alps. The first aim was to identify specific snow and weather conditions associated with forest avalanche releases by applying a hierarchical clustering method. Based on that, we created a classification tree model to obtain meteorological parameters which increase the probability of such events in addition to a generally high avalanche danger level. An improved understanding of snow and weather conditions which are linked to avalanche releases in forests could support avalanche warning and forest services in forecasting forest avalanches. Finally, we present a logistic trend analysis over 41 years based on data of 14 snow and weather stations (SWS) located in the Swiss Alps at elevations where forest avalanches are likely to occur. Analyzing past changes in snow and weather situations associated with avalanche releases in forests potentially driven by climate change could help to predict the activity of such events in the future.

7.2 Data and methods

7.2.1 Data

7.2.1.1 Avalanche data set

The bases for our analyses are 189 naturally released forest avalanches that occurred in winters between 1985/86 and 2005/06. They are spread evenly over the Swiss Alps and cover elevations from 700 to 2200 m asl. 126 of these avalanches were recorded during a project focused on forest avalanches (Schneebeli and Meyer-Grass, 1993). These forest avalanches mainly occurred as slab avalanches (approx. 68%) while the remaining 32% are documented as glide (24%) or loose snow avalanches (8%); about 52% released from a wet snowpack. The other 63 avalanches were extracted from the Avalanche Damage and Accident Database of the WSL Institute for Snow and Avalanche Research (SLF). For these avalanches, we assume a higher percentage of dry snow avalanches since they mainly released during the winter months of January and February (approx. 70%).

To distinguish characteristic weather situations with a high probability of forest avalanche releases from a generally high probability of avalanche occurrence, we generated a second data set of 189 avalanches naturally released in open unforested terrain during the same time period and at similar elevations as the forest avalanches. Furthermore, these non-forest avalanches recorded in the SLF Avalanche Damage and Accident Database are neither
released on the same day nor within the previous and following 3 days of an avalanche of the forest avalanches data set.

In order to define typical weather situations for forest avalanche occurrence, we generated a data set of 21 snow and weather variables for each avalanche event as well as of five additional variables describing site conditions, i.e. forest type, elevation, aspect (northness and eastness) and the month of release (Table 7.1). Information on snow and weather conditions are continuously recorded by SWS operated by the SLF and the Swiss Federal Office for Meteorology and Climatology (MeteoSwiss) which are evenly distributed over the Swiss Alps. Therefore, different spatial and non-spatial interpolation methods were used to reconstruct the actual snow and weather conditions on the day of and on the 4 days prior the avalanche event for its geographical position.

**Table 7.1.** Variables on site, snow and weather conditions. Numbers added to the symbols specify measurements for the day (1), within a 3-day (3) and a 5-day period (5) prior to the avalanche events.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean air temperature[^{a}] [°C]</td>
<td>Ta1, Ta3, Ta5</td>
<td>-</td>
</tr>
<tr>
<td>Air temperature differences [°C]</td>
<td>ΔTa3, ΔTa5</td>
<td>Differences between Ta1 and Ta3 or Ta1 and Ta5</td>
</tr>
<tr>
<td>Sum of sunshine duration[^{a}] [min]</td>
<td>S1, S3, S5</td>
<td>-</td>
</tr>
<tr>
<td>Sum of precipitation[^{a}] [mm]</td>
<td>N1, N3, N5</td>
<td>-</td>
</tr>
<tr>
<td>Sum of new snow height[^{a}] [cm]</td>
<td>HN1, HN3, HN5</td>
<td>-</td>
</tr>
<tr>
<td>Wind speed[^{a}] (categorical)</td>
<td>W1, W3, W5, W(<em>{\text{max}}) 1, W(</em>{\text{max}}) 3, W(_{\text{max}}) 5</td>
<td>Mean (W) and maximum (W(_{\text{max}})) wind speeds</td>
</tr>
<tr>
<td>Snow depth[^{a}] [cm]</td>
<td>HS</td>
<td>HS on the day of release</td>
</tr>
<tr>
<td>Forest type (categorical)</td>
<td>-</td>
<td>1) Deciduous, 2) mixed, 3) evergreen and deciduous coniferous, and 4) deciduous coniferous forests</td>
</tr>
<tr>
<td>Elevation [m asl]</td>
<td>H</td>
<td>Elevation of avalanche starting point</td>
</tr>
<tr>
<td>Aspect [-]</td>
<td>ExpNS, ExpOW</td>
<td>Northness (ExpNS) = cos(x); Eastness (ExpOW) = sin(x), where x is the aspect of the avalanche starting point [°]</td>
</tr>
<tr>
<td>Month of release (categorical)</td>
<td>Nov, Dec, Jan, Feb, Mar, Apr, May</td>
<td>-</td>
</tr>
</tbody>
</table>

\[^{a}\]See text for further description of variable
7.2.1.2 Air temperature

The daily mean air temperature \((T_a)\) was interpolated based on the lapse rate which was determined by the measurements of five SWS separately for each of the seven traditional snow climatological regions of the Swiss Alps (Brabec et al., 2001) to account for spatial variability. The SWS were chosen due to available data records and the required even distribution over an elevation gradient since air temperature decreases almost linear with an increase in elevation:

\[
T_a(h) = a_i h + b_i
\]  

(7.1)

where \(h\) is the elevation [m] of an avalanche starting point in region \(i (i = 1, \ldots, 7)\), and \(a_i\) and \(b_i\) are regression coefficients.

7.2.1.3 Sunshine duration

The sunshine duration \((S)\) depends on the season, cloudiness and topography. We used the recorded sunshine duration of the weather station closest to the respective avalanche event.

7.2.1.4 Precipitation

The spatial variability of daily precipitation is not only driven by large-scale weather situations, but also highly dependent on topography especially on elevation. However, in contrast to air temperature this relationship is not linear. Therefore, we split the area of the Swiss Alps in 27 smaller regions with similar climatic and topographic conditions. For each region, three to five weather stations evenly distributed over an elevation gradient were chosen dependent on the availability of recorded data to interpolate precipitation using the arithmetic mean value on the daily sum of precipitation:

\[
N_i = \frac{1}{n_i} \sum_{j=1}^{n_i} x_j
\]  

(7.2)

where \(n_i\) is the number of weather stations in region \(i (3 \leq n_i \leq 5)\) and \(x_j\) is the daily sum of precipitation [mm] measured by station \(j (j = 1, \ldots, 5)\) in region \(i (i = 1, \ldots, 27)\).

7.2.1.5 Wind

Wind speed as well as wind direction are highly dependent on topography. While wind speed is the highest at isolated summits and ridges, in-between it can be similar to low elevations. We used wind speeds measured by the three weather stations closest to an avalanche starting
point to classify mean and maximum values for wind speed based on the wind index of Gabl (1988) (Table 7.2). The most likely wind category out of the three was assigned to each avalanche event.

Table 7.2. Wind categories according to Gabl (1988).

<table>
<thead>
<tr>
<th>Wind category</th>
<th>Wind speed [m/s]</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>Calm, smoke ascends vertically</td>
</tr>
<tr>
<td>1</td>
<td>1 – 3</td>
<td>Light winds, noticeable on the skin</td>
</tr>
<tr>
<td>2</td>
<td>4 – 8</td>
<td>Moderate winds, moving flags, snow drifting starts</td>
</tr>
<tr>
<td>3</td>
<td>9 – 17</td>
<td>Heavy winds</td>
</tr>
<tr>
<td>4</td>
<td>&gt;17</td>
<td>Storm, hindered walking, large snow drifts</td>
</tr>
</tbody>
</table>

7.2.1.6 Snow depth

The point measurements of 173 snow stations were used to interpolate the snow depth for the area of the Swiss Alps. We used an interpolation model which was originally developed to produce area wide snow depth maps for Switzerland (Auer et al., 2004; Foppa et al., 2007). This spatial interpolation method is based on the general dependency of snow depth and elevation and is later adjusted through the in situ snow depth information to represent local and regional characteristics of the snow distribution. The two parts of the interpolation method are described as follows:

\[ HS = G + A \]  

(7.3)

where \( HS \) is the snow depth [cm]; \( G \) is the base value [cm]; and \( A \) is the compensation value [cm].

The country-wide base value \( G \) describes the relationship between snow depth and elevation and is calculated with the following formula:

\[ G = f(x) = ah^n \]  

(7.4)

where \( a \) and \( n \) are the coefficients of the exponential term and \( h \) is the elevation [m] of the respective release area.

The compensation value \( A \) counts for regional variations in snow depth by a distance dependent weighting scheme including the measured snow depths of the three neighboring snow stations to the predicted point value:
\[ A = \frac{h}{\sum_{i=1}^{3} \frac{1}{a_i}} \cdot \sum_{i=1}^{3} \left[ \frac{1}{a_i} \left( s_i - G(h_i) \right) \right] \]  

(7.5)

where \( h \) is the elevation of the respective release area [m]; \( a_i \) is the distance between the snow station \( i (i = 1, 2, 3) \) and the respective release area; \( s_i \) is the by station \( i \) measured snow depth [cm] and \( h_i \) is the elevation of snow station \( i \) [m].

### 7.2.1.7 New snow height

The new snow height was interpolated similarly to air temperature separately for the seven traditional snow-climatological regions of the Swiss Alps. Within each region, we chose the measured new snow height of the snow station with the smallest differences in elevation to the respective avalanche starting point.

### 7.2.2 Cluster analysis

Non-hierarchical \( k \)-means clustering methods (Fromm, 2009) and nearest neighbors techniques (e.g. McClung and Tweedy, 1994; Brabec and Meister, 2001) were already used to define specific weather situations with a high probability of avalanche occurrence in open unforested terrain to support avalanche forecasting. Concerning the clustering method for our data set, we used the “clValid” add-on package to the “R” system for statistical computing which allows selecting simultaneously multiple clustering algorithms, validation measures, and numbers of clusters (Brock et al., 2008; R Development Core Team, 2011). We applied a hierarchical-agglomerative clustering algorithm to group our data set on forest avalanches into clusters representing specific snow and weather conditions with a high probability of avalanche releases in forests. Hierarchical clustering yields a dendrogram which can be cut at a chosen height to produce the desired number of clusters (Kaufman and Rousseeuw, 1990). Since the parameters are measured on different scales, the 21 variables on snow and weather conditions were standardized using a zero mean-unit variance standardization. Ward's (1963) hierarchical clustering method was then employed to build more and more similar partitions out of the initial data set; the distance measure used was the Euclidian distance. A hierarchical method requires a stopping rule regarding the predicted number of clusters (\( N \)) which best reproduces the underlying structure after the clustering procedure. In addition to the number of clusters recommended by the analysis with “clValid”, Mojena's (1977) rule was applied to verify the result of the cluster analysis. Therefore, the dendrogram was pruned based on the
rule to select a group level corresponding to the first stage $j$ with $j = 1, \ldots, N-2$ cluster satisfying:

$$\alpha_{j+1} > \bar{\alpha} + k s_{\alpha}$$

(7.6)

where $\alpha_{j+1}$ represents the value of the criterion in stage $j+1$; $k$ is the standard deviation; and $\bar{\alpha}$ and $s_{\alpha}$ are, respectively, the mean and unbiased standard deviation of the $\alpha$ distribution.

When using Ward's clustering method this stopping rule recommends values of $k$ between 2.75 and 3.50 to find the number of clusters which ‘best’ approximates the underlying structure (Mojena, 1977). Assessing the quality of our clustering results, internal validation measures within the “clValid”-package were applied which take only the data set and the clustering partition as input and uses intrinsic information in the data set (Brock et al., 2008). Measures reflecting the connectedness, compactness, and separation of the cluster partitions were calculated as the connectivity, silhouette width and the Dunn index where the two latter ones are both examples of non-linear combinations of the compactness and separation. Connectivity has a value between zero and $\infty$ and should be minimized; the Dunn index has a value between zero and $\infty$ and should be maximized as well as the silhouette width which lies between −1 and 1 (Brock et al., 2008). The results of the cluster analysis are groups of forest avalanches; each representing a typical snow and weather situation under which they are likely to occur.

After the cluster analysis, we run a discriminant analysis (DA) using the same 21 predictor variables on snow and weather conditions to check for misclassified items and to refine the clusters. Principle component analysis (PCA) and descriptive statistics were then applied to characterize the groups. Differences among clusters in variables on site conditions which were not used to group the data were tested by applying the Kruskal–Wallis and Pearson's Chi-squared test respectively for categorical data with $p$-values $\leq 0.05$ considered significant.

### 7.2.3 Classification trees

Classification and regression trees (Breiman et al., 1998) are well established in avalanche forecasting and research to identify situations with a high probability of avalanche occurrence and to predict such events in open unforested terrain (e.g. Davis et al., 1999; Hendrikx et al., 2005; Kronholm et al., 2006). Assuming that forest avalanches only occur if the avalanche danger level is generally high, we used classification trees to distinguish specific snow and weather conditions which increase the probability of avalanche releases in forests from
situations with a generally high avalanche danger level. In order to test the relative importance of variables that most influence avalanche releases in forests and to find thresholds for this classification, we calculated binary classification trees for the whole data set on the 189 forest avalanches and the 189 avalanches which were released in open unforested terrain as well as for the potential groups of forest avalanches released under certain snow and weather conditions identified within the cluster analysis. We used the classification tree model of the “party” add-on package to the “R” system to model conditional inference trees (Hothorn et al., 2006; R Development Core Team, 2011). These non-parametric classification trees are based on a well defined theory of conditional inference and tree growth is restricted by statistical stopping rules. Based on predefined $p$-values ($p \leq 0.05$) for the association of predictor variables and the response variable, this statistical approach ensures that the right sized tree is grown and no form of pruning or cross-validation is needed.

### 7.2.4 Trend analysis

In a next step, we analyzed if the frequency of typical snow and weather conditions for forest avalanche releases did change during the past decades. The investigation period for this trend analysis focuses on the last 41 years (winters of 1970/71–2010/11) in order to have a reasonable number of SWS, which are well distributed in regard to the different climatic regions of the Swiss Alps and elevations where forest avalanches occur. We ended up with 14 stations between 1000 and 1900 m asl, where all necessary meteorological parameters were available as consistent long-term records in a daily resolution. Combinations of meteorological contributory factors and associated thresholds determined through the cluster analysis and classification were used to identify and count the number of days between November and May with a high probability of forest avalanche occurrence. Since this count record is based on binominal and discrete data, traditional linear regression techniques could not be applied, because the assumptions of uniform variance and Gaussian residuals are not satisfied. Instead, we used logistic regression for estimating and testing long-term trends in the occurrence of favorable conditions for forest avalanches at each station. Logistic regression is a special case of a formal generalization of linear regression concepts commonly summarized under the term generalized linear models and can be applied for trend modeling of rare events (Frei and Schär, 2001). Our calculations are based on the glm command in the software package R (R Development Core Team, 2011). In particular, we used the logit function as link function and the maximum likelihood principle for parameter estimation, which was also used to test for statistical significance where we defined $p$-values of
0.05 < p ≤ 0.10 as significant respectively highly significant for \( p \leq 0.05 \). Furthermore, when testing of statistical significance we have corrected for overdispersion (excessive variance) in the data set, which is an implicit account for possible serial correlation in the annual series (McCullagh and Nelder, 1989).

### 7.3 Results

#### 7.3.1 Types of forest avalanches

The cluster analysis generated two different clusters ‘best’ representing the underlying structure of our data set. Validating these results by comparing the internal validation measures connectivity (5.86), Dunn index (0.38) and silhouette width (0.25) with other clustering techniques, the chosen hierarchical clustering method performs best for our data set. Cluster A contains 93 and cluster B 96 forest avalanche events released under different snow and weather conditions as presented in the dendrogram (Fig. 7.1). The height of the dendrogram branches is a measure of the distances, i.e. the dissimilarity between the clusters. While clusters A and B are clearly separated, cluster A seems to be more homogeneous than cluster B where the height of the branch to the next split is relatively small compared to the height of the respective branch within cluster A. This points to a higher inhomogeneity among the objects of cluster B compared to those of cluster A. The follow-up discriminant analysis revealed that 97% of all objects was assigned to the correct cluster. We refined clusters A and B by exchanging six misclassified forest avalanche events without changing the number of objects within each cluster. Differences between clusters A and B are relatively well represented in the biplot where the first two principle components (PC1 and 2) describe 55.9% of the variance (Fig. 7.2). Objects of cluster A are grouped in the left side of the biplot and objects of cluster B are concentrated in the right side.
Fig. 7.1. Dendrogram using Ward’s hierarchical-agglomerative clustering technique. Gray rectangles separate clusters A and B best representing the underlying structure of the data set on forest avalanches applying Mojena’s stopping rule ($k = 2.75$).

Fig. 7.2. Biplot of the (scaled) first two principal components (PCs) displaying differences between forest avalanches of cluster ‘A’ and cluster ‘B’. Snow and weather variables are drawn as vectors. PC1 explains 39.7% of the variance, PC2 accounts for 16.2%. PC1 is mainly defined by the variables HN5, HN3, N5, N3, S5 and S3, while PC2 is determined by Ta5, Ta3, Ta1, dT5, dT3 and W3.
Comparing snow and weather conditions of the two identified forest avalanche types A and B, and with those associated with avalanche events outside of the forests (Figs. 7.3–7.9) enables a clearer characterization of the two situations. Avalanches of cluster A mainly occurred under permanently cold temperatures below -1°C (Fig. 7.3), the relationship between air temperature and avalanche occurrence is not that strong for objects of cluster B where the ranges of 1-, 3- and 5-day mean air temperatures (Ta1, Ta3 and Ta5) are rather wide (Table 7.3). Both clusters are characterized by a slight increase in air temperature over 3 (ΔTa3) as well over 5 days (ΔTa5) prior to an avalanche release. However, there is a significant difference in the sum of sunshine duration between the two clusters. 75% of the avalanches of cluster A were released on days with less than 26 min of sunshine (S1) and after periods with a generally low insolation. In contrast, avalanches of cluster B occurred on days with a sum of sunshine duration of 165 min in average and after 3- and 5-day periods (S3, S5) with high insolation and median values are close to those of the 189 avalanches released outside forests (Fig. 7.4). Clusters A and B also differ significantly in the sum of new snow height (HN) as well as in the sum of precipitation (N). Cluster B is characterized by low amounts of new snow on the day of release (HN1, mean = 5 cm), within a 3-day (HN3, mean = 26 cm) and a 5-day period (HN5, mean = 42 cm) prior the event. The sum of new snow height of cluster A exceeds mean values of 20 cm for HN1, 70 cm within 3 days and almost reaches 90 cm within 5 days prior to the event. The distribution of the sum of new snow height of the non-forest avalanches within a 5-day period lies between cluster A and cluster B avalanches (Fig. 7.5). Median values between cluster A and non-forest avalanches differ significantly with higher amounts of new snow for cluster A avalanches within a 3-day period as well as on the day of release. Avalanches of cluster A also tend to release on days with a higher snow depth (HS) compared to cluster B and avalanches released outside forests (Fig. 7.6). Due to outliers the ranges of both clusters are relatively wide (Table 7.3). Avalanches of cluster A are characterized by higher mean and maximum wind speeds in contrast to cluster B (Fig. 7.7). Furthermore, comparing the distribution of cluster A forest avalanches with the percentage of non-forest avalanches on wind categories shows considerable differences for 1- and 3-day maximum (Wmax1, Wmax3) values as well as for mean values on the day of release (W1). In contrast to that, the difference between mean wind speeds within a 3-day period (W3) is not that strong (Fig. 7.7).
### Table 7.3. Descriptive statistics for variables of clusters A and B which were used to group the data set.

<table>
<thead>
<tr>
<th>Variable</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
<tr>
<td>Cluster A</td>
</tr>
<tr>
<td>Mean</td>
</tr>
<tr>
<td>1-day mean air temperature $T_{a1} \ [°C]$</td>
</tr>
<tr>
<td>3-day mean air temperature $T_{a3} \ [°C]$</td>
</tr>
<tr>
<td>5-day mean air temperature $T_{a5} \ [°C]$</td>
</tr>
<tr>
<td>3-day air temperature differences $\Delta T_{a3} \ [°C]$</td>
</tr>
<tr>
<td>5-day air temperature differences $\Delta T_{a5} \ [°C]$</td>
</tr>
<tr>
<td>1-day sum of sunshine duration $S_{1} \ [\text{min}]$</td>
</tr>
<tr>
<td>3-day sum of sunshine duration $S_{3} \ [\text{min}]$</td>
</tr>
<tr>
<td>5-day sum of sunshine duration $S_{5} \ [\text{min}]$</td>
</tr>
<tr>
<td>1-day sum of precipitation $N_{1} \ [\text{mm}]$</td>
</tr>
<tr>
<td>3-day sum of precipitation $N_{3} \ [\text{mm}]$</td>
</tr>
<tr>
<td>5-day sum of precipitation $N_{5} \ [\text{mm}]$</td>
</tr>
<tr>
<td>1-day sum of new snow height $H_{N1} \ [\text{cm}]$</td>
</tr>
<tr>
<td>3-day sum of new snow height $H_{N3} \ [\text{cm}]$</td>
</tr>
<tr>
<td>5-day sum of new snow height $H_{N5} \ [\text{cm}]$</td>
</tr>
<tr>
<td>Snow depth $H_{S} \ [\text{cm}]$</td>
</tr>
</tbody>
</table>
Fig. 7.3. Differences in 1- (Ta1), 3- (Ta3) and 5-day mean air temperatures (Ta5) of clusters A and B, and avalanches released outside forests (non-forest). Boxplots show minimum, the lower quartile (Q 0.25), the median (Q 0.5), the upper quartile (Q 0.75) and maximum values for each category. Points are relative positions of extreme values.

Fig. 7.4. Differences in 1- (S1), 3- (S3), and 5-day sum of sunshine durations (S5) of clusters A and B, and avalanches released outside forests (non-forest). Boxplots show minimum, the lower quartile (Q 0.25), the median (Q 0.5), the upper quartile (Q 0.75) and maximum values for each category. Points are relative positions of extreme values.
Fig. 7.5. Differences in 1- (HN1), 3- (HN3) and 5-day sum of new snow heights (HN5) of clusters A and B, and avalanches released outside forests (non-forest). Boxplots show minimum, the lower quartile (Q 0.25), the median (Q 0.5), the upper quartile (Q 0.75) and maximum values for each category. Points are relative positions of extreme values.

Fig. 7.6. Differences in snow depth (HS) on the day of avalanche releases of clusters A and B, and avalanches released outside forests (non-forest). Boxplots show minimum, the lower quartile (Q 0.25), the median (Q 0.5), the upper quartile (Q 0.75) and maximum values for each category. Points are relative positions of extreme values.
Fig. 7.7. Percentage of avalanche events within clusters A and B, and avalanches released outside forests (non-forest) on the four wind categories for 3- and 1-day mean wind speeds (top), and 3- and 1-day maximum wind speeds (bottom). Categories are 1) 0–3 m/s, 2) 4–8 m/s, 3) 9–17 m/s, and 4) >17 m/s.

Fig. 7.8. Top: Percentage of avalanche events within clusters A and B on forest types. Bottom: Percentage of avalanche events within clusters A and B on month of release.
The two groups of forest avalanches differed also in site conditions (Table 7.4) such as the type of forest in which they were released (Fig. 7.8), and aspect and elevation (Fig. 7.9). Avalanches of cluster A are more likely to occur in coniferous forests (deciduous and evergreen) close to the upper treeline (>1700 m asl) at north-exposed slopes. Avalanches of cluster B were released in all aspects equally, but mainly below 1700 m asl in deciduous forests. Differences in the month of avalanche occurrence are not statistically significant, however, avalanches of cluster A were released mostly in February while avalanches of cluster B occurred more often in March (Fig. 7.8).

**Table 7.4.** P-values for the Kruskal–Wallis test and Pearson's Chi-squared test for categorical variables (*) testing of significant differences between clusters A and B of variables which were not used to group the data set. Values labeled with * and ** are significant ($0.01 < p \leq 0.05$) and highly significant ($p \leq 0.01$), respectively.

<table>
<thead>
<tr>
<th>Variable</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forest type*</td>
<td>$&lt;0.001^{**}$</td>
</tr>
<tr>
<td>Elevation [m asl]</td>
<td>$&lt;0.001^{**}$</td>
</tr>
<tr>
<td>Northness ExpNS [-]</td>
<td>$&lt;0.001^{**}$</td>
</tr>
<tr>
<td>Eastness ExpOW [-]</td>
<td>0.01*</td>
</tr>
<tr>
<td>Month of release*</td>
<td>0.1</td>
</tr>
</tbody>
</table>
A classification tree which included all forest and non-forest avalanches (n = 378) had an overall accuracy of 73%. A rather high percentage (52%) of forest avalanches was misclassified by this model in contrast to only 3% misclassified objects of avalanches released outside forests emphasizing that forest avalanches only occur if the avalanche danger level is generally high. The classification tree model with only forest avalanches of cluster A and all non-forest avalanches shows a low overall misclassification rate of 8%. However, 18 (19%) of the 93 avalanches that occurred in forests were still misclassified by the model. The best tree to determine snow and weather conditions which are associated with the occurrence of forest avalanches in addition to a generally high avalanche danger level is presented in Figure 7.10. This tree is based on the initial data set on the 93 forest avalanches of cluster A and 93 selected non-forest avalanches that occurred at elevations above 1700 m as a variable which differs significantly between clusters A and B (Fig. 7.9). The classification matrix for this tree gives an overall accuracy of 90%, with 168 of the 186 cases identified correctly (Table 7.5). The number of misclassified objects of 10 out of 93 (11%) of avalanches that occurred in forests is a little higher than the overall accuracy, but still lower as the misclassification rate of cluster A forest avalanches of the tree which included all non-forest avalanches. The first four splits are determined by variables on wind speed as mean and maximum values: at the top of the tree, the mean wind speed on the day of the avalanche event splits the data set in 71 mainly non-forest avalanches (W1 < 3 m/s) and 115 mostly forest avalanches. The following splits reveal that avalanches tend to occur in forests after periods with generally higher mean wind speeds (W3 > 3 m/s) and under stormy conditions (Wmax5 > 17 m/s) in contrast to avalanches released at similar elevations outside the forest. Close to terminal nodes, the differences of forest to non-forest avalanches are determined by a lower insolation (S5 < 73 min) or less new snow on the day of release (HN1 < 26 cm). Compared to the models for cluster A, classification trees for only cluster B avalanches had very high misclassification rates of 26% for a tree which included all non-forest avalanches and 30% for a classification tree based on a subset of 96 non-forest avalanches which occurred at elevations below 1700 m asl.
Fig. 7.10. Classification tree model of cluster A forest avalanches and 93 non-forest avalanches of elevations of >1700 m asl (n = 186) based on 21 snow and weather variables (see Table 7.1). The distribution of responding classes ‘in’ (forest avalanches) and ‘out’ (non-forest avalanches) within the terminal nodes are displayed in the barplots at the bottom of the tree. The n-value exhibits the number of avalanches which are explained by the according variable.

Table 7.5. Classification matrix for the classification tree model (Fig. 7.10), with observed cases in columns, and the predicted cases in rows. Misclassification rates are 10.8% for forest avalanches and 8.6% for avalanches which were released in open unforested terrain.

<table>
<thead>
<tr>
<th></th>
<th>Observation ‘in’</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>in</td>
<td>out</td>
<td>Total</td>
</tr>
<tr>
<td>Forecast ‘in’</td>
<td>83</td>
<td>8</td>
<td>91</td>
</tr>
<tr>
<td>out</td>
<td>10</td>
<td>85</td>
<td>95</td>
</tr>
<tr>
<td>Total</td>
<td>93</td>
<td>93</td>
<td>186</td>
</tr>
</tbody>
</table>

Finally, we can specify two characteristic situations where forest avalanches are likely to occur as different combinations of site, snow and weather conditions as ‘new snow forest avalanches’ (type 1) and ‘old snow forest avalanches’ (type 2) to be applicable for forecasting purposes (Table 7.6). Thresholds for variables are deduced from the distribution of variables which differ considerably between cluster A (type 1) and cluster B (type 2). We applied the lower (Q 25) and upper (Q 75) quartiles to define minimum or maximum thresholds assuming that 75% of all observed avalanches lay above or below these thresholds. Additional information on type 1 avalanches was derived from the classification tree model (Fig. 7.10) and preliminary thresholds were adjusted with expert knowledge.
Table 7.6. Forest avalanche types defined by site, snow and weather conditions to be useful for forest avalanche forecasting.

<table>
<thead>
<tr>
<th>Variable to observe</th>
<th>Type 1 (new snow forest avalanches)</th>
<th>Type 2 (old snow forest avalanches)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aspect</td>
<td>North-exposed slopes</td>
<td>All aspects</td>
</tr>
<tr>
<td>Elevation</td>
<td>&gt;1700 m asl</td>
<td>&lt;1700 m asl</td>
</tr>
<tr>
<td>Forest type</td>
<td>Open coniferous forests</td>
<td>Deciduous and mixed forests</td>
</tr>
<tr>
<td>Temperature</td>
<td>1-, 3- and 5-day mean air temperatures &lt;0°C</td>
<td>3- and 5-day temperature differences &gt;0°C</td>
</tr>
<tr>
<td>Sunshine duration</td>
<td>1-day sum of sunshine duration &lt;30 min</td>
<td>1-day sum of sunshine duration &gt;30 min</td>
</tr>
<tr>
<td></td>
<td>3-day sum of sunshine duration &lt;60 min</td>
<td>3-day sum of sunshine duration &gt;90 min</td>
</tr>
<tr>
<td></td>
<td>5-day sum of sunshine duration &lt;210 min</td>
<td>5-day sum of sunshine duration &gt;240 min</td>
</tr>
<tr>
<td>New snow height</td>
<td>1-day sum of new snow height &gt;10 cm</td>
<td>1-day sum of new snow height &lt;10 cm</td>
</tr>
<tr>
<td></td>
<td>3-day sum of new snow height &gt;50 cm</td>
<td>3-day sum of new snow height &lt;40 cm</td>
</tr>
<tr>
<td>Snow depth</td>
<td>Total snow depth &gt;100 cm</td>
<td>Total snow depth &gt;30 cm</td>
</tr>
<tr>
<td>Wind</td>
<td>1-day mean wind speed &gt;3 m/s</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>3-day maximum wind speed &gt;17 m/s</td>
<td></td>
</tr>
<tr>
<td>Main time to occur</td>
<td>February</td>
<td>February - March</td>
</tr>
</tbody>
</table>

7.3.2 Trends in snow and weather situations associated with forest avalanche releases

In order to test for long-term trends in the occurrence of snow and weather situations which are associated with forest avalanche releases, we defined a day as a ‘new snow forest avalanche day’ if:

- \( T_{a1}, T_{a3} \) and \( T_{a5} < 0°C \),
- \( H_{n1} > 10 \) cm, \( H_{n3} > 50 \) cm,
- \( S_1 < 30 \) min, \( S_3 < 60 \) min, \( S_5 < 210 \) min and,
- \( H_{s} > 100 \) cm.

An ‘old snow forest avalanche day’ is characterized by:

- \( \Delta T_{a3}, \Delta T_{a5} > 0°C \),
- \( S_1 > 30 \) min, \( S_3 > 90 \) min, \( S_5 > 240 \) min,
- \( H_{n1} < 10 \) cm, \( H_{n3} < 40 \) cm and,
- \( H_{s} > 30 \) cm.
The thresholds for snow and weather variables were set based on our previous findings and were adapted with expert knowledge. Wind variables were excluded from the trend analysis, since data on mean and maximum wind speeds were not available in a reasonable quality over the observed time period.

The number of days with meteorological conditions associated with the occurrence of new snow forest avalanches decreased at 11 of the investigated 14 stations (79%) during the last 41 years; also, trends for old snow forest avalanche days are negative at 12 of 14 stations (86%) independent from elevation and climatic region (Table 7.7). The decreasing trends are significant at four of the stations for both new and old snow forest avalanches, but mostly at high-elevation stations. Examples for the number of potential forest avalanche days at four SWS located at different elevations as well as in different climatic regions of the Swiss Alps are presented in Figure 7.11. The annual variations at a station as well as differences in the total number of counted forest avalanche days between the SWS are rather high for some stations, however, the shown negative trends are significant for new snow forest avalanche days at the stations Arosa, S. Bernardino and Airolo as well as for old snow forest avalanches at Arosa and Ulrichen. Since situations which are associated with new snow forest avalanches are generally rare, ranging between 0 and 235 counted days at the individual stations, the estimated positive trends at three SWS are a result of the low number of counted events (Poschiavo 0, Scuol 3, Engelberg 9) and, therefore, the calculations of trends are not meaningful. Old snow forest avalanche days occurred more often (117 to 2117 times during the 41 winters), however, the positive trends at two stations are very small, i.e. almost zero.

![Counts of potential new and old snow forest avalanche days at four SWS and the fits of the logistic trend model to the data.](image-url)
Table 7.7. Trends in potential new and old snow forest avalanche days over the observation period 1970/71–2010/11.

<table>
<thead>
<tr>
<th>SWS</th>
<th>Elevation [m asl]</th>
<th>New snow forest avalanches</th>
<th>Old snow forest avalanches</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Trend</td>
<td>p-value</td>
</tr>
<tr>
<td>Arosa</td>
<td>1840</td>
<td>-0.025</td>
<td>0.062*</td>
</tr>
<tr>
<td>Samedan</td>
<td>1710</td>
<td>-0.024</td>
<td>0.449</td>
</tr>
<tr>
<td>Zermatt</td>
<td>1638</td>
<td>-0.068</td>
<td>0.083*</td>
</tr>
<tr>
<td>S. Bernardino</td>
<td>1638</td>
<td>-0.028</td>
<td>0.040**</td>
</tr>
<tr>
<td>Davos</td>
<td>1590</td>
<td>-0.022</td>
<td>0.213</td>
</tr>
<tr>
<td>Montana</td>
<td>1427</td>
<td>-0.011</td>
<td>0.590</td>
</tr>
<tr>
<td>Ulrichen</td>
<td>1345</td>
<td>-0.016</td>
<td>0.271</td>
</tr>
<tr>
<td>Adelboden</td>
<td>1320</td>
<td>-0.018</td>
<td>0.692</td>
</tr>
<tr>
<td>Scuol</td>
<td>1303</td>
<td>0.017</td>
<td>0.736</td>
</tr>
<tr>
<td>Disentis</td>
<td>1197</td>
<td>-0.043</td>
<td>0.181</td>
</tr>
<tr>
<td>Airolo</td>
<td>1139</td>
<td>-0.057</td>
<td>0.018**</td>
</tr>
<tr>
<td>Poschiavo</td>
<td>1078</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Engelberg</td>
<td>1035</td>
<td>0.056</td>
<td>0.278</td>
</tr>
<tr>
<td>La Chaux-de-Fonds</td>
<td>1018</td>
<td>-0.048</td>
<td>0.244</td>
</tr>
<tr>
<td>All SWS mean</td>
<td></td>
<td>-0.027</td>
<td>0.025**</td>
</tr>
<tr>
<td>High SWS mean</td>
<td>&gt;1500</td>
<td>-0.033</td>
<td>0.003**</td>
</tr>
<tr>
<td>Low SWS mean</td>
<td>&lt;1500</td>
<td>-0.022</td>
<td>0.181</td>
</tr>
</tbody>
</table>

*Significant (0.05 < p ≤ 0.10).
**Highly significant (p ≤ 0.05).

In addition to the trends calculated at the single SWS, the overall mean of all SWS (Fig. 7.12) as well as mean values of potential forest avalanche days at stations above 1500 m asl show significant negative trends for both new and old snow forest avalanche days (Table 7.7). Figure 7.12 also reveals that on average only about 2 days per year have favorable conditions for new snow forest avalanches. In contrast, conditions which increase the probability of old snow forest avalanche releases were observed on average at 23 days per year. Mean trends for stations below 1500 m asl are also negative, but not statistically significant.
7.4 Discussion and conclusions

The aim of this study was to give a comprehensive overview on snow and weather conditions associated with avalanche releases in forests and to analyze past changes in the occurrence of such situations potentially driven by climate change.

Analyzing 21 snow and weather variables of a data set on 189 avalanches naturally released in forests, revealed two types of forest avalanches. They can be characterized as ‘new snow forest avalanches’ (cluster A) and ‘old snow forest avalanches’ (cluster B) corresponding to the types of instability for open terrain slab avalanches (Schweizer et al., 2003). This subclassification differs between (1) new snow instabilities as a result of overloading due to rapid precipitation during storm which leads to direct-action avalanches, and (2) climax avalanches which follow from old snow instabilities due to failure of a buried persistent weak layer (McClung, 2002). Direct-action avalanches are the most frequent case of damaging avalanches starting in forests (Frey et al., 1987).
Our analysis demonstrates that the main contributory factors for new snow forest avalanche releases are cold temperatures, heavy and intense snowfall and high wind speeds. The snow falling during a stormy period is piling up in forest gaps and forests with a less dense structure. In addition, the interception of falling snow by trees as a key process for preventing avalanche formation in forests is reduced, when temperatures are low and insolation is missing. The cohesion of snow itself strongly increases at temperatures above −3°C and, therefore, the interception efficiency of forests decreases below this threshold (Pfister and Schneebeli, 1999). Furthermore, due to low temperatures the sublimation of previously intercepted snow is reduced which remains longer on branches and, thus, the following falling snow accumulates on the forest floor (Imbeck and Ott, 1987). The snow mass accumulated during a single storm event is sufficient for direct-action avalanches and could release due to the resulting increase in instability (Frey et al., 1987). Furthermore, in such situations we assume that due to higher wind speeds branches begin to oscillate and can completely unload the intercepted snow mass (Pfister and Schneebeli, 1999) which could trigger forest avalanches since the unloaded snow mass might be comparable to a skier's impact.

New snow forest avalanches of our data set often occurred in deciduous coniferous forests formed by European larch (Larix decidua Mill.) near timberline with a usually open, less dense structure and, therefore, the effect of interception on the spatial distribution of snow depth might be less significant compared to evergreen coniferous forests. The spatial variability of the strength of the snowpack under a larch is still detectable, i.e. a significantly higher stability was found in areas where the snowpack was influenced by larch crowns (Schneebeli and Meyer-Grass, 1993; Schweizer et al., 1995). However, due to the less dense structure of such forests a continuous layering similar to that in clearings with some distortions below the crowns is more likely and, therefore, weak layer formation such as surface hoar, depth hoar and surface crusts are still possible in open larch stands (Gubler and Rychetnik, 1991). The highest percentage of new snow forest avalanches of our data set released in evergreen coniferous forests above 1700 m asl which are denser compared to larch stands; the intercepting effect is higher and its effect on snow distribution and accumulation usually prevent avalanche releases in such forests which are dominated by Norway spruce (Picea abies (L.) H. Karst.). However, avalanche releases are still possible in forest gaps of a certain size where maximum snow accumulation usually occurs in gaps width of 1 to 2 times the height of the surrounding trees (Imbeck and Ott, 1987).
Cluster A also contains a special type of powder forest avalanches also known as “Wildschneelawinen” which occur in periods of permanently cold conditions as extremely loose and noncohesive snow starts to move through the forest (SLF, 2000). Moreover, stems which usually stabilize the snow cover as a main effect of protection forests are not able to hinder this uncohesive snow to move further downwards without a significant loss of flow energy (Imbeck and Meyer-Grass, 1988). After a certain distance the moving snow may develop into a destructive avalanche of high speed and large dimensions which can pose substantial hazard to settlements and infrastructure below the forest (SLF, 2000).

Applying a classification tree model, new snow forest avalanches can be distinguished from situations with a generally high probability of avalanche occurrence in open unforested terrain by higher mean and maximum wind speeds and lower insolation over a 5-day period. We assume that under such specific conditions wind reduces the snow interception by tree crowns causing higher snow accumulation in forest gaps. The estimated overall accuracy of 90% of this tree based on 93 new snow forest avalanches and 93 selected non-forest avalanches that occurred at elevations above 1700 m asl exceeds the desired 80% performance limit suggested by Föhn (1998) for models based on meteorological parameters. Our classification tree illustrates the specific snow and weather conditions which are associated with new snow forest avalanche releases and, thus, can be considered in forecasting such events.

In contrast, conditions under which old snow forest avalanches are likely to occur are not that clearly definable. The dendrogram already shows that this cluster includes various types of forest avalanches, as within cluster B the heights of the branches to the next splits are relatively small. Old snow forest avalanches occur in various types of forests in all aspects, but mainly below 1700 m asl. This type of climax forest avalanche contains dry (48%) and wet snow (52%) avalanches released as slab, loose snow and glide snow avalanches. For example, slab forest avalanches of this cluster can follow from instabilities due to the failure of a buried layer of kinetic growth crystals composing persistent weak layers such as surface hoar and depth hoar which are able to grow in forest gaps of a certain size (Shea and Jamieson, 2010). Imbeck and Ott (1987) observed that the temperature gradient in the snowpack could even be higher in forests compared to unforested terrain which fosters depth hoar formation and leads to instabilities in the snow cover.

The main contributory factors for old snow forest avalanche releases within a 5-day period are high insolation and an increase in air temperature which could cause a loss in the stability of
the snow cover fostering glide and wet snow forest avalanches (Meyer-Grass and Schneebeli, 1992). Old snow forest avalanches mainly occur at low elevations in deciduous forests mostly dominated by European beech (*Fagus sylvatica* L.) which are more prone to those avalanche types. In forests they follow periods of high insolation where the intercepted snow melts and the dripping meltwater creates small funnels which are ports of entry for meltwater (Bründl et al., 1999).

The two classification tree models on old snow forest avalanches have shown high misclassification rates of 26 and 30% and, therefore, are not useful for operational purposes (Föhn, 1998). These findings suggest that old snow forest avalanches occur under similar snow and weather conditions as avalanches in open terrain and that a 5-day period of observing snow and weather conditions might be too short to forecast such events. In particular, wet snow avalanches are notoriously difficult to predict as the triggering conditions depend on complex interactions of water percolation, topography and snowpack properties (Mitterer et al., 2011).

Our analyses are based on interpolated snow and weather variables measured outside forests to describe situations inside the forest and, therefore, do not reflect the actual situation in the forest. Due to their sporadic occurrence and a non-continuous monitoring, observation data on avalanches as well as measurements of snow and weather parameters in forested areas are rare (Teich et al., 2012a, see Chapter 4). However, avalanche forecasters usually use the information from SWS outside forests in their considerations (Gubler, 1993; Schweizer et al., 2003). The presented thresholds for snow and weather parameters associated with forest avalanche releases are especially useful to predict situations with an additional high probability of new snow forest avalanche releases at elevations above 1700 m since these events can develop into destructive avalanches which pose substantial hazard to the forest cover as well as to settlements and infrastructure below the forest.

The analyses of long-term trends in the occurrence of snow and weather conditions associated with forest avalanche releases at 14 SWS in the Swiss Alps revealed significant negative trends at 4 stations for both new and old snow forest avalanches. The numbers of days with favorable snow and weather conditions for new snow forest avalanche releases are generally small and decreased at 79% of the SWS between 1970/71 and 2010/11; situations which are associated with the occurrence of old snow forest avalanches happening more often, but the number of these days decreased as well at 86% of the SWS independent from the climatic
region and elevation. The significant trends were detected mostly at high-elevation stations (>1600 m asl) for both new and old snow forest avalanches. The relatively high thresholds for snow depth at the day of release and the sum of new snow height over a 3-day period to be counted as a new snow forest avalanche day may influence their decreasing tendency. An indication that extreme snow depth and snow fall may decrease in the Swiss Alps at all elevations with a less clear pattern between 800 and 1500 m asl for extreme snowfalls was already mentioned by Marty and Blanchet (2011) and that the coming decade will show whether observed decreases in extreme snow depth and snow fall will become significant.

The decreasing trend in the number of days where old snow forest avalanches are likely to occur could be a result of warmer temperatures, more rain events and a shorter snow cover duration especially at low elevations (Marty, 2008; Serquet et al., 2011). In addition, a shift from old dry to wet snow forest avalanches is likely as it is expected for open terrain avalanches (Martin et al., 2001).

It should be noted that the results of the trend analysis are valid for single SWS records. They do not show trends in the actual occurrence of forest avalanches since there are no long-term records available on observed events. Assumptions of the size of forest avalanches which could have been released at a potential forest avalanche day are not possible since our analyses are based on a data set which included destructive as well as non-destructive forest avalanches with runout distances ranging between 25 and 1750 m.

The applied logistic regression model provides a suitable statistical method to test for trends in individual count records. Validating the defined combinations of snow and weather parameters and their threshold to identify a new respectively an old snow forest avalanche day based on daily measurement at the SWS Davos has shown that 49 out of 52 new snow forest avalanche events observed in the area between 1986 and 1999 were predicted by our deterministic model. The number of actual released old snow forest avalanches in this area was rather small and none of the six events was defined as an old snow forest avalanche day. However, this could have been different for another SWS located in a different region in the Swiss Alps with a higher number of observed old snow forest avalanches.

Despite some limitations of the methods used, our findings can be seen as an indication for possible impacts of climate change on favorable meteorological conditions for forest avalanche occurrence. In combination with the currently observed increase in forest cover density in the Swiss Alps (Bebi et al., 2001; Brändli, 2010; Krumm et al., 2011) it is thus
likely that avalanche releases in forested terrain will be less frequent in the future which will influence decisions on where and when avalanche defense structures should be built in mountain forests. The estimated negative trends, however, do not challenge the importance of an effective protection forest management since other natural hazards such as landslides and rockfall (Beniston et al., 2011) as well as forest disturbances caused by wind, fires or bark beetles might become more frequent due to changing climate conditions (Dale et al., 2001).

**Acknowledgments**

We thank Mathias Ulmer for his assistance in generating the data set, and Alec van Herwijnen, Martin Schneebeli and one anonymous reviewer for valuable comments on earlier versions of the manuscript. This study was funded by the CCES (Competence Center Environment and Sustainability of the ETH Domain) within the project MOUNTLAND and co-financed by the WSL-BAFU-Program “Forest and Climate Change”.
Chapter 8

Paper VI

Potential impacts of climate change on snow avalanches starting in forested terrain

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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.

8.1 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 who 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., 2012a, see Chapter 4).

Under climate change, frequency and magnitude of forest avalanches are likely to be affected by changing snow regimes and meteorological conditions (Teich et al., 2012b, see Chapter 7) as 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. 8.1), 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., 2014, see Appendix C).

![Fig. 8.1. Factors and feedback effects which influence the future forest avalanche regime.](image)

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.

8.2 Past trends in snow and weather conditions associated with forest avalanche releases

8.2.1 Types of forest avalanches

Recently, Teich et al. (2012b, see Chapter 7) 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 8.1). 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., 2012b, see Chapter 7). Applying Ward’s (1963) hierarchical clustering method revealed two different clusters best representing the underlying structure of the initial data set.

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.
Table 8.1. Forest avalanche types defined by site, snow and weather conditions, which may be used for forest avalanche forecasting (according to Teich et al., 2012b, see Chapter 7).

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

8.2.2 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. (2012b, see Chapter 7) 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., 2012b, see Chapter 7), 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 ($p \leq 0.10$).

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. 8.2) 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.

![Mean number of potential new snow (top) and other forest avalanche days (bottom)](image)

**Fig. 8.2.** 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).

### 8.3 Trends in forest development

#### 8.3.1 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).

8.3.2 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 $\alpha = 0.05$).

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. 8.3). Especially the number of stems per ha of trees with a DBH $\leq 7$ 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 8.3.1).

![Image](image.png)

**Fig. 8.3.** 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.

### 8.3.3 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., 2012a, see Chapter 4). 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., 2012a, see Chapter 4).
In the context of climate change and related changes in mountain forest structure (see Section 8.3.2), 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. 8.4).

**Fig. 8.4.** 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 $1 < \text{DBH} < 15$ cm, $\text{DBH} > 6$ cm and $\text{DBH} > 16$ cm. Loess curves were fitted to the data built on locally weighted non-linear regressions.

**8.4 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 4.6 x 3.4 km area in Davos, Switzerland, we used the spatially explicit model TREEmig-AVAL (Zurbriggen et al., 2014, in prep., see Appendices C and D) 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., 2014, in prep., see Appendices C and D). 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. 8.5).

![Fig. 8.5. 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.](image)

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 Figure 8.2. 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., see Appendix D), 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.

8.5 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., 2010a). 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.

Acknowledgements

The studies presented were mainly funded by the CCES (Competence Center Environment and Sustainability of the ETH Domain) within the project MOUNTLAND and partly co-financed by the WSL-BAFU-Program “Forests and Climate Change”.
Chapter 9

Synthesis

9.1 Main conclusions

The goal of this PhD project was the investigation of avalanche-forest interactions in the avalanche track and runout zone and their implementation in simulation and evaluation tools to support natural hazard and protection forest management. To cope with future environmental changes, the thesis explicitly addressed climatically induced shifts in the importance and reliability of the protective effects of mountain forests against snow avalanches. The objectives were approached in six first- and five co-authored papers completed during this PhD project. Referring to the initial research questions and hypotheses (Chapter 1.2.1), the main conclusions can be summarized as follows:

• **Differing forest structures have significant influences on runout distances of small- to medium scale avalanches which are released in forests or directly above the treeline** (Chapter 4).

• **The impact of forest structures can be modeled within a mass detrainment approach and implemented in avalanche simulation tools** (Chapters 5 and 6).

• **The improved avalanche modeling in forested terrain will also enhance the spatially explicit quantification and evaluation of mountain forests’ protective function** (Chapter 3).

• **In the future, expected decreases in snow cover depth and duration, fewer heavy snowfall events, and increases in air temperature will reduce avalanche releases in forests** (see Chapter 7).

• **Forest avalanches can decrease both in frequency and in magnitude, and are influenced not only by changing climate conditions but also by current trends in forest expansion and changes in forest structure** (see Chapter 8).

My PhD project and research interests are arranged at the interface between snow avalanches and forests. Directions in this research area are mainly driven by the aim to improve our knowledge on avalanche-forest interactions in a way that helps to enhance forest management and avalanche forecasting rather than by the detailed understanding of one single small-scale
process. Nevertheless, my research on snow avalanches in forested terrain contributes to different levels of scientific work (see Section 9.3). The new insights gained from this PhD project lead to recommendations which can support natural hazard and protection forest management.

In the subsequent sections, I first discuss important findings of this thesis with regard to the initial research questions and emphasize the impact of the results on the practical implementations. Second, I highlight how this work was accomplished in the vein of the funding project MOUNTLAND. And, finally, I will give an outlook on potential future research in the cross-disciplinary field of snow avalanches and mountain forests.

9.2 Implementation of the findings in natural hazard and protection forest management

Mountain forests are an important defense measure against snow avalanches in densely populated mountainous regions such as the European Alps (e.g. Brang et al., 2006; Gruber and Bartelt, 2007; Grêt-Regamey et al., 2012a). Both protective effects of forests, hindering avalanche formation and limiting avalanche runout of small- to medium-scale avalanches, have to be considered when maintaining the protective function (Bebi et al., 2009). To support natural hazard and protection forest management in a changing environment four key research questions (see Chapter 1.2.1) were addressed in this thesis:

1) How can the protective effects of forests be quantified in a spatially explicit manner in order to support decision-making in mountain forest and natural hazard management?

In Switzerland the management and maintenance of protection forests are subsidized by public funds (BAFU, 2004). Since these funds are limited, the forest sector is under pressure to work cost-efficiently while maintaining adequate protection against natural hazards. Paper I shows how one can apply a GIS-based risk analysis to quantify and value the protective effects of mountain forests in a spatially explicit manner. By calculating the risk as the product of the probability of a damaging event and its consequences, the protective function of forests can be translated into an economic value (e.g. Grêt-Regamey et al., 2008a). The presented methodical framework would potentially allow comparisons of costs and effects of silvicultural interventions and/or alternative investments in engineering defense structures (see also Appendix A). If applied on a larger scale, it provides useful information for a consistent allocation of public funds and helps to better account for trade-offs between
“avalanche protection” as a key ecosystem service (ES) in mountainous regions and competing ES requiring more open forest structures (e.g. Grêt-Regamey et al., 2013). However, until now only little knowledge existed on decelerating effects of forest structures on avalanche runout which could be implemented in evaluation tools (Bebi et al., 2009). Thus, the analysis and modeling of avalanche-forest interactions in the avalanche track and the runout zone were addressed in research questions 2 and 3:

2) *What structural conditions of forests are needed to decelerate or even stop snow avalanches of a certain size?*

This thesis has shown that forest structure has a significant influence on runout distances of small- to medium-scale avalanches released in forested terrain (see Paper II). In particular, the starting zone stem density of small diameter trees (1-15 cm) significantly affects runout distances of avalanches which start in evergreen coniferous and mixed forests. This is not true for larger avalanches released far above the treeline, where avalanche size characteristics and the distance an avalanche runs through open terrain before penetrating into forest mainly determine runout distance (see also McClung, 2003; Anderson and McClung, 2012). The findings emphasize that it is important to treat these two cases differently in protection forest as well as natural hazard management: For avalanches starting in forested terrain or directly above the treeline, forest management should focus on measures to enhance regeneration and surface roughness, for example by maintaining high levels of dead wood. In contrast, engineering defense structures are key in potential avalanches starting zones located far above forests. Based on the results presented here, the improved knowledge and understanding of avalanche-forest interactions in the avalanche path will support optimized and regionally adapted decision making: Effective protection forest management helps forming forest stands within and directly below potential starting zones that stop small- to medium-scale avalanches. Furthermore, forest and civil engineers should take this effect of forests and its limitations into account when establishing the dimensions of avalanche defense structures in potential starting zones within forested areas or directly above treeline. Avalanche simulation software could support such decisions; however, previous versions of avalanche models lack the implementation of local avalanche-forest interactions.
3) How can numerical avalanche simulation models be improved by implementing knowledge on avalanche-forest interactions?

Previous studies have attempted to model the effect of forests on avalanche runout by increasing the total basal friction for forested areas compared to open unforested terrain for destructive large-scale avalanche events (Gubler and Rychetnik, 1991; Bartelt and Stöckli, 2001; Gruber and Bartelt, 2007; Casteller et al., 2008; Takeuchi et al., 2011). This is however not valid for modeling small-scale avalanches in forested terrain. That is, the friction approach was applied to simulations of 40 observed small- to medium-scale avalanches by varying one of the friction parameters ($\xi$) (see Appendix B). The comparison between observed and simulated runout distances revealed that 78% of the avalanches were still overestimated when applying the smallest chosen $\xi$-value. This deficiency suggested that not only an increase in friction, but also the potential mass removal by trees has to be taken into account when modeling the decelerating effect of forests on the flow of small- to medium-scale avalanches.

Therefore, the observed stopping of snow mass by trees growing in the avalanche path is now described with a detrainment function (see Paper III). Implemented in a numerical avalanche model, this function leads to a deceleration and significant runout shortening of small- to medium-scale avalanches. The decelerating effect of different forest types is parameterized by the empirical detrainment coefficient $K$ which now can be defined based on four forest characteristics: forest type, crown coverage, vertical structure and surface roughness (see Paper IV). As the suggested forest characteristics can be largely derived from remote sensing data (orthophotographs, Lidar-data), possibly combined with sporadic field samples, there is a high potential for large-scale assessments.

Likewise, an extensive investigation of forest characteristics is inevitable for a robust assessment of the impact of changing climate conditions on avalanches in forested terrain. First analyses of the impact of climate change based on existing scarce data have been undertaken in the present thesis.

4) What are the potential impacts of changing climate conditions on avalanches in forested terrain?

Avalanches starting in forested terrain are rare and usually small, but can be a threat to infrastructure below the forest. For example, a period of widespread high activity of forest
avalanches was observed in late February 2012 in Switzerland. About 30 avalanches were reported to the SLF since they buried roads, railways and ski-runs. The weather situation was characterized by a sudden increase in air temperature which led to a high activity of wet and glide snow avalanches in general; however, the high number of avalanche releases in forests was surprising and challenging for safety authorities (Techel et al., 2013). In such situations, the presented characterization of snow and weather conditions which were associated with forest avalanche releases could support avalanche warning and forest services in forecasting forest avalanches (see Paper V). The estimated negative trends in the past occurrence of such favorable situations can however be seen as an indication for possible impacts of climate change. In combination with the currently observed increase in forest cover extent and density in the Swiss Alps (Bebi et al., 2009; Brändli, 2010; Krumm et al., 2011), it is thus likely that avalanche releases in forested terrain will be less frequent and limited in magnitude in the future. The simulation results of the forest-landscape model TREEMig-AVAL applied to a forested slope in a high alpine valley emphasize these assumptions (see also Appendix D). 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 (see Paper VI).

The presented findings however do not challenge the importance of an effective protection forest management, but reveal possible integrations in future management strategies. For example, the relative importance of forests’ protective function against snow avalanches could decrease at lower elevations compared to other natural hazards, i.e. predicted higher frequencies of other natural hazards such as landslides and rockfall (e.g. Beniston et al., 2011) may require differing management strategies. Moreover, changing climate conditions may cause more frequent forest disturbances by wind, forest fires or bark beetle outbreaks (e.g. Dale et al., 2001; Raffa et al., 2008; Seidl et al., 2011). Such disturbances will also shape mountain forests and can at least temporally increase the risk of subsequent avalanches by creating new potential avalanche release areas. Therefore, resistant and resilient forest stands are key for sustainable avalanche protection, in particular restoring the protective function after large-scale disturbances will be challenging in the future. Forest management concepts and guidelines are often well adapted to regionally specific avalanche-forest 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 and potential changes of forest disturbance regimes should be more considered in the future.
Mountainous regions are highly sensitive to changing environmental conditions and will be affected considerably by climate change (e.g. Schröter et al., 2005; Nogués-Bravo et al., 2007; McCain and Colwell, 2011; Gottfried et al., 2012). Evaluation and simulation tools as presented in this thesis allow the integration of potential ecological and economic consequences due to changing environmental conditions in decision processes for sustainable natural hazard and protection forest management.

9.3 Achievements within the interdisciplinary MOUNTLAND project

Environmental changes due to changing climate conditions as well as land-use changes and their influence on the future protective capacity of mountain forests constitute a major challenge for science and society. For adaptation, mitigation and sustainable management strategies, policy makers and practitioners need the support from the scientific community with reliable information about potential developments, associated consequences and underlying uncertainties (IPCC, 2007). The process of science works at multiple levels, for example by improving process knowledge based on a specific hypothesis, by translating more complex theories into models, and by developing practical tools based on such models to shape policy and support decision processes. The inter- and transdisciplinary project MOUNTLAND in which this doctoral thesis was embedded, followed this strategy by contributing to different levels of science and implementation focusing on aspects of land-use and climate change in three study regions in Switzerland (see Chapter 1.2.3). Improved process knowledge gained, for example from experiments, was embedded in ecological and economical models which facilitated the development of adapted land-use practices and innovative policy solutions for mountain regions (Huber et al., 2012a, b). Finally, the gained knowledge was disseminated to a broad audience including stakeholders and inhabitants of mountainous regions, for example summaries of several studies were published in German in MOUNTLAND-specific issues in the Swiss Forestry Journal and in Agrarforschung Schweiz (Huber et al., 2012a, b).

Within MOUNTLAND, this thesis focused on the topic “snow avalanches in forested terrain” likewise by bridging gaps between different scientific disciplines, for example:

- Improved process understanding on avalanche-forest interactions was described in the form of a detrainment function and operationalized for avalanche simulation which in turn will help to improve the presented spatial explicit evaluation of the ES “avalanche protection”.
• Gained process knowledge on meteorological contributory factors which increase the probability of avalanches releases in forests was the basis for modeling past trends in the occurrence of favorable situations and will support forest avalanche forecasting.

Regarding the interface between science and society, and to reach a broad audience, several findings of this PhD thesis were published in German and are accessible to the public (Bebi et al., 2012a; Bebi et al., 2012b, see Appendix E; Teich, 2012; Teich, 2013; Techel et al., 2013).

Furthermore, the interdisciplinary workflow of MOUNTLAND was also pursued during this PhD project resulting in two co-authored papers (see Appendix C and D). Some findings of this thesis have supported the work of Natalie Zurbriggen which in turn provided an important part of the review and synthesis paper on "Potential impacts of climate change on snow avalanches starting in forested terrain" (see Chapter 8).

9.4 Future research directions

The present PhD thesis yields new insights for science and society at the interface between snow avalanches and forests, but also reveals limitations pointing to future research directions at different levels of science and implementation:

Investigating processes requires a comprehensive data base. The analyses conducted in this thesis were based on an adequate number of observed avalanches in forested terrain; however some analyses were still restricted by the amount of available data. For example, more data on forest avalanches and related meteorological conditions would have been necessary to refine the cluster which contains so-called “other forest avalanches” leading to more detailed insights separately for old and wet snow avalanches. In addition, studying the development of the snowpack in forest gaps over time, i.e. how snow and weather conditions are linked to the growth and development of weaknesses dependent on the distance to the surrounding trees, would strengthen the findings presented in this thesis. Regular field measurements and monitoring of the snow cover stratigraphy in different mountain forest ecosystems could provide stronger evidence for forest avalanche forecasting.

In general, observation data on avalanche events in forests are rare. Further research would greatly profit from more field data aiming at establishing a comprehensive database on avalanche observations in forested terrain in cooperation with other European Alpine countries. Additional experiments, for example chute experiments with varying sizes and densities of obstacles aligned in the avalanche path could also improve process understanding.
on avalanche-forest interactions. New measurements should include not only avalanche runout distance, but also additional parameters such as avalanche velocity, flow depth and mass balance. This would also encourage studies on the influence of surface roughness on avalanche runout and avalanche release. Due to climate change, higher frequencies of other natural disturbances such as wind, forest fires or bark beetle outbreaks can be expected (e.g. Dale et al., 2001; Raffa et al., 2008; Seidl et al., 2011) and the remaining dead wood temporarily increases surface roughness (Brown et al., 1998; Rammig et al., 2007). Yet relatively little knowledge exists on the consequences for avalanche protection provided by mountain forests. That is, research should focus on interactions between effective heights of dead wood and avalanche flow depths determining the mass deposited behind obstacles in the avalanche path (Faug et al., 2004; Naaim et al., 2004) as well as on decay rates and associated mechanical stabilities (Schönenberger et al., 2005). This thesis has shown that the nature of the surface cover in terms of stumps and shrubs, smooth or scree slopes has a significant influence on avalanche runout of small- to medium-scale avalanches and that this effect is more important for wet glide snow avalanches than for dry snow avalanches. Especially glide snow avalanches often start on steep slopes in deciduous forests threatening infrastructure below such forests. With climate change, wet snow avalanches are assumed to partly replace dry snow avalanches at lower elevations (Martin et al., 2001). As experienced during this work, existing knowledge on the interactions between surface roughness and avalanche release as well as avalanche flow with regard to different snow types is rather poor and should be a key future research task.

A promising development for future research and forest assessment is that high resolution remote sensing based data (e.g. Lidar-data) are becoming increasingly available over large areas. Lidar-data are especially helpful to map current forest structures and surface roughness. Numerous forest variables and characteristics can be derived from Lidar-data serving as input for avalanche and forest dynamics models. For avalanche simulation tools, classifying types of forests with different structural conditions based on Lidar-data could be used to calculate potential release areas within forests, and to define forest patches with varying mass detraining effects automatically.

The presented methodical framework for a spatially explicit quantification and evaluation of the protective effects of forests is a valuable first step to integrate such tools in decision processes. The next step would be to implement the improved process knowledge on avalanche-forest interactions and their simulation to also account for varying effects of
different forest structures on avalanche runout. Moreover, the protective function of forests is not a steady condition and tools supporting management strategies need to take the long-term development of forests including potential disturbance interactions and involved uncertainties into account (Wehrli et al., 2006; Bebi et al., 2009; Hanewinkel et al., 2011). An enhanced risk-based approach should therefore include additional modeling components of avalanche and forest dynamics.

Effective and cost-efficient management of protection forests needs to consider: (1) the constant pressure from economic and population growth (Spehn et al., 2002), which influences the distribution of the damage potential and entails a growing demand for environmental and recreational service (Grêt-Regamey et al., 2012a), (2) changing environmental conditions (e.g. Nogués-Bravo et al., 2007), and (3) limited subsidization (BAFU, 2004). Mountain forest management thus needs to prioritize between competing management objectives at large spatial and temporal scales as well as between different silvicultural interventions at smaller scales. A vision for future research could be to develop an interactive spatially explicit evaluation tool, in close collaboration with forest engineers, landscape planners and policy makers, which allows to simulate the influence of different management strategies on structural dynamics and, therefore, on forests’ protective effects under climate change and land-use scenarios. Such a tool could be built on a risk-based approach allowing comparisons of costs and benefits of diverging management options and, moreover, to account for trade-offs with other ES in terms of a multifunctional and sustainable management of mountainous regions.
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Appendix A

Paper VII

Avalanche protection by forests - A choice experiment in the Swiss Alps

Received 14 March 2011
Received in revised form 29 September 2011
Accepted 3 October 2011
Available online 13 November 2011

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Abstract

Forests provide a variety of ecosystem goods and services to society, which often have the typical characteristics of a public good: non-excludability and non-rivalry. One of these services is avalanche protection of forests. A monetary valuation of this service would be helpful to provide efficient and effective protection to the local population. We present the results of a case study from the Swiss Alps, where we determined the willingness to pay for avalanche protection based on a choice experiment combined with virtual reality visualizations. Furthermore, we compare these results with the costs of alternative technical measures for natural hazard mitigation as well as with the results of a risk-based evaluation. We conclude that the willingness to pay for avalanche protection of forests is about the same range as the collective risk related to a 300-years avalanche event and within a range similar to the per-household costs of alternative measures. However, willingness to pay is substantially higher than the costs of silvicultural measures to maintain protection forest.

Keywords: Cost–benefit analysis, Environmental services, Public goods, Natural hazards, Risk, Visualization

1 Introduction

1.1 Background

Forests generate a wide range of ecosystem goods and services (ES) to the population (MA, 2005). One of the main ESS of forests in mountainous regions is the protection of people and infrastructure against natural hazards, such as snow avalanches (Brang et al., 2006). In Switzerland, about 43% of the forests have a protective function (Brändli, 2010). Since this service is a typical public good, it is seldom marketed and, thus, information about its economic value is lacking.

Planning and maintaining avalanche protection by forests often requires decisions concerning different technical and silvicultural measures, even more, since catastrophic storm events have increased in recent decades (Usbeck et al., 2010). In order to provide a comprehensive basis for decision-making in landscape planning and costefficient forest management, alternative evaluation techniques can be applied (Grêt-Regamey et al., 2008b; Olschewski et al., 2008).

Recent studies have shown that Choice Experiments (CE) are feasible instruments to value hazard-mitigating services of forests. While some authors focus e.g. on the determination of the value of statistical life (Rheinberger, 2009), others concentrate on particularities such as the impact of small risk changes on the valuation results (Leiter and Pruckner, 2009). Further, Haegeli et al. (2010) used CE to investigate decision-making strategies of different groups of recreational travelers in avalanche terrains. As a novelty, we combine a choice experiment determining the willingness to pay for avalanche protection with risk-based evaluation techniques, virtual reality visualizations, and alternative cost estimations in a comprehensive interdisciplinary analysis. Thereby, our study goes beyond the conventional costeffectiveness approach of avalanche protection measures by determining benefits based on stated preferences instead of avoided costs (compare e.g. Fuchs et al., 2007).

1.2 Study area

The Swiss municipality Andermatt, Canton Uri, has about 1250 inhabitants with additional overnight accommodation for 1500 tourists, and lies at an altitude of about 1450 m above sea level (m asl). Our study area comprises the north facing slope of ‘Gurschen’ reaching an altitude of about 2000 m asl with a gradient continuously above 30°. The annual average temperature is 2.7°C, with a margin of -6.7°C in January and 11.8°C in July. The annual average precipitation is 1280 mm and snow height is 1.7 m on average with extremes of more than 3.0 m (Olschewski et al., 2011).

The protection forest is highly important for preventing avalanche hazards. This has been officially recognized by putting a ban on access and harvesting since the year 1397. Lining and reforestation projects starting from 1874 on led to an expansion of the protection forest from 4 ha to about 24 ha nowadays, which is dominated by Norway spruce (Picea abies (L.) H. Karst) mixed with individuals of European larch (Larix decidua Mill.) and Swiss stone pine (Pinus cembra L.). The core area consists of an about 300-year-old spruce forest surrounded by younger afforested areas. The protection forest
has partly been destroyed by the storm ‘Vivian’ in 1990; this area has been reforested with Norway spruce. In the area above the protection forest additional technical linings have been installed since the 1950s (Olschewski et al., 2011).

2. Methodology

2.1 Damage potential and risk analysis

Risk analyses allow for a transformation of the protective function into economic values. To evaluate this function in our study region, we determined the damage potential of an avalanche event with a reoccurrence period of 300 years. The risk of this extreme event has been calculated following the recommended uniform procedure for risk analyses (Bründl et al., 2009; Borter, 1999), where risk is defined as the product of the probability of a damaging event and its consequences

\[ R_j = \sum p_j \cdot A_j \]  

(1)

where \( R_j \) is the risk depending on scenario \( j \), \( p_j \) is the probability that scenario \( j \) occurs, and \( A_j \) is the damage potential as the sum of damages to objects and people affected in scenario \( j \).

The approach for valuing the impact of the assumed wind-throw area as well as of different forest structures on the annual collective risk of the municipality Andermatt is based on the methodical framework presented in Teich and Bebi (2009). In addition to the classical risk analysis, this procedure of a GIS-based risk evaluation contains a classification of forest structures based on aerial photographs, the calculation of potential avalanche release areas within the forest and the prediction of avalanche runout distances using the two-dimensional numerical avalanche dynamics program RAMMS (Christen et al., 2010).

The damage assessment includes the identification of endangered objects located in the runout areas of the simulated avalanches. Thus, the damage potential consists of expected damages to exposed buildings and the expected loss of lives in these buildings (Bründl et al., 2009).

2.2 Choice experiment

We determined the willingness to pay (WTP) for avalanche protection by applying a choice experiment. This stated preference technique aims at determining, which factors or attributes are most important for the choice decision (Train, 2003). It is assumed that the choice decision depends on the utility derived from the different attribute levels: the higher a positive attribute level, the higher the utility, and consequently, the higher the probability to be chosen. The approach is based on random utility theory, where the utility of individual \( n \) from alternative \( i \) can be expressed as

\[ U_{ni} = V_{ni} + \varepsilon_{ni} \]  

(2)

with \( U \) being the utility function, \( V \) the observable component given by the attributes, and \( \varepsilon \) the unobserved random component (Louviere, 2001). We assumed this component to be independently and identically ‘extreme value’ distributed, which allows to apply a multinomial logit model for data analysis. While this seems to be a rather restrictive assumption, according to Train (2003) it can also be interpreted as a ‘natural outcome of a well-specified model’, when the target is to specify the utility function well enough, so that the logit model is the appropriate one. Furthermore, a possible violation is supposed to be more problematic when substitution patterns are to be forecasted instead of estimating average willingness to pay as done in our case (compare Train, 2003).

One of the acknowledged caveats of a logit model is that respondents' preferences are supposed to be homogeneous. In contrast, a mixed-logit model would allow to take heterogeneous preferences into account. This is especially useful in case that the sample consists of several segments, each of which with a unique and specific choice preference (Train, 2003). However, we refrained from using a mixed-logit model and the respective segmentation, given the small sample size and the relatively low response rate.

Special emphasis has been put on a clear and concise wording of the questionnaire. As questions related to the valuation of natural hazards might lead to misunderstanding and distorted answering, we conducted expert interviews, focus groups and pre-tests to clarify possible ambiguities.

In our basic scenario we assume that a wind throw has damaged about 1 ha of the protection forest. This scenario is particularly appropriate for our study region, because most of the population in Andermatt is still familiar with the
consequences of the storm Vivian in 1990. Furthermore, it enables us to determine, which aspects or attributes of avalanche protection are actually important to the population. To do this, alternative measures to restore avalanche protection were introduced and described by five different attributes: type of measure, starting time, duration, damage avoidance and costs (compare Table 1).

**Table 1.** Attributes and levels of protection alternatives.

<table>
<thead>
<tr>
<th>Attributes</th>
<th>Levels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type (TY)</td>
<td>Logs Grills Bridges Nets</td>
</tr>
<tr>
<td>Damage avoidance (DA, in %)</td>
<td>50/60/70 60/70/80 70/80/90 70/80/90</td>
</tr>
<tr>
<td>Duration (T, in years)</td>
<td>15/20/25 20/25/30 60/70/80 60/70/80</td>
</tr>
<tr>
<td>Starting time (ST, in years)</td>
<td>1 / 3 / 5 1 / 3 / 5 1 / 3 / 5 1 / 3 / 5</td>
</tr>
<tr>
<td>Costs (CO, in USD)</td>
<td>100/150/200 200/250/300 400/500/600 400/500/600</td>
</tr>
</tbody>
</table>

*All calculations have been made in CHF. For publication purposes, CHF values have been transformed into USD based on a 1:1 exchange rate (CHF/USD), which approximately reflects the average exchange rate throughout 2010.

Different level labels have been assigned to the same attribute in order to reflect particularities of the respective technical measures. According to Hensher et al. (2005) this does not cause any problems, as long as the labels for quantitative attributes are equally spaced within each attribute. In our example the costs of logs but also their potential to avoid damages is supposed to be lower than that of grills, bridges and nets. Additionally, life time differs due to earlier natural decomposition of wooden materials. Note that the attribute ‘Type’ has four different level labels, which are held constant. The payment vehicle has been designed as a one-time (lump-sum) payment. Thus, costs (in USD) were supposed to be added to the households’ income tax bill of the specific year, in which the protection measure is implemented.

Different combinations of attribute levels are combined in choice sets consisting of three options (compare Table 2). Each respondent was asked to choose one out of three options from 10 subsequent choice sets.

When deciding which experimental design to apply, we focused on two basic requirements: (i) a minimal overlap between options and (ii) a balance of level attributes, whereas orthogonality was given minor importance (compare Johnson et al., 2007). We opted for the so-called ‘short-cut design’, developed by Sawtooth (2008). This design ensures that each option within a choice set is built by choosing attribute levels used least frequently in previous options for a specific respondent with the aim to minimize overlap, i.e., to keep the options in any task as different from one another as possible (Sawtooth, 2008).

Additionally, the design takes into account that one-way frequencies of the attribute levels are balanced, which is appropriate for our analysis given that we aimed at estimating main effects, only. Furthermore, given the small sample size and a low expected response rate, the short-cut design seemed to be promising to generate more information by combining utmost different options in every choice situation.

**Table 2.** Example of a choice set.

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Option A</th>
<th>Option B</th>
<th>Option C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>Steel bridges</td>
<td>Wooden grills</td>
<td>Wooden logs</td>
</tr>
<tr>
<td>Start in years</td>
<td>in 3 years</td>
<td>in 5 years</td>
<td>in 1 year</td>
</tr>
<tr>
<td>Duration in years</td>
<td>70 years</td>
<td>30 years</td>
<td>20 years</td>
</tr>
<tr>
<td>Damage avoided</td>
<td>80% 60% 70%</td>
<td>60% 70% 80%</td>
<td>70%</td>
</tr>
<tr>
<td>Cost per hh</td>
<td>500 USD</td>
<td>150 USD</td>
<td>250 USD</td>
</tr>
<tr>
<td>Choice</td>
<td>□</td>
<td>□</td>
<td>□</td>
</tr>
</tbody>
</table>

We further specified the observable component \( V \) given in Eq. (2) as depending on the discounted risk reduction \( DR \), the costs per household \( CO \) and the type of protection measure \( TY \) (compare Eq. 3):

\[
V_{ni} = \alpha \cdot DR_{ni} + \beta \cdot CO_{ni} + \gamma \cdot TY_{ni}
\]  

(3)

Eq. (4) shows in detail how the discounted risk reduction \( DR \) (in USD) is determined: the first component considers the time \( ST \) (in years) it takes to establish protection measures and includes the discount rate \( \delta \) (in percent). The second term sums up the discounted annual risk reduction \( R \) during the project duration \( T \) (in years) (compare Alberini et al., 2007).

\[
DR = e^{-\delta \cdot ST} \cdot \int_{0}^{T} R \cdot e^{-\delta t} dt
\]  

(4)

By assuming that utility depends on different attributes, we can (i) determine whether there is a significant positive or negative impact, and (ii) analyze trade-offs between specific attributes by building the ratio of any two coefficients. The reason can easily be seen in Eqs. (5) and (6),
where the total derivative of the utility function \(U\) (e.g. with respect to risk reduction and costs) is set to zero:

\[
dU = \left(\frac{\partial U}{\partial DR}\right) dDR + \left(\frac{\partial U}{\partial CO}\right) dCO = \alpha \cdot dDR + \beta \cdot dCO = 0
\]

(5)

\[
\frac{\alpha}{\beta} = \frac{dCO}{dDR}
\]

(6)

The marginal value or implicit price of an attribute can thus be calculated as the negative of its coefficient divided by the coefficient of the cost variable, and reflects people's WTP to achieve more of the respective attribute (Bennett and Adamowicz, 2001). Note that in our particular case the ratio of \(\alpha\) and \(\beta\) reflects the increase in costs that keeps the household at a constant utility level given a reduction in avalanche risk.

\[
WTP = -\frac{\alpha}{\beta} \cdot DR
\]

(7)

### 2.3 Visualization

In order to avoid anomalies within non-market valuation studies the evaluability of attribute levels is crucial. Particularly for communicating attribute levels of primarily visual environmental goods, such as land-cover change, visual stimuli have proved to be very effective (Bateman et al., 2009). The use of visual stimuli is not new in preference studies and techniques, such as photomontages, photo manipulations or 3D landscape visualizations based on Geographical Information Systems (GIS), have been used for representing the landscape view corresponding to scenarios of land-cover change (Laforêt et al., 2008; Grêt-Regamey et al., 2007; Tress and Tress, 2003; Ode et al., 2009). Recent findings show that integrating virtual reality visualizations into choice experiments reduces the variability of preferences and significantly reduces the asymmetry between willingness to pay (WTP) for gains and willingness to accept (WTA) for corresponding losses (Bateman et al., 2009). For these reasons we applied 3D landscape visualization techniques to increase respondents' familiarity with the basic scenario and the alternative protection measures.

In contrast to the manipulation of two dimensional photos, 3D landscape visualization offers powerful means to reproduce the conditions given in the study region rather realistically using GIS data as a basis and provide views from any perspective. A digital elevation model with 2 m resolution, orthophotos as well as land-cover data such as building footprints, forest areas and existing steel bridges for avalanche protection were used as input data to the software package ‘Visual Nature Studio’ (VNS 3; www.3dnature.com). Following a general visualization workflow, further objects were added to the basic 3D landscape model (Wissen Hayek et al., 2010). Trees were represented by billboards based on photos and buildings as simple house models with generic facade textures based on photos taken in the study area. 3D models of technical constructions for avalanche protection were generated with ‘Google SketchUp Pro’ (http://sketchup.google.com). Iterative consultation of experts for the evaluation of intermediate results and adaptation of the visualizations according to their feedback, ensured a precise representation of protection measures and vegetation. In this way, we developed a virtual 3D landscape model of relative high visual realism (compare Fig. 1).
3. Results

3.1 Damage assessment and risk analysis

Under current conditions – without wind throw – the damage potential in our study region adds up to approx. 20.5 million USD for an avalanche event with a 300-years reoccurrence period. This corresponds to an annual collective risk of approx. 68,500 USD for the municipality of Andermatt. The respective avalanche release areas and runout zones are shown in Fig. 2 (left and right side).

Assuming that a wind throw has damaged about 1 ha of the protection forest (yellow filled area in the middle of Fig. 2), the damage potential would increase up to approximately 29.5 million USD, resulting in an annual collective risk of approx. 98,500 USD. Thus, the additional risk generated by the wind throw area is about 30,000 USD per year. Referring to a project duration of 80 years, which is the highest level of our attribute ‘duration’, the discounted risk sums up to 470 USD per household.

3.2 Choice experiment

All households in Andermatt have been sent a postal invitation to participate in an online survey, and of a total of 488 households 129 completed the survey, i.e., 26%. Possible explanations for this relatively low response rate can be found in the specific circumstances of our survey. The abstract theme of avalanche protection or the switch from postal invitation to internet questionnaire might have impeded a broader participation. However, the ascertained socio-demographic data (education, age, income, household size,…) indicated that a sufficiently broad coverage has been reached, thereby reducing the possible impact of a self-selection bias. The statistical analysis has been conducted by using the ‘BIOGEME’-software (Bierlaire, 2003, 2008). All selected attributes have a significant influence on the result (compare Table 3). The coefficients have the expected sign: discounted risk reduction (DR) is positively related to utility, while increasing costs (CO) have a negative impact on the derived utility. The discount rate \( \delta \) has been estimated simultaneously and results in 14.5%.

The willingness to pay (WTP) for avalanche risk reduction can be determined, as described above, by building the ratio of the respective coefficients (compare Eq. 8):

\[
WTP = -\hat{\alpha} / \hat{\beta} \cdot DR = -\frac{0.00104}{-0.00484} \cdot DR = 0.215 \cdot DR
\] (8)
According to Eq. (4), the discounted risk reduction depends on project duration, starting time, damage avoidance, and the discount rate. Table 4 shows some possible combinations of these attributes. Note that for the statistical routine $DR$ has been multiplied by 0.01 and coded accordingly in order to avoid conditioning problems due to different parameter magnitudes. Thus, the ratio $\hat{\alpha}/\hat{\beta}$ in Eq. (8) has to be multiplied by the same figure to properly reflect the correct dimension of WTP.

The estimated willingness to pay (lump-sum at the beginning of the project) varies between 110 USD for Scenario A (starting after 5 years with a duration of 15 years and a damage avoidance of 50%) and 390 USD for Scenario C depending on the combination of attributes. The respective annuities as constant payments throughout project life time are given in the last column of Table 4. Note that these results relate to avalanche protection in general, i.e., irrespective of the type of measure. Consequently, they can also be interpreted as willingness to pay for protection by forests, under the condition that the forest has a similar effectiveness as technical measures in preventing avalanches.

### 3.3 Costs of avalanche protection

Efficiency requires the comparison of benefits and costs. While benefits have already been estimated as risk reduction and WTP, we additionally determined the costs of alternative protection measures. These are, on the one hand, alternative costs of constructing and maintaining technical protection, completed by reforestation with the aim that growing trees can take over the protection function in the future. On the other hand, there are avoidance costs of silvicultural measures taken to maintain the existing forest and to reduce vulnerability to storm events right from the start. For all measures current investment costs and future maintenance costs are determined and discounted to the present. Then these values are assigned to all households assuming that the municipality has to bear 25% of the overall costs (compare Table 5).

### 4 Discussion

Valuation of public goods such avalanche protection is often based on the determination and comparison of costs. However, cost estimates do not necessarily reflect the benefits generated by protection measures. Our study takes both costs and benefits into account.

### Table 3. Estimated coefficients and log-likelihood function.

<table>
<thead>
<tr>
<th>Attributes</th>
<th>Coefficient</th>
<th>Std err</th>
<th>t-test</th>
</tr>
</thead>
<tbody>
<tr>
<td>Risk reduction (DR)</td>
<td>0.00104</td>
<td>0.000144</td>
<td>7.18</td>
</tr>
<tr>
<td>Costs (CO)</td>
<td>-0.00484</td>
<td>0.000458</td>
<td>-10.58</td>
</tr>
<tr>
<td>Type (TY)</td>
<td>0.341</td>
<td>0.0664</td>
<td>5.14</td>
</tr>
<tr>
<td>Discount rate (δ)</td>
<td>0.145</td>
<td>0.0270</td>
<td>5.39</td>
</tr>
<tr>
<td>Log L</td>
<td>-1301.21</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Table 4. Willingness to pay (WTP) based on different attribute levels.

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Project duration (T)</th>
<th>Starting time (ST)</th>
<th>Damage avoidance (DA)</th>
<th>Annual risk reduction (R)</th>
<th>Discounted risk reduction (DR)</th>
<th>Lump sum payment (WTP)</th>
<th>Annuity (WTP)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(years)</td>
<td>(years)</td>
<td>(%)</td>
<td>(USD)</td>
<td>(USD)</td>
<td>(USD)</td>
<td>(USD)</td>
</tr>
<tr>
<td>A</td>
<td>15</td>
<td>5</td>
<td>50</td>
<td>16,700</td>
<td>50,750</td>
<td>110</td>
<td>18</td>
</tr>
<tr>
<td>B</td>
<td>60</td>
<td>3</td>
<td>70</td>
<td>23,300</td>
<td>107,150</td>
<td>230</td>
<td>33</td>
</tr>
<tr>
<td>C</td>
<td>80</td>
<td>1</td>
<td>90</td>
<td>30,000</td>
<td>180,700</td>
<td>390</td>
<td>56</td>
</tr>
</tbody>
</table>
4.1 Willingness to pay and collective risk

Interestingly, the comparison of the willingness to pay for risk reduction based on the CE results and the collective risk caused by our hypothetical wind throw area have about the same level. Note that WTP for risk reduction has not directly been asked for, but has been determined indirectly by combining several attributes (damage avoidance, starting time and duration of the project). This procedure proved to be advantageous because it reduces probable cognitive difficulties of the respondents to understand the risk concept, especially when taking the different time horizons of the alternative measures into account.

Concerning the collective risk estimates, it has to be taken into account that the expected loss of human lives has been valued by an amount of approx. 5 million USD each (Bründl et al., 2009). As a consequence, the expected mortalities contribute about 90% to overall risk, which means they have overwhelming impact compared to damages of buildings. Thus, reducing the assumed average number and presence of people in exposed buildings, would lead to a substantial reduction of the annual collective risk. However, our approach would allow for including such changes by adapting the respective lower discounted risk reduction in Eq. (8). Recently, other authors have applied probabilistic approaches to consider uncertainty related to input parameters when estimating avalanche risks (Grêt-Regamey and Straub, 2006).

4.2 Willingness to pay and alternative costs

When comparing the costs of the alternative measures with the estimated willingness to pay, we found that WTP for risk reduction is substantially higher than the costs of wooden measures against avalanches (logs and grills), whereas costs of steel bridges and nets would not be covered by WTP. (Note that we assumed that the households’ contribution sums up to 25% of the overall costs, which represents a realistic cost sharing between municipality, canton and federal state in Switzerland.) This indicates that the population of Andermatt seems to be well acquainted with the situation on the spot: the combination of wooden constructions and reforestation measures is regarded as an adequate solution, when disturbances create new avalanche release areas within forested terrain (Olschewski et al., 2011).

However, the preferable solution from an economic point of view is the maintenance of the existing forest, because protection is provided at lowest costs. While this is desirable also from the ecological point of view, the result crucially depends on whether avalanche protection can actually be ensured in the long run. Therefore, maintenance and silvicultural management should focus on both increasing effectiveness against avalanches as well as reducing vulnerability to heavy storm events. Furthermore, the early and steady regeneration of the forest is crucial for a fast re-establishing of the protection function, once a wind throw has taken place.

4.3 Interest rate

The estimated interest rate of 14.5% is slightly higher compared to other studies related to natural hazards and mortality risks. Rheinberger (2009) found that people discount mortality risks by about 12%, whereas Alberini et al. (2006) estimated that people discount future risk by 7.4 to 9.1% depending on the model specification. Moore and Viscusi (1990) determined a margin from 1 to 14% for people discounting fatality risks. One possible explanation for the relatively high discount rate might be seen in the age structure of the respondents in our study region: The average age was 53; 65.4% of all respondents belonged to the class aged 40–64, which is a substantially higher proportion than the respective figure (35.5%) for the average population in Switzerland (Swiss Statistics, 2010). Therefore, we re-estimated the model for different age classes separately. We found that the estimated discount rate drops to 13.6%, when just considering respondents aged 50 or younger. This indicates that the age structure of the participants had influence on the results.

4.4 Landscape esthetics

Willingness to pay for avalanche protection might be influenced by esthetical aspects related to specific protection measures. We took this point into account by asking how important landscape esthetics has been when making choice decisions between the options. 75% of the respondents answered that this aspect was ‘important’ or ‘rather important’, whereas only 10% said it was unimportant. This result stresses the role of visualizations for the perception of the
different options but also for the understanding of the questionnaire as a whole. As one of the advantages of an online survey, respondents had the opportunity to enlarge the visualizations by pop-up windows on the screen, thereby getting a better impression of the wind throw area and the visual impact of the technical measures. As a result, only 5% of the respondents found the questionnaire ‘incomprehensible’ or ‘partially incomprehensible’, and just 2% judged the selected scenarios to be unrealistic. However, due to the small sample size and the low response rate we refrained from using more demanding models, such as mixed-logit, which would have allowed to take heterogeneous preferences into account.

5 Conclusions

Combining a choice experiment with risk-based evaluation techniques, and GIS-based 3D landscape visualization, as well as alternative cost estimations based on engineering and silvicultural knowledge, surely is a complex procedure. As mentioned by Hoyos (2010), conducting such studies needs strong interdisciplinary collaboration. However, it turned out to be an adequate approach to value and compare different aspects of avalanche protection services. The present study provides valuable information to decision-making in the fields of landscape planning and silvicultural management. The comparison of WTP with risk and cost estimates, give guidance towards efficient solutions for avalanche protection in mountainous regions.

Acknowledgement

This project has been conducted under the EU-COST-Action E45 (EUROFOREX) and financed by the Swiss State Secretariat for Education and Research (SER). We would like to thank all people involved in the organization and realization of this study, especially the local authorities and inhabitants of Andermatt.

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Appendix B

Paper VIII

Avalanche simulations in forested terrain: A framework towards a Bayesian probabilistic model calibration

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Abstract

Avalanche dynamics models are used for hazard zoning and engineering to predict runout distances and impact pressures of snow avalanche events. The effect of mountain forests as an effective biological protection measure against avalanches has rarely been addressed in this context. Avalanche runout distances of small to medium avalanches are strongly influenced by the structural conditions of forests in the avalanche path; however, this varying decelerating effect has not yet been implemented in avalanche models. Within the two-dimensional avalanche dynamics program RAMMS the standard Voellmy-Salm model can be applied to predict runout distances, flow velocities and impact pressures in complex three-dimensional terrain. Currently, the occurrence of forests is realized by increasing but constant friction parameters $\mu$ (dry-Coulomb type friction) and $\xi$ (velocity squared friction) compared to open unforested terrain. Back-calculations of 41 well documented small avalanches which released in forests of the Swiss Alps emphasize the need for a further calibration dependent on differences in forest structure. Since the friction parameters are more conceptual than physical, they must be fitted by matching model results and recorded data which basically involves solving an inverse problem. A way of providing probabilistic statements about unobservable information is Bayesian inference. Therefore, we present a framework for a Bayesian probabilistic model calibration of the friction parameter $\xi$ accounting for differences in forest structure in the avalanche path. Considering different forest characteristics within avalanche simulations will improve current applications for avalanche models, e.g. in mountain forest and natural hazard management.

1 Introduction

Avalanche dynamics models are widely used for hazard zoning and engineering to predict runout distances and impact pressures of snow avalanche events. The effect of mountain forests as an effective biological protection measure against avalanches has been rarely addressed in this context (Teich and Bebi, 2009); however, avalanche flow in forested terrain is strongly influenced by the condition and composition of vegetation in the avalanche path (e.g. Bartelt and Stöckli, 2001; Teich et al., 2012a). This effect has not yet been implemented in avalanche models (Anderson and McClung, 2012).

The Voellmy-Salm (VS) model (Salm, 1993) is the basis for hazard mapping in Switzerland. This numerical avalanche model requires two empirical friction coefficients to be defined by the avalanche expert; the total basal friction is split into a velocity independent dry-Coulomb type friction $\mu$ and a velocity dependent “viscous” or “turbulent” friction $\xi$. A sensitivity analysis on the influence of varying friction parameters for forests of a VS-based two-dimensional avalanche dynamics program has shown that slight alternations especially of the friction parameter $\xi$ for forests could have a vital impact on risk calculations (Teich and Bebi, 2009). However, friction parameters for forested areas were only rarely verified with real avalanche events (e.g. Casteller et al., 2008; Takeuchi et al., 2011).

Since the friction parameters are more conceptual than physical, they cannot be measured for real avalanches and must be fitted by matching avalanche dynamics model results and recorded data which basically involves solving an inverse problem (Ancey et al., 2003). A way of providing probabilistic statements about unobservable information is Bayesian inference. Bayesian methods have already received attention in avalanche modeling (e.g. Straub and Grêt-Regamey, 2006; Gauer et al., 2009; Eckert et al., 2010); however, they have never been applied to calibrate the friction parameters of an avalanche dynamics model to improve avalanche simulations in forested terrain.

We applied the two-dimensional numerical avalanche dynamics program RAMMS (Christen et al., 2010) and back-calculated several avalanche events in forests. We compared the model output with observed runout distances to estimate the decelerating effects of different forest structures, and propose a Bayesian probabilistic framework to calibrate the friction parameter $\xi$ for avalanche simulations in forested terrain based on the observations.

Implementing avalanche-forest interactions into numerical avalanche simulations will open new fields of application for avalanche models, e.g. for managing mountain forests and by better accounting for the protective effect of forests in natural hazard mapping.
2 Avalanche simulations in forested terrain

The two-dimensional avalanche dynamics program RAMMS (RApid Mass MovementS) is a practical tool to predict avalanche runout distances, flow velocities and impact pressures in complex three-dimensional terrain by solving a system of partial differential equations using first and second order finite volume techniques (Christen et al., 2010). The model allows to apply two different flow rheologies: (1) the standard Voellmy-Salm (VS) model (Salm, 1993), or (2) a random kinetic energy (RKE) model which additionally includes the random motion associated with the mass of flowing granules.

For our purpose, we applied the VS model which employs a ‘Voellmy-fluid’ flow law and splits the total basal friction into a velocity independent dry-Coulomb term (friction coefficient $\mu$) and a velocity dependent “viscous” or “turbulent” friction (friction coefficient $\varsigma$) (Salm, 1993). Currently, the presence of forest in the avalanche path is realized by increasing but constant friction parameters, i.e. $0.02$ is added to the $\mu$-value and $\varsigma$ is set to $400 \text{ m/s}^2$.

In order to evaluate the performance of RAMMS in forested terrain, we back-calculated 41 small avalanches which released in forests of the Swiss Alps with runout distances ranging between 50 and 700 m (for details see Teich et al., 2012a; Feistl et al., 2012; Teich et al., 2012b). We applied the friction parameters $\mu$ and $\varsigma$ which were calculated automatically in RAMMS based on a digital elevation model (DEM) with a spatial resolution of 2 m and a shapefile characterizing forested areas. The avalanche simulations were accomplished assuming a 10 year return period, the stopping criteria of a 10% flow momentum threshold, a minimum flow height of 10 cm and a simulation time of 100 s. For the interpretation of the simulated avalanche runout distance, we used the maximum flow momentum as the product of flow height and velocity in m$^2$/s for avalanches with a release volume $V_R \geq 50$ m$^3$ or the maximum flow height for avalanches below this $V_R$ threshold. The avalanche runout distance was measured along a representative flow line following the stream network identified by a GIS software.

Selected forest structural parameters (forest type and crown closure (see Table 1), vertical structure, stage of development), the type of snow (dry or wet snow avalanche), the mean slope angle over the whole avalanche area and the cross-slope curvature (flat or gully) were assigned to all 41 avalanches based on collected field data, orthophotographs and DEM analyses (for details see Teich et al., 2012a). Spearman’s rank correlation coefficient ($r_S$) was then calculated and tested for significance ($p \leq 0.05$) to evaluate statistical dependencies between those variables and the modeled runout distances compared to the observed ones ($\Delta$runout in %).

### Table 1. Description of the forest parameters ‘forest type’ and ‘crown closure’ which were assigned to each observed forest avalanche.

<table>
<thead>
<tr>
<th>Forest parameter</th>
<th>Categories and description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Forest type</td>
<td>(1) “Mixed forests” contain deciduous forest, mostly dominated by European beech (<em>Fagus silvatica</em> L.), (2) “Evergreen coniferous forest” dominated by Norway spruce (<em>Picea abies</em> (L.) H.Karst.), (3) “Deciduous coniferous forest” formed by European larch (<em>Larix decidua</em> Mill.) at the upper tree line</td>
</tr>
<tr>
<td>Crown closure</td>
<td>(1) Dense to loose (Crown coverage &gt;70%), (2) Scattered (Crown coverage 40-70%), (3) Open (Crown coverage &lt;40%)</td>
</tr>
</tbody>
</table>

The comparison of observed with simulated runout distances of our dataset reveals that runout distances of 28 avalanches were overestimated by the model (Fig. 1); for two avalanches by more than 400%. Calculations of Spearman’s rank correlation coefficient have shown that the only variable which affects the difference between observed and simulated runout distances significantly was the mean slope angle ($r_S = 0.32; p = 0.042$) which supports our initial hypothesis that the varying effect of forests on avalanche runout is unsatisfactorily represented within RAMMS.

Even if the influence of different forest types was not statistically significant, we assume varying decelerating effects of the three forest types of our dataset since avalanche runout distances were highly overestimated by the avalanche model in mixed forests (median = 137%; mean = 166%) and evergreen coniferous forests (median = 117%, mean = 146%), but relatively well predicted in deciduous coniferous forests (median = 100%, mean = 120%). Based on cross-correlations between the forest parameters, we chose crown coverage as a second variable characterizing forest density for the characterization of differences in forest structure to be implemented in avalanche
simulations. Regarding the practical application, both forest parameters (forest type and crown coverage) are easy to delineate from orthophotographs.

3 Bayesian probabilistic model calibration

In general, Bayes’ theorem allows for updating a prior probabilistic model of unknown parameters $\Theta$ with the observed data $q$ of the process under consideration. Bayes’ theorem in its general form is given by:

$$p_{\Theta|q}(\Theta) \propto L(\theta|q) p_\Theta(\Theta)$$  \hspace{1cm} (1)

The likelihood function $L(\theta|q)$ describes how likely the observed realizations of the random process $q$ are, given a particular value of the variables $\theta$. The posterior probability distribution $p_{\Theta|q}(\Theta)$ represents the probabilistic solution to the inverse problem and is, thus, the joint probability function between the a-priori states of information associated to both the prior and the likelihood.

Here, $\zeta$ is the parameter modeled probabilistically while the second friction coefficient $\mu$ is considered deterministically, i.e. $\mu$ is part of a set of constants $c$ which includes all inputs to the model that are considered as deterministic such as topography or the release height. Since different $\zeta$-values are used in the avalanche model for the different topographical classifications and surfaces, we do not represent $\zeta$ by a single random variable. Instead, a parameter scenario represents the random variable $\Theta_z$ with realizations $\theta_1, ..., \theta_{10}$ based on the original choice of the automatic assignment procedure of the avalanche model with varying $\zeta$-values for forested areas (100-1000 m/s²), assuming that one of these scenarios contains the “true” value for the respective forest conditions, yet it is unclear which.

Figure 2 shows the Bayesian network (BN) for the probabilistic calibration of the friction parameter $\zeta$. BNs are directed acyclic graphs (DAGs) where each random variable in the model corresponds to a node and arrows between nodes show direct dependencies to structure the problem (see e.g. Jensen and Nielsen, 2007). Because the model is only a simplified representation of reality and some parameters which are considered as deterministic are actually uncertain, the error term $\varepsilon$ is assumed to be additive in the runout distance. This random error term must be included since the avalanche model cannot exactly match the observed avalanches as some inaccuracies and errors are always present. Based on the defined forest conditions which affect modeled as well as observed runout distances, we end up with nine cases where the corresponding $\zeta$-value needs to be updated for.

As mentioned above, statistics used for the posterior formulation are calculated from the evidence available before the probabilistic solution to the inverse problem, i.e. observations and model predictions. For estimating the posterior for each forest condition included in
Θ_ξ, it is required to integrate the posterior which can be solved numerically. This solution yields a full description of the uncertainty associated with Θ_ξ conditioned on the available data in contrast to deterministic optimization approaches where only one set of best estimates is retrieved. To solve the posterior integral, we will use WinBUGS (Lunn et al., 2000) which is a flexible software for Bayesian analysis using Markov chain Monte Carlo (MCMC) methods. Resulting posterior distributions for Θ_ξ will allow estimating updated ξ-values to be applicable for simulations of small avalanches in forested terrain by accounting for differences in forest structure.

4 Conclusions and outlook

The comparison between observed and simulated runout distances of 41 small avalanches applying currently used ξ-values for forests has shown that runout distances were relatively well predicted by RAMMS in deciduous coniferous forests, but highly overestimated in mixed forests and evergreen coniferous forests. Therefore, we assume that values for ξ < 400 m/s² need to be assigned to areas covered with the two latter forest types.

The proposed Bayesian probabilistic framework is a promising approach for the calibration of RAMMS to better perform in forested terrain. In contrast to deterministic optimizations, this approach gives a full description of uncertainties associated with the updated ξ-values conditioned on the available observation data.

Simulations with alternating ξ-values for forested areas (100-1000 m/s²) revealed also that runout distances of 19 avalanches were still overestimated by RAMMS when applying the smallest chosen ξ-value of 100 m/s². This indicates that calibrating only one friction parameter of the avalanche model might probably not lead to satisfying simulations in every case, and that other physical processes in avalanche dynamics modeling need to be taken into account when simulating small forest avalanches (Feistl et al., 2012).

Implementing avalanche-forest interactions into numerical avalanche simulations will improve current applications for avalanche models, e.g. for managing mountain forests and by better accounting for the protective effect of forests in natural hazard mapping. Especially when it comes to decisions about the size and extent of avalanche defense structures in potential starting zones in forested areas or directly above the treeline, forest and civil engineers could benefit from reliable avalanche simulations in forested terrain. Thus, there is an increasing need to consider different forest characteristics within avalanche simulations to be applicable for a practical natural hazard management.

Acknowledgements

We thank Marc Christen for his assistance performing the RAMMS simulations. This study was funded by the CCES (Competence Center Environment and Sustainability of the ETH Domain) within the project MOUNTLAND.

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Explicit avalanche-forest feedback simulations improve the performance of a coupled avalanche-forest model

Received 5 January 2013
Received in revised form 13 August 2013
Accepted 7 September 2013
Available online 28 October 2013

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Abstract

Many temperate and boreal mountain landscapes are strongly affected by snow avalanches. Forests can reduce avalanche release probability, leading to a positive feedback between forests and avalanches. The effects of this feedback, especially when influenced by changing environmental conditions, make the projection of the future developments of mountain forests and avalanches challenging.

In order to study this feedback under a wide range of environmental situations, we coupled a forest landscape model with a new probabilistic avalanche module. The coupled model TREEMIG-AVAL allows yearly spatially explicit simulations of climatically driven forest dynamics, with species-specific growth, mortality, and reproduction. Simulated spatially explicit avalanche release is driven by climate, topography, forest type and density. These factors, together with additional factors increasing tree mortality, influence the strength of the positive feedback between forests and avalanches. We investigated (a) the influences of the three environmental factors temperature, slope steepness, and additional mortality on the simulated dynamics of mountain forests and avalanches, (b) the plausibility of TREEMIG-AVAL, and (c) whether the complexity of TREEMIG-AVAL could be reduced. The sensitivity of avalanche release probability to environmental changes was thus compared between TREEMIG-AVAL and two simplified model versions.

The three environmental drivers had strong and often nonlinear influences on the simulated forest and avalanche dynamics. The simulated avalanche release probability showed linear to sigmoidal decreases with temperature, a peak-shaped response to slope steepness, and steep sigmoidal increases with additional mortality. However, these response shapes of avalanche release probability to each environmental factor changed along the axes of the two other factors studied. These interactions suggest that future mountain forest simulation studies should explicitly account for the influence of environmental drivers on the avalanche-forest feedback.

The simulations showed that the behavior of TREEMIG-AVAL is plausible and comparable to expert knowledge and previously published literature. Moreover, large differences in the sensitivity of the avalanche release probability to the environmental factors were apparent between TREEMIG-AVAL and the simplified model versions, revealing that for plausible simulations of avalanche-prone mountain regions it is necessary to explicitly account for the avalanche-forest feedback in TREEMIG-AVAL. In particular the simulated treeline was sensitive to changes in model structure and prone to underestimation of the avalanche release probability in the simplified model versions. When the feedback is explicitly accounted for, TREEMIG-AVAL is a useful tool for simulation studies of mountain forests including spatially explicit disturbances.

Keywords: Avalanche-forest feedback, Forest landscape model, Explicit feedback simulation, Mountain forests, Sensitivity analysis, TreeMig-Aval

1 Introduction

Mountain landscapes are influenced by various interacting factors including climate, topography, natural disturbances, and anthropogenic land use (Holtmeier and Broll, 2005; Kulakowski et al., 2011). In temperate mountain landscapes, snow avalanches are one of the most important disturbances (Bebi et al., 2009), and are expected to remain important also under a changing climate (Laternser and Schneebeli, 2003).

Avalanche release can often be prevented by forests, and accordingly, avalanche protection is considered one of the most important ecosystem services of mountain forests in the Swiss Alps (Grêt-Regamey et al., 2008; Teich and Bebi, 2009). Nevertheless, under certain combinations of climatic and topographical conditions and forest composition and structure, avalanches are still released from forested areas (Schneebeili and Meyer-Grass, 1992). In general, avalanche release probability decreases with increasing forest area and density (Bebi et al., 2009). Conversely, where avalanches are released, forests are subject to increased tree mortality and decreased growth, size and stand density (Kulakowski et al., 2006). This leads to an increase in the probability of further avalanches, and therefore to a positive feedback between the vegetation and disturbance (sensu Wilson and Agnew, 1992).

Both forests and disturbances, and therefore also the occurrence and strength of their
feedback, are influenced by local conditions such as topography and climate (Teich et al., 2012a,b). Furthermore, additional factors increasing tree mortality, such as livestock grazing, browsing, timber harvesting, insect damage, snow breakage, frost events, and snow fungi, can change the forest composition and structure and may influence the susceptibility of the forest to avalanche release (Kulakowski et al., 2011; Veblen et al., 1994). These disturbance interactions can be influenced by changing climatic conditions (Kulakowski et al., 2006), and vice versa, changes in the avalanche-forest feedback may change the sensitivity of forests to climate change (Bekker and Malanson, 2009).

Interactions between climate, topography, and additional mortality influence the avalanche-forest feedback, and can lead to high spatial and temporal complexity (Bigler et al., 2005; Kulakowski et al., 2011). This makes projections of future dynamics of mountain forests and avalanche release under environmental change extremely difficult. For the analysis of interactions between forests, avalanches, and changing environmental conditions, dynamic models are useful because of their potential to address large time spans and environmental gradients, and the possibility to analyze feedbacks (Malanson et al., 2011; Marston, 2010). However, despite several studies with explicit disturbance simulations (e.g., Fagre et al., 2005; Miller and Urban, 1999; Perry and Millington, 2008; Schumacher and Bugmann, 2006; Wimberly, 2004), forest models often lack an explicit and dynamic representation of disturbances (Marston, 2010; Seidl et al., 2011).

Avalanche dynamics have been studied in detail previously (e.g., Christen et al., 2010; Gruber and Bartelt, 2007), but to our knowledge they have never been explicitly implemented in forest models. Avalanche models often focus on single events over seconds to hours and centimeters to meters, and usually do not take into account forest dynamics and effects of different forest structures (Teich and Bebi, 2009). In contrast, forest models usually focus on trends over several decades to centuries and meters to kilometers, and the temporal and spatial patterns of disturbances are rarely simulated as an emergent model property (Seidl et al., 2011). Due to these differences in scale, coupling such models remains challenging (Perry and Millington, 2008).

A further challenge when coupling forest and avalanche models is the increase in model complexity, which can lead to equifinality, increased uncertainty, or model overfitting. Therefore, Van Nes and Scheffer (2005) suggested to analyze the behavior of the model, rerun the analysis with simplified model versions, and compare the outcomes of all versions, in order to remove unnecessary complexity of a model.

We coupled the dynamic spatially explicit forest landscape model TREEmig (Lischke et al., 2006; Rickebusch et al., 2007) with a new probabilistic and spatially explicit avalanche module. TREEmig was selected due to its ability to simulate long-term forest dynamics, its spatially explicit and spatially linked setup, and the species-specific calculation of forest dynamics. Here, we present the coupled model TREEmig-AVAL, and address the following questions:

1. What are the influences of the three factors temperature, slope steepness, and additional mortality on simulated avalanche release probability?
2. Can avalanches, and their feedback with forests, be plausibly represented in a forest landscape model despite the differences in scale?
3. Can the complexity of the coupled model be reduced without leading to loss of plausibility?

We analyzed the plausibility and sensitivity of TREEmig-AVAL, and examined whether simplified model versions, (a) without explicit simulation of the avalanche-forest feedback in the forest model or (b) without explicit simulation of forest dynamics in the avalanche module, could provide equally plausible results.

2 Model description

The coupled model TREEmig-AVAL allows the spatially explicit simulation of interactions between forests and avalanches, and influences of environmental changes on avalanches and forests (Fig. 1; see also Supplementary Material A).

2.1 Forest model

TREEmig (Lischke et al., 2006; Rickebusch et al., 2007) simulates tree establishment, growth, competition, reproduction, and mortality for each grid cell, driven by the yearly bioclimatic drivers day-degree sum (sum of mean daily temperatures above a 5.5°C developmental threshold),
minimum winter temperature, and a drought stress index. State variables are the densities of trees per species, height class and cell, and the cells are spatially linked by seed dispersal. TREEMig 1.0 simulates forest dynamics on grid cells of 100 m to 1 km. Within each cell, TREEMig simulates environment- and growth-related mortality rates, and a low background mortality which is often used in forest gap models (e.g. reviewed in Keane et al., 2001). Additional disturbances can be simulated by increasing the background mortality, but these disturbances are randomly distributed in space and time, and therefore not suitable for simulations of spatially explicit disturbances covering multiple connected cells.

Fig. 1. Diagram of the main components of the coupled avalanche-forest model TREEMig-AVAL, emphasizing the yearly interaction between forest and avalanches, and the factors influencing simulated forests and avalanches.

Five main changes were introduced into TREEMig 1.0 to adapt it for mountain forest simulations, resulting in TREEMig 1.0mf (for more information on the five main changes see Supplementary Material B). (a) The resolution was increased to 25 m cell side length based on a trade-off between sufficiently small cells for avalanche simulations and sufficiently large cells for forest dynamics simulations on a landscape scale. (b) Parameters of some of the mountain forest species were adapted. (c) Ground vegetation was introduced as a functional type to improve the simulation of light availability for tree seedlings. (d) Snow-induced mortality was introduced for conifers, representing the negative influence of snow on growing season length, and the potential harmful effects of snow fungi. (e) To link the forest simulation with the avalanche module, the new variables species specific crown area ($CA_{sp}$), total percent crown coverage ($pc_{tot}$), coniferous percent crown coverage ($pc_{cnf}$), and maximum gap size ($mgap$) were derived from the height class state variable.

### 2.2 Avalanche module

We analyzed historical avalanche release, forest, and climate data of Switzerland to derive equations for probabilistic avalanche release simulations. The avalanche release probability per cell and year ($P_{ar}$) consists of a topography- and forest-related avalanche release probability ($P_{arTF}$) multiplied with a climatic avalanche release probability ($P_{arC}$):

\[
P_{ar} = P_{arTF} \cdot P_{arC}
\]

For the $P_{arTF}$ simulations, three avalanche release situations $i$ were distinguished based on the different mechanisms leading to avalanche release (Bebi et al., 2001; Schneebeli and Bebi, 2004; Viglietti et al., 2010) in unforested areas ($i = 1; pc_{tot} < 20\%$), coniferous forests ($i = 2; pc_{cnf} \geq 60\%$, including *Larix decidua* L.), and mixed and broadleaf deciduous forests ($i = 3; pc_{cnf} < 60\%$, 'mixed forests'). Two data sources were available: a spatially explicit 50-year (1950–2001) avalanche release data set for unforested terrain (Gruber and Bartelt, 2007; Maggioni and Gruber, 2003) and a 5-year (1985–1990) avalanche release and forest data set for forested terrain (Meyer-Grass and Schneebeli, 1992). The 5-year forest avalanche data set included topographic and forest information for avalanche and control (avalanche free) areas, given as mean value per area ($\leq 0.3$ ha). Based on the available forest type information, the data set was split into coniferous and mixed forest subsets. The spatially explicit 50-year non-forest avalanche data were linked to a 25-m elevation model (DEM, Swiss Federal Office of Topography, 1994), and topographic information was extracted for avalanche areas and an equal number of randomly selected control (avalanche free) areas, using ESRI ArcMap 9.3.

We performed a separate logistic regression (binomial generalized linear model; GLM) on the avalanche and control data for each of the three avalanche release situations $i$, using topographic and forest data (where applicable) as predictors. The predictor variables were selected based on four criteria: (a) biological and physical significance in avalanche prediction (Schneebeli and Meyer-Grass, 1992), (b) a minimum of one forest-related variable per GLM in the two forest avalanche release situations, (c) availability of the variables in TREEMig, and (d) absence of significant correlations between the variables.
The variables were included in their linear and quadratic forms, and a stepwise reduction and tenfold cross-validation were used to select the predictor variables in the final models. The GLM variable selections and parameter estimates for each avalanche release situation \( i \) are given in Eqs. (2–4) and further information is given in Supplementary Material C.2. On unforested slopes \((i = 1, \text{Eq. 2})\), \( P_{\text{arc}} \) is mainly determined by slope steepness \((\text{slp})\) and curvature \((\text{crv}, \text{slope channelization})\), together with slope aspect \((\text{nth}, \text{northing}; \text{est, easting})\). In addition to \( \text{slp} \), the total percent coverage \((\text{pctot})\) and maximum gap size \((\text{mgap})\) are important in coniferous forests \((i = 2, \text{Eq. 3})\), while \( \text{pctot} \) and the coniferous percent coverage \((\text{pcnf})\) are important in mixed forests \((i = 3, \text{Eq. 4})\).

\[
\text{glm}_1 = a_i + b_1 \cdot \text{slp} + c_1 \cdot \text{slp}^2 + d_1 \cdot \text{crv} + e_1 \cdot \text{est} + f_1 \cdot \text{est}^2 + g_1 \cdot \text{nth} \\
\text{glm}_2 = a_2 + b_2 \cdot \text{slp} + c_2 \cdot \text{slp}^2 + d_2 \cdot \text{pctot} + e_2 \cdot \text{mgap} \\
\text{glm}_3 = a_3 + b_3 \cdot \text{slp} + c_3 \cdot \text{pcnf} + d_3 \cdot \text{pctot}
\]

To calculate \( P_{\text{arc}} \), the GLM predictions \( \text{glm}_i \) were backtransformed from logit scale to probabilities, and multiplied with a reference factor \((\text{ref}_i)\) for each avalanche release situation \( i \). Different reference factors were necessary to convert the avalanche release probability to the spatial and temporal resolution and configuration of TREEMIG-AVAL (Eq. 5 and Supplementary Material C.3).

\[
P_{\text{arcTF}} = \left(1 + e^{-\text{glm}_i}\right)^{-1} \cdot \text{ref}_i
\]

In the TREEMIG-AVAL simulations, \( P_{\text{arcTF}} \) is only calculated for slopes 28–60°, because avalanches are rarely released from slopes outside this range (McClung and Schaeerer, 2006). In the simulations, the three avalanche release situations are distinguished in each cell and year based on the forest structure and composition, and the GLM equation for the respective release situation is applied. \( \text{pctot} \) is used to distinguish between forested and unforested cells (threshold 20%; Bebi et al., 2009), and \( \text{pcnf} \) is used to distinguish between cells with coniferous and mixed forest (threshold 60%; estimated from Bebi et al., 2009; Schneebeli and Meyer-Grass, 1992).

The climatic avalanche release probability \( P_{\text{arc}} \) was approximated by monthly minimum temperatures and aggregated to yearly time steps (see Supplementary Material C.4). We used Swiss monthly temperatures from 11 weather stations over 30 years (Swiss Federal Office of Meteorology and Climatology, MeteoSchweiz) to estimate the proportion of each month that could have enough snow for avalanches (winter length). Additionally, we used the monthly temperature data to estimate snow accumulation and avalanche probability with empirical relationships (see Supplementary Material C.4), and averaged the monthly avalanche probability over the winter months of the historical temperature data (November–April). The resulting monthly avalanche release probability (11.9%) was then used for all winter months in the model (according to the winter length definition above). In each simulation year the number of winter months is multiplied with this probability to obtain the yearly climate influence \( P_{\text{arc}} \).

### 2.3 Model coupling

The interface between TREEMIG and the avalanche module consists of the input of forest structure information into the avalanche module, and the input of avalanche-induced mortality into TREEMIG (see Supplementary Material A). The avalanche module was coupled with TREEMIG by aggregating avalanches to 1-year time steps, and by downscaling the forest dynamics to 25 m cell side length (see Supplementary Material B.1). This resolution focuses on ecologically relevant properties for forest dynamics and enables simulations of larger areas and longer time spans for both forests and avalanches.

In TREEMIG-AVAL, the temperature drivers for forest dynamics are the yearly sum of mean daily temperatures above a 5.5°C developmental threshold \((\text{DDsum}>5.5°C)\), the minimum winter temperature \((\text{WiT})\) influencing tree growth and mortality, and the mean May–June temperature \((\text{MJT}; \text{see also Supplementary Material B.4})\) influencing the timing of the snow melt and thus the snow-induced mortality. The temperature driver of the avalanche dynamics is the mean snow season length in forested and unforested areas \((\text{WiLenFor}, \text{WiLenBar}; \text{see also Supplementary Material C.4})\).

In each time step, after the release probability \( P_{\text{arc}} \) is calculated, a uniform random number of
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[0,1] is compared against $P_{ar}$ in each cell. An avalanche is released in the current cell if the random number is smaller than $P_{ar}$ in the current cell and at least one of the four direct neighboring cells, representing a neighborhood influence on avalanche release over a distance of 25 m. In this study, a small simulation transect was used (described below) and a single random number was drawn yearly for the whole transect. The different simulation steps that included stochasticity, i.e. the climate sequence, avalanche release and flow, and additional mortality (described below), were implemented with independent pseudo-random number streams. The avalanche flow direction and length were simplified for the purpose of this study (described below, and in Supplementary Material A.2), and the full avalanche flow module will be described in future contributions. For all cells affected by avalanches, mortality is set to 20% for *Alnus viridis* (Chaix) DC., due to this species’ higher elasticity compared to other species in the study area (Stokes et al., 2012), and to 100% for all other tree species, while the ground vegetation is assumed to have no avalanche mortality.

### 3 Simulations

#### 3.1 Transect and simulation design

To be able to study a wide range of environmental factors under controlled conditions, an artificial transect was used in this study, representing a linear elevation gradient across an Alpine treeline ecotone, ranging approximately 1600–2600 m asl. Climate data for this transect were taken from the region of Davos (eastern Swiss Alps) based on CRU climate data (University of East Anglia, Norwich, UK) interpolated with DAYMET (Thornton et al., 1997). In the artificial transect, 3 rows with 30 cells each were used along the elevation gradient. The gradient spanned temperatures of 250–975 $DD_{sum>5.5^\circ C}$, and ranged from above the treeline (<300 $DD_{sum>5.5^\circ C}$), across a coniferous forest (ca. 300–700 $DD_{sum>5.5^\circ C}$), to a mixed forest (>700 $DD_{sum>5.5^\circ C}$; Fig. 2). The ranges of the other temperature drivers were -10.8 to -6.8°C ($W_i T$), 1.6–8.3°C ($MJT$), and 9–5.8 months and 9.8–6.4 months ($WiLenFor$ and $WiLenBar$, respectively).

The climatic drivers were drawn from distributions as done in TREEMIG 1.0 for long-term data (Lischke et al., 2006), but their mean and variability were kept constant over simulation time. Slope curvature and aspect were constant over the whole transect, simulation time, and for all scenarios (no curvature and east aspect). To simplify the analysis, the environmental gradients and scenarios were applied independently of each other, despite potential co-dependencies such as between the climatic and topographic steepness.

The three cell rows were used with identical environmental conditions and cyclic boundary conditions along the long transect sides for seed dispersal. Avalanches were simplified to flow only in the center row of the transect, leaving the two adjacent rows unaffected to allow seed input from neighboring forested cells initiating succession after avalanches. The avalanche flow length was strongly simplified (see Supplementary Material A.2), by applying a constant avalanche stopping probability of 50% in each cell. Despite this simplification, the simulations produced realistic maximum avalanche flow lengths (data not shown) compared to observations (Teich et al., 2012b).

To account for effects of stochasticity, all simulations were repeated 30 times using 30 sets of pseudo-random number streams. To initially provide seeds of all species in all cells, the first 100 simulation years were run without avalanches and reproduction dynamics with seeds available everywhere, followed by 900 years with explicitly simulated avalanches and reproduction dynamics.

The output variables were avalanche release probability ($P_{ar}$) and treeline position, which was defined as the highest cell in the transect with percent crown coverage $pc_{tot} \geq 20\%$ (Kulakowski et al., 2011). To study the behavior of the GLM
equations in the dynamic simulations, the variability in $P_{ar}$ distributions was assessed with the interquartile range, and the unimodality of the $P_{ar}$ distributions was tested with Hartigans’ dip-test (Hartigan and Hartigan, 1985).

### 3.2 Sensitivity analysis

The sensitivity of $P_{ar}$ was analyzed along the temperature gradient of the transect, and among different slope steepness and additional mortality scenarios. The slope steepness scenarios were varied from $30^\circ$ to $45^\circ$ steepness in steps of 2–3°, and from $45^\circ$ to $60^\circ$ in steps of 5°. The scenarios of additional mortality of individual trees ($M_{ai}$) can be interpreted as tree mortality caused by stochastic small-scale factors other than (and thus in addition to) climate, old age, or avalanches. $M_{ai}$ was random in space and time, drawn independently for each cell, and applied as a constant parameter within simulation runs, but was varied among different simulation runs. For the setup and values of $M_{ai}$ scenarios, please see Supplementary Material A.2. All combinations of slope steepness and additional mortality scenarios were analyzed, with each combination in a separate set of 30 simulations.

### 3.3 Effects of model complexity

The sensitivity analysis was repeated also for two simplified model versions, using the same temperature gradient, slope steepness scenarios, and additional mortality scenarios. We compared the results of TREEMIG-AVAL (a) to results of the model version ‘TMA-NOFB’, where the explicit simulation of the avalanche-forest feedback was omitted (Fig. 3A), and (b) to results of the model version ‘TMA-NODYN’, where forest dynamics were replaced by an average forest (Fig. 3B).

For the simulations with TREEMIG-AVAL, yearly avalanche release probabilities were calculated, avalanche release events were simulated, and avalanche-induced mortality was applied to the forest. Therefore, the avalanche release probability was influenced by previous avalanches, resulting in a dynamically simulated positive feedback. In the first simplification (TMA-NOFB), we calculated yearly forest dynamics and the associated avalanche release probability, but did not simulate avalanche release, avalanche-induced mortality, and thus the resulting feedback to $P_{ar}$ (Fig. 3A). In TMA-NOFB, disturbances were hence only represented in the form of additional mortality scenarios without the influence of forests (Fig. 3A). This simplification represents disturbance simulations in many forest models, where prescribed mortality is applied instead of simulating disturbances as an emergent model property (Seidl et al., 2011). For the output analysis of both TREEMIG-AVAL and TMA-NOFB, the yearly $P_{ar}$ was averaged over the last 100 of the 1000 simulated years and over the 30 repetitions for each scenario and each cell.

In the second simplification (TMA-NODYN), TREEMIG 1.0mf was used to simulate an average forest without the avalanche module, with disturbances represented only in the additional mortality scenarios. After the simulation the forest structure and composition ($p_{tot}$, $p_{cncf}$, $mgap$) was averaged over the last 100 of the 1000 simulated years and the 30 repetitions for each scenario and each cell, and $P_{ar}$ was calculated with Eqs. (2–5) as a static value for each cell and scenario (Fig. 3B). This approach represents avalanche models on smaller time scales, which often assume forest structure and composition to be constant (Grêt-Regamey et al., 2008; Teich and Bebi, 2009).

### 4 Results

#### 4.1 Temporal dynamics

The development of avalanche release probability $P_{ar}$ over time showed variability among stochastic repetitions, but similarities in
the avalanche-forest feedback and thus in the changes of $P_{ar}$ in space and time were apparent (compare Fig. 4A and B). These changes in $P_{ar}$ are strongly linked to the forest composition and density. In our results, at temperatures below ca. 700 $DDsum_{>5.5°C}$ crown coverage ($pc_{tot}$) can be inferred approximately from $P_{ar}$ by an inverse relationship. In all analyzed stochastic repetitions, the sharp boundaries between low and high $P_{ar}$ are close to the 20% $pc_{tot}$ threshold (black solid line in Fig. 4) and thus can be interpreted as treelines (Figs. 4 and 5). However, increasing temperatures along the transect (>700 $DDsum_{>5.5°C}$) result in higher proportions of simulated broadleaf deciduous species (Fig. 2), and the relationship between $P_{ar}$ and $pc_{tot}$ deviates from linearity with increasing proportions of broadleaf deciduous species. Additionally, under different slope steepness scenarios the relationship between $P_{ar}$ and $pc_{tot}$ changes further (Fig. 5). Therefore, $pc_{tot}$ cannot be used alone to predict $P_{ar}$, but should be used in combination with variables for forest composition and topography.

![Fig. 4. Two TREEMIG-AVAL realizations of temporal dynamics of avalanche release probability $P_{ar}$ along a temperature gradient ($DDsum_{>5.5°C}$). The solid line represents the treeline, defined as the highest cell with crown coverage ≥20%, and the dotted line represents the average location of the undisturbed treeline. Two different sets of pseudo-random number streams but otherwise identical simulation settings were used, on the same transect at 33° slope steepness, without additional mortality. Note that the temperature axis is reversed to represent an elevational transect.]

![Fig. 5. Simulated avalanche release probability ($P_{ar}$) time series with feedback for two additional mortality scenarios (A, without additional mortality; B, with additional mortality of 0.11), and five slope steepness scenarios (panel rows). All runs share the same initialization for the applied pseudo-random number streams. $P_{ar}$ (color scale) is shown over the last 100 simulation years (x-axis) and along a climatic gradient ($DDsum_{>5.5°C}$, y-axis), which is reversed to represent an elevational transect. The influence of slope steepness leads to a peak in $P_{ar}$ at 40–45°, and the influence of additional mortality increases with increasing slope steepness.]}
The effects of the feedback were visible as changes in treeline position over simulation time (Fig. 4). During some years (e.g. 920–950 in Fig. 4A), avalanches repeatedly destroyed forest near the treeline (400–600 \(DDsum>5.5\degree C\)), pushing treelines to higher temperatures and thereby increasing future avalanche release probability at low temperatures. Avalanches were also released within forested areas, visible as abrupt increases of \(P_{ar}\) below treeline (years 930, 935, 990 in Fig. 4A; below solid line). In the absence of large avalanches (e.g. years 900–920 in Fig. 4A), the forest was able to recover from previous avalanches (illustrated by lighter colors in Figs. 4 and 5) and the treeline shifted to lower temperatures. This recovery was faster at higher temperatures, therefore the feedback strength increased with decreasing temperature.

### 4.2 Sensitivity analysis

#### 4.2.1. Temperature

Lower temperature limits of tree growth (ca. 325 \(DDsum>5.5\degree C\); Fig. 2) only determined the treelines in the absence of avalanches, whereas with the simulated avalanche-forest feedback the highest simulated treelines were at \(\geq400\ DDsum>5.5\degree C\) (Fig. 4). The response of \(P_{ar}\) to the temperature gradient followed a mostly sigmoidal curve (Figs. 6A and 7A). In the upper parts of the transect, the sensitivity of \(P_{ar}\) to the temperature gradient was highest (Fig. 4), resulting in a strong positive feedback. Overall, \(P_{ar}\) was highest at low temperatures, and lowest at intermediate temperatures (600–700 \(DDsum>5.5\degree C\); Figs. 4A and 5A). The higher proportion of simulated deciduous trees resulting from higher temperatures (\(\geq700\ DDsum>5.5\degree C\); Fig. 2) led to lower avalanche protection despite high forest densities (Figs. 5A and 6A).

#### 4.2.2. Temperature and slope steepness

In the absence of additional mortality, the influence of slope steepness was nonlinear, with a peak in \(P_{ar}\) at intermediate slopes (40–45\(^\circ\); Fig. 5A). At this slope steepness, the avalanche-forest feedback was strongest, and avalanches depressed treelines to much higher temperatures (\(\geq500\ DDsum>5.5\degree C\)) than at less steep or steeper slopes (30\(^\circ\) and 50\(^\circ\) steepness: treelines at \(\geq400\ DDsum>5.5\degree C\); Figs. 5A and 6A). On steep slopes the differences in \(P_{ar}\) along the temperature gradient were stronger than on less steep slopes (Fig. 5A). Therefore, slope steepness influenced the sensitivity of \(P_{ar}\) to temperature. Similarly, the interaction between slope steepness and temperature also led to changes in the sensitivity of \(P_{ar}\) to slope steepness at different positions in the transect, i.e. at different temperatures (Fig. 7A). While at high temperatures (\(\geq800\ DDsum>5.5\degree C\)) increases in slope steepness showed almost linear increases in \(P_{ar}\), the influence of slope steepness was nonlinear at lower temperatures (\(\leq400\ DDsum>5.5\degree C\); Fig. 7A).

#### 4.2.3. Temperature, slope steepness, and additional mortality

Introducing additional mortality with \(M_{ai} = 0.11\) led to more avalanches, lower proportions of the transect being forested, longer recovery times of the forest after avalanches, and lower forest densities (Fig. 5B). The influence of additional mortality increased with increasing slope steepness (Fig. 5B). Similarly, differences in \(P_{ar}\) along the temperature gradient were less pronounced when \(M_{ai} = 0.11\) (Fig. 5B), and generally decreased with increasing \(M_{ai}\) (Figs. 6A and 7B) due to the decreases in forest cover with increasing \(M_{ai}\). These results underline the interacting effects of additional mortality with both slope steepness and temperature. The highest sensitivity to \(M_{ai}\) occurred at intermediate temperatures and intermediate slopes (Fig. 6A), with a steep sigmoidal response of \(P_{ar}\) to increases in \(M_{ai}\), similar to a threshold response. However, increases in additional mortality above 0.4 did not induce further changes (Fig. 7B), because above this mortality level the forest was not able to persist, and \(P_{ar}\) depended only on climate and topography (therefore \(M_{ai} > 0.4\) is not shown in Fig. 6). Accordingly, the sensitivity of \(P_{ar}\) to changes in temperature decreased with increasing additional mortality (Fig. 7B).

### 4.3 Model complexity

The comparison of TREEMIG-AVAL to the two simplified model versions showed strong differences in the resulting \(P_{ar}\) (compare Fig. 6A–C). In the absence of additional mortality (\(M_{ai} = 0\)), \(P_{ar}\) was generally lower in TMA-NOFB, where the avalanche-forest feedback was switched off (Fig. 6B), than in TREEMIG-AVAL (Fig. 6A). Furthermore, areas where \(P_{ar}\) was very low (\(<0.025\)), which can be interpreted as forested areas, were observed more often, and generally reached lower temperatures. This illustrates the lowering effect of the feedback on treeline position in TREEMIG-AVAL (Fig. 6A) compared to TMA-NOFB (Fig. 6B).
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Fig. 6. Avalanche release probability $P_{ar}$ for different model versions (columns) and scenarios (rows and axes), averaged over 100 simulation years and 30 repetitions. $P_{ar}$ isolines are shown in steps of 0.025. Slopes are shown in panel rows, while additional mortality ($x$-axis) and temperature ($DDsum_{<5.5°C}$; $y$-axis) are shown within panels. The temperature axis is reversed to represent an elevational transect.

In TMA-NOFB and TREEMIG-AVAL (Fig. 6C), in the absence of additional mortality all slope scenarios showed sharp treelines along the temperature gradient (illustrated by narrow isolines in Fig. 6). Furthermore, at intermediate temperatures ($600–700 DDsum_{<5.5°C}$), an increase in additional mortality (especially around $M_{ai} = 0.2$) led to a threshold behavior in $P_{ar}$.

Both simplified model versions showed low sensitivity to additional mortality at $M_{ai} < 0.2$, and threshold responses around $M_{ai} = 0.2$. At higher levels of additional mortality ($M_{ai} > 0.3$), model versions were more similar again because forests were not able to persist, and $P_{ar}$ depended on climate and topography only.

4.4 Variability

The variability around the mean $P_{ar}$, measured as interquartile range (IQR) over 100 simulation years and the 30 repetitions, was
highest where the steepest $P_{ar}$ transitions occurred (Fig. 7C-D). For example, in the absence of additional mortality, the highest IQRs were found at intermediate temperatures and intermediate slopes (Fig. 7C), which were associated with a high sensitivity of $P_{ar}$ to changes in environmental factors (Section 4.2; Fig. 7A). Similarly, high IQR were observed at intermediate temperatures ($600–700 \text{DDsum}>5.5^\circ\text{C}$) and low $M_{ai}$ (Fig. 7D). These situations with high IQR were also associated with increases in the dip statistic, a measure for deviation of the $P_{ar}$ distributions from unimodality (Fig. 7E, F). Significant deviations from unimodality were found in situations where the dip statistic exceeded ca. 0.02 (within the outermost contour lines in Fig. 7E and F). The conditions that led to steep transitions and high sensitivities of $P_{ar}$ were therefore associated with multimodal distributions of $P_{ar}$ over the 100 years and the 30 repetitions (Fig. 7G).

Fig. 7. Averaged avalanche release probability and its variability over 100 simulation years and 30 sets of pseudo-random number streams, simulated with TREEMIG-AVAL, (A) for different slope scenarios ($x$-axis) and temperatures ($\text{DDsum}>5.5^\circ\text{C}$; $y$-axis), without additional mortality; and (B) for different additional mortality scenarios ($M_{ai}$; $x$-axis) and temperatures ($\text{DDsum}>5.5^\circ\text{C}$; $y$-axis), at a slope of $42^\circ$. The variability around the mean $P_{ar}$ is shown as interquartile range IQR (C and D, for the means shown in A and B). The dip statistic (E, F) represents the distance from a unimodal distribution. Significance was reached at approximately $\text{dip} \geq 0.02$ (near the outermost contour lines in E, F). Distributions of $P_{ar}$ for three examples (G, scenarios marked in E with lower-case letters) illustrate different modalities resulting from the simulations.
5 Discussion

5.1 Avalanche release sensitivity to environment

The $P_{ar}$ sensitivity to changes in environmental conditions, analyzed in our first research question, changed along the axes of the three factors temperature, slope steepness, and additional mortality, ranging from linear to steep sigmoidal (threshold-like) changes in $P_{ar}$. These threshold-like sensitivities of $P_{ar}$ and the variability of $P_{ar}$ around the thresholds are discussed in Section 5.4. The interactions between $P_{ar}$ and forest growth resulted in the avalanche-forest feedback as an emergent model property. The three environmental factors influenced the strength of this feedback by altering the ratio between forest regeneration speed and avalanche recurrence rate, also known as transient form ratio (Brunsden and Thornes, 1979). Such dependencies of feedback strength on the environment have been reported before in other simulated and natural systems (e.g. Bekker and Malanson, 2009; Corenblit et al., 2011).

The three environmental factors showed interactions, where changes in one factor altered the sensitivity of $P_{ar}$ to the other factors. Some of these interactions are inherent within the GLMs used in the $P_{ar}$ simulations, and are expected based on observed phenomena (McClung and Schaerer, 2006; Schneebeli and Meyer-Grass, 1992), while others are emergent properties of the coupled model.

One example for interactions inherent to the GLMs is the interaction between $slp$ and $crv$ in $glm_1$ (Fig. C1), illustrating that in channelized slopes (negative $crv$), $P_{ar}$ is increased compared to non-channelized slopes even at low slope steepness (McClung and Schaerer, 2006). Similarly, the interaction between $pc_{tot}$ and $pc_{cnf}$ in $glm_1$ (Fig. C2) corroborates the theory that the sensitivity of coniferous crown coverage ($pc_{cnf}$) on $P_{ar}$ is higher in low density forests (low $pc_{tot}$) than in high density forests (high $pc_{tot}$), where the total crown coverage is more important (Bebi et al., 2009). Due to possible interactions among the GLMs, it was important to also confirm the plausibility of the combined GLMs in the coupled model in addition to the plausibility of the variables within the GLMs. As the interactions were also plausible in the dynamic simulation results (e.g. Fig. 7A and B), the empirical basis included in the GLMs is still valid for the coupled model.

An example for interactions emerging from the coupled model is between slope steepness and temperature (Fig. 7A). While at low temperatures and low forest density $P_{ar}$ was strongly sensitive to slope steepness, the sensitivity decreased with increasing temperature and forest density (Fig. 6A). However, with increased feedback strength at steep slopes, simulated treelines were controlled more by avalanche mortality than by temperature, and thus can be described as orographic treelines (Holtmeier and Broll, 2005).

Other emergent interactions are caused by additional mortality, which for example can be caused by other natural disturbances or human land use. Additional mortality increased the strength of the feedback, and reduced the avalanche protection function of the forest. The sensitivity of the forest to additional mortality was influenced by topography and climate, causing sudden changes in forest and avalanche dynamics when thresholds of additional mortality were crossed. Such interactions between different disturbances, and between disturbances and other environmental factors, have been observed and simulated before, such as between spruce beetle outbreaks and fire (Bigler et al., 2005), between anthropogenic land use and avalanches (Kulakowski et al., 2011), between anthropogenic land use, climate, and fire (Schumacher and Bugmann, 2006), and between spruce beetle outbreaks, avalanches, and fire (Veblen et al., 1994). In our simulations, the feedback was triggered by additional mortality even in situations where it was otherwise absent, e.g. at low slope steepness (Fig. 5A, 30°). Once a feedback between the vegetation and its environment is triggered, it may change ecosystem trajectories (Scheffer and Carpenter, 2003), even on larger scales (Rietkerk et al., 2011).

5.2 Model plausibility

For our second research question, the plausibility of TREEMIG-AVAL was assessed in the overall model behavior and in the GLM components of the avalanche module. GLM equations have previously been used for landslide probability calculations (Vorpahl et al., 2012b), where they performed well compared to other statistical models. The quality of the individual GLMs in TREEMIG-AVAL was satisfying (Table C2), and the selected variables and the sign of their parameter estimates
conformed to theory (Gruber and Bartelt, 2007; Maggioni and Gruber, 2003).

GLMs have also been used successfully to aggregate the bark beetle module of the stand level hybrid patch model PICUS into the large scale matrix model EFISCEN (Seidl et al., 2009). Similarly, we used GLMs to aggregate avalanches to yearly time steps in TREEMIG-AVAL to allow long-term simulations of avalanches on an ecologically relevant time scale. However, due to the limited knowledge of the effect of long-term climate on avalanche activity (Martin et al., 2001), the temporal aggregation was strongly simplified.

Due to these simplifications, the snow level required for avalanche release can only be simulated as absent or potentially present, but without more precise information about the number of avalanches within snow-rich areas. A more detailed simulation of avalanche release would require explicit simulation of meteorological avalanche triggers at a higher temporal and spatial resolution than possible here. Several mechanistic avalanche models simulate avalanches at this level of spatial and temporal detail (e.g. Christen et al., 2010; Gruber and Bartelt, 2007), but these models do not usually permit simulations on large spatial scales or with long-term climate change scenarios, and do not include influences of forest dynamics (e.g. Teich and Bebi, 2009). An advantage of the aggregation used in TREEMIG-AVAL is that simulations are feasible on large spatial and temporal scales, while the approximated avalanche probability is sensitive to climate change both directly, and indirectly via climate-induced changes in forests.

The spatial downscaling of the forest, in combination with the temporal aggregation of the avalanches, balanced the resolution requirements of both processes, and resulted in plausible forest and avalanche patterns both without avalanches (Fig. 2; Supplementary Material B.1) and with avalanches (Fig. 4 and 5). The avalanches released from below treeline in our simulations are associated with an increasing proportion of simulated deciduous crown coverage along the temperature gradient (Fig. 2), which is in accordance with observations (Bebi et al., 2009; Teich et al., 2012a). Deciduous trees provide less protection against avalanches as their crowns contribute less to snow interception and radiation and temperature modification, two of the main protection mechanisms that evergreen trees provide (Bebi et al., 2009).

The influences of the three environmental factors on $P_w$ agreed with the theoretical model (Fig. 1) and showed plausible interactions. In the simulated system, the environmental factors were nonlinear determinants of the avalanche-forest feedback strength and therefore of the treeline. Similar results have been found before where feedbacks influenced treeline abruptness (Malanson et al., 2011), location (Bader et al., 2008), and treeline patterns in general (Bekker and Malanson, 2009). The nonlinearity of the feedback response to the environment suggests that with future environmental change, simulation studies that take into account feedbacks between vegetation and disturbance will gain in importance.

5.3 Model complexity

In comparison to the high plausibility of TREEMIG-AVAL, the model simplifications studied in the third research question would be appropriate if the results after the simplification were not significantly different from before the simplification (Van Nes and Scheffer, 2005). However, the differences among the sensitivity results of the model versions (Fig. 6) demonstrate that the complexity of TREEMIG-AVAL can not be reduced by omitting forest dynamics entirely or by only omitting the avalanche-forest feedback.

The large differences between model versions at low temperatures (Fig. 6) indicate that especially treelines are sensitive to the level of model complexity. The treelines at lower temperatures resulting from the simplified models compared to TREEMIG-AVAL suggest that treeline elevations are overestimated if the avalanche-forest feedback is not explicitly simulated in TREEMIG-AVAL. Furthermore, the underestimation of the sensitivity of $P_w$ to additional mortality at low $M_w$ (<0.2) suggests that the simplified model versions overestimate the forest resilience to additional mortality.

In TREEMIG-AVAL, spatial patterns near treeline and sensitivities to environmental gradients were only represented plausibly when forest dynamics and the avalanche-forest feedback were explicitly included. Using models simplified in terms of feedback or forest dynamics for simulations of mountain forests affected by snow avalanches would therefore likely lead to overestimations of treelines, forest resilience, and avalanche protection. This stands in contrast to an analytical approximation of a dynamic model, where feedbacks were found to
be irrelevant (Tepley and Thomann, 2012), but agrees with earlier findings where landscapes could only be represented realistically if disturbances were taken into account explicitly (Istanbulluoglu and Bras, 2005). The importance of explicitly simulating feedbacks between vegetation and disturbance was also concluded from simulations of bark beetle influence on forest development (Seidl et al., 2007), and from landslide simulations in tropical forests (Vorpahl et al., 2012).

5.4 Variability in avalanche release probability

The coincidence of high $P_{ar}$ sensitivity and variability and multimodal $P_{ar}$ distributions with treeline situations suggests that the steep transition of mean $P_{ar}$ along the temperature gradient may be due to switches between forested and unforested states of cells close to treeline. Multimodality suggests alternative attractors in the system analyzed (Scheffer and Carpenter, 2003), but may also be influenced by switches between the three avalanche release situations and therefore between the GLM predictor equations applied in each situation. Due to the different predictor variables used in the GLMs, and the thresholds used to define avalanche release situations, multimodality may arise from discontinuities in the predicted $P_{ar}$ along the $pc_{tot}$ and $pc_{cnf}$ gradients. However, the three avalanche release situations also exhibit demonstrably different dependencies on the environment in reality (Bebi et al., 2009; McClung and Schaerer, 2006), and justify the use of separate predictor equations and variables in the model, at the risk of increasing the $P_{ar}$ variability.

Other uncertainties may also have led to increased variability, such as those inherited from TREEMIG 1.0 and those in species parameters, which are discussed elsewhere (Nabel et al., 2012, 2013). Additionally, the different sample sizes and time spans covered by the input data (Table C2) may have influenced the GLM predictor equations. Due to the sporadic occurrence of forest avalanches and a non-continuous monitoring, observation data on avalanche releases in forested areas are rare (Teich et al., 2012a), and using all available data sets in combination was a first necessary step towards the dynamic modeling of the avalanche-forest feedback. As new data sets become available in the future, the reliability of the predictor equations may be improved with better equations. Due to such uncertainties, our results should be seen as an exploratory analysis of the processes involved (sensu Perry and Millington, 2008). Even though a part of the variability around $P_{ar}$ may stem from model uncertainty, we maintain that the distribution of $P_{ar}$ at treelines could still be multimodal, driven by the variability of the ecotone over time, and the high sensitivity of treelines to environmental changes.

6 Conclusions

The sensitivity of the avalanche release probability in TREEMIG-AVAL was nonlinear, and showed strong interactions among the environmental factors. Such interactions suggest that with the anticipated future changes in climate, the relationship of avalanche release probability to temperature, additional mortality, and slope steepness will change, potentially leading to strong changes in the avalanche-forest feedback. Simulation studies for environmental change scenarios should therefore account for potential interactions between environmental factors.

Despite the different temporal and spatial scales involved in forest and disturbance dynamics, avalanches and their feedback with forests were plausibly represented in TREEMIG-AVAL. A main advantage of TREEMIG-AVAL is the simulation of the avalanche-forest feedback as an emergent model property, which allows spatially explicit simulations of environmental change scenarios over long time spans.

The comparison of TREEMIG-AVAL with two simplified model versions demonstrated that the simulated treeline ecotone in particular was sensitive to changes in model structure and was prone to underestimation of the avalanche probability if the forest dynamics and the avalanche-forest feedback were not explicitly simulated. Environmental drivers as well as the feedback between forest and disturbance dynamics should therefore be accounted for explicitly in simulation studies of future mountain forests in areas with high disturbance frequencies.

We conclude that TREEMIG-AVAL is a valuable tool for long-term simulation studies of forest dynamics including spatially explicit avalanche disturbances in mountain areas, and after model validation it can be applied for spatially explicit simulations with environmental change scenarios.
Acknowledgements

We would like to thank I. Barbeito, M. Bavay and B. Poulter for valuable discussions, D. Schmatz for help with the climate data, T. Wuest for help with the computing cluster, and two anonymous reviewers for their constructive comments. NZ was supported by the project MOUNTLAND funded by the Competence Centre Environment and Sustainability of the ETH Domain (CCES). JN was supported by the Swiss National Science Foundation Grant 315230-122434.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.ecocom.2013.09.002.

References


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Supplementary Material

Explicit avalanche-forest feedback simulations improve the performance of a coupled avalanche-forest model

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submitted to Ecological Complexity

A Coupled TreeMig-Aval

A.1 Simulation flowchart

Figure A1: Flowchart of the coupled TreeMig-Aval model. Avalanche-related new components are highlighted in the red box, with the according sections of the main text and the supplementary material given in brackets. For the study presented here, the avalanche flow module was simplified, and represented as constant parameters instead of explicit simulations (see main text). For more detailed flowcharts of TreeMig, see the online appendix of Lischke et al. (2006).
A. Coupled TreeMig-Aval

A.2 Model simplifications in this study

In the study presented here, the simulations in TREEMIG-AVAL were simplified in three main aspects. First, the avalanche flow was not simulated spatially explicitly. The flow direction was one-dimensional (along the transect), and the flow length was represented by a constant parameter to randomly determine the flow length. To avoid a bias of increased avalanche flow in the lowest cells of the transect if all avalanches flow to the end of the transect, random flow lengths were determined by applying a constant avalanche stopping probability in each cell. This probability was set to 50%, to be able to study a balanced avalanche-forest feedback while avoiding extreme situations of full avalanche or forest dominance. For the scope of the study presented in the main text, this simplification produced results close enough to avalanche flow length observations (Teich et al., 2012b). A more mechanistic description of spatially explicit avalanche flow direction and length will follow in future work (Zurbriggen et al., in prep).

The second simplification in the TREEMIG-AVAL simulations presented here concerned the additional mortality scenarios. The probability of additional mortality of an individual tree (\(M_{ai}\)) is given by the probability of a small-scale within-cell disturbance event (\(dp\)), multiplied with the probability of individual tree death in case of disturbance (\(di\), disturbance intensity). The scenarios with different \(M_{ai}\) values were set up using 10% steps simultaneously in \(dp\) and in \(di\), which means only scenarios with \(dp = di\) were analyzed, resulting in \(M_{ai}\) values of \(\{0, 0.01, 0.04, 0.09, 0.16, 0.25, 0.36, 0.49, 0.64, 0.81, 1\}\), with one additional scenario at \(M_{ai} = 0.11 (di = dp = 0.33)\). Since these scenarios covered the full range of possible outcomes of avalanche release probability \(P_{ar}\) (see diagonal black lines in Fig. A2), and the effects of \(di\) and \(dp\) were nearly symmetrical (i.e. high \(dp\) and low \(di\) resulted in similar \(P_{ar}\) as low \(dp\) and high \(di\)), \(M_{ai}\) scenarios where \(dp \neq di\) were not analyzed to keep the number of dimensions to a minimum.

Another simplification was used in the tree mortality applied after avalanches. Theoretically, avalanche-induced mortality depends on several factors, such as tree species and size, among others. Implementing this in the avalanche module would have required detailed data on avalanche-induced mortality to parameterize all species and size classes, which was not available. Additionally, different avalanche types can cause different types of damage to the trees, not all of them leading to (immediate) tree mortality. However, this level of detail in avalanche mortality simulation was not possible in our model. To simplify the model, a standard mortality of 100% was used for all size classes, and for all but two species. Based on the limited knowledge that was available, we set the mortality of Alnus viridis to 20%, and allowed full survival of the ground vegetation functional type, because these species show much higher survival in avalanches than other species.

![Figure A2: \(M_{ai}\) scenarios split into effects of \(di\) and \(dp\), showing avalanche release probability in one example cell (700 DDSum\(_{3,5} = 5\), 35° slope steepness) averaged over 100 years, along disturbance probability (\(dp\)) and intensity (\(di\)). The resulting \(P_{ar}\) is nearly symmetrical along \(di = dp\) (diagonal lines). The symmetrical effects of \(di\) and \(dp\) were also observed in the other transect cells.](image)
B. Changes from TreeMig 1.0 to TreeMig 1.0mf

B.1 Increased spatial resolution

For the combination of TreeMig (Lischke et al., 2006) with a snow avalanche module, the previous spatial resolution of 100 m cell side length (“100-m cells”) was increased to 25 m cell side length (“25-m cells”). The cell size was chosen due to the trade-off between the smallest cell size possible in TreeMig and the largest cell size plausible for avalanche simulations. TreeMig was upscaled from the forest gap model FORCLIM (Bugmann, 1994; Bugmann and Cramer, 1998) with distributions of trees within cells instead of repetitions of patch simulations (Lischke et al., 1998). This upscaling was based on the assumption that a random spatial distribution results in a Poisson distribution of the densities which converges to a normal distribution for large numbers. Hence, if cell sizes and thus numbers of trees are too small this assumption could be violated. Additionally, smaller cell sizes would limit the simulation extent to small areas due to the associated increased computational costs. To maintain the advantage of the large simulation extents possible in TreeMig, the cell sizes should not be too small, and we found that with 25-m cells the simulation extent was still large enough for landscape-level simulations.

In avalanche simulations, the cell size determines the size of the smallest avalanche that can be simulated. As large avalanches are less frequent than small avalanches, simulating only large avalanches would neglect an important part of the avalanche-forest feedback. Recent avalanche models have used 5-m cells (Bühler et al., 2011), but cells larger than 25 m are seldom used.

The patch size of 833 m$^2$ (1/12 ha) used in TreeMig 1.0 was not altered despite the potential violation of associated modeling assumptions. In gap models, several patches are simulated and averaged for the final representation of each cell. In TreeMig, repeated simulation of patches is replaced by the use of Poisson distributions (approximated by normal distributions) of numbers of trees per species and size, represented by their mean (Lischke et al., 1998, 2006). This mean was assumed to represent the conditions in the center of the cell, and the theoretical overlap of patches between cells (because patch size 833 m$^2$ > cell size 625 m$^2$) was not taken into account. To test if the distribution approach of TreeMig is still valid for the smaller cell size despite this overlap, we compared the mean total biomass per hectare (t/ha) between the two cell sizes. The smaller cell size was then accepted on the condition that the change does not alter the forest dynamics and therefore biomass. In the comparisons biomass was chosen as a representative variable for forest conditions. The other forest-related variables used in avalanche probability simulations, percent coverage and maximum gap size, were not used due to their lower sensitivity to potential differences between cell sizes. For example, different levels of biomass can lead to the same percent coverage, due to different foliage to stem biomass ratios of different tree species. Thus equal levels of percent coverage do not necessarily mean equivalent levels of biomass between cell sizes. Similarly, the maximum gap size (i.e. the largest gap diameter) does not account for the overall size of the gap and is thus less likely than biomass to detect differences between cell sizes.

To compare the biomass between the two cell sizes, we ran two sets of 100 simulations with TreeMig 1.0, using different pseudo-random number streams, on a 6.5 km x 6.4 km area near Davos, for 25-m cells and 100-m cells. In this simulation area, ca. 60’000 25-m cells and ca. 3750 100-m cells, respectively, were suitable for forest growth. For the purpose of these test simulations, we derived the 25-m climate data from a 100-m climate data set, which led to 16 climatically identical 25-m cells within each 100-m cell. In the comparison of the two resolutions under identical environmental drivers, a difference in biomass between the two simulation sets would indicate an influence of the resolution. We compared the total biomass per hectare (t/ha) after 600 simulation years in each 25-m cell to its underlying 100-m cell, by applying a t-test on the 100 simulation results for each cell pair. The results of the t-test were thus spatially explicit. No obvious patterns in space were found, and very few significant differences were seen: 5.2% (1.1%) of all 25-m cells were significantly different from their paired 100-m cell at $p < 0.05$ ($p < 0.01$), respectively. Because the elevational distribution of biomass is of central importance in the sensitivity study described in the main text, we additionally compared the biomass between the two resolutions along an elevational gradient (Fig. B1). Due to the stochasticity in TreeMig, increased variability around the mean biomass is seen in simulations
B. Changes from TreeMig 1.0 to TreeMig 1.0mf

near the treeline, which may explain some of the significant differences found in the spatially explicit comparison.

Due to the small differences in only few cells, we concluded that the two resolutions produced highly comparable results, and that the use of 25-m cell side length in TreeMig 1.0mf does not alter the local forest dynamics.

![Figure B1: Biomass (t/ha) comparison between 25-m cells (blue) and associated 100-m cells (green). The boxplots show medians, inter-quartile ranges (IQR), extreme values (within 1.5·IQR), and outliers. The black boxes and line show a density distribution of elevations in the study area, given as #cells/10.](image)

B.2 Species parameter changes

Species parameters for some of the mountain forest species used in TreeMig 1.0 were adapted to better reflect mountain forests near treeline, with a special focus on the species-specific biomass distribution along elevational gradients (Table B1). The parameter values were calibrated by comparing simulation results to known patterns along elevational gradients, such as simulated by Schumacher et al. (2004) for the same geographic area. *Castanea sativa* Mill., previously included in TreeMig 1.0, was removed in TreeMig 1.0mf.

<table>
<thead>
<tr>
<th>Species</th>
<th>$D_{\text{max}}$</th>
<th>$H_{\text{max}}$</th>
<th>$A_{\text{max}}$</th>
<th>$G$</th>
<th>$d_{\text{min}}$</th>
<th>$d_{\text{75}}$</th>
<th>$W_{\text{I}}$</th>
<th>$L_{\text{s}}$</th>
<th>$L_{\text{a}}$</th>
<th>$M_{\text{1min}}$</th>
<th>$S_{\text{D_{max}}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Abies alba</em></td>
<td>100</td>
<td>44</td>
<td>300</td>
<td></td>
<td>800</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>Picea excelsa</em></td>
<td>180</td>
<td>50</td>
<td></td>
<td>275</td>
<td>300</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>Pinus sylvestris</em></td>
<td></td>
<td></td>
<td></td>
<td>275</td>
<td>330</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>Pinus montana</em></td>
<td>95</td>
<td>27</td>
<td>400</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>Acer pseudoplatanus</em></td>
<td>110</td>
<td>42</td>
<td>280</td>
<td></td>
<td>700</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><em>Alnus viridis</em></td>
<td>25</td>
<td>6</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>100000</td>
</tr>
</tbody>
</table>

B.3 Ground vegetation functional type

A new functional group representing high alpine grasses and dwarf shrubs was added (Table B2) to improve simulated seedling light levels according to natural light levels of tree seedlings underneath canopies of alpine dwarf shrubs, tall grasses, and herbs. The shading capacity parameter was set to the maximum (sType/N = 5), while all other parameters were estimated to represent dwarf shrub and grass canopies. These other parameters were less important for the purpose of the sensitivity study described in the main text, as the shading capacity of the ground vegetation is reached relatively quickly (< 5
B. Changes from TreeMig 1.0 to TreeMig 1.0mf

simulation years), and the ground vegetation size, age, biomass, and numbers of individuals were not evaluated in the simulations of forest biomass.

Table B2: Parameter values for the ground vegetation functional type. Values were estimated to represent dwarf shrub and grass canopies. Variable abbreviations are listed in Table B3.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>sType/B</td>
<td>D</td>
</tr>
<tr>
<td>sType/N</td>
<td>5</td>
</tr>
<tr>
<td>D_{max}</td>
<td>20</td>
</tr>
<tr>
<td>H_{max}</td>
<td>2</td>
</tr>
<tr>
<td>A_{max}</td>
<td>100</td>
</tr>
<tr>
<td>G</td>
<td>2000</td>
</tr>
<tr>
<td>DD_{min}</td>
<td>200</td>
</tr>
<tr>
<td>d75</td>
<td>6000</td>
</tr>
<tr>
<td>WiT</td>
<td>-60</td>
</tr>
<tr>
<td>DrT</td>
<td>0.5</td>
</tr>
<tr>
<td>NTol</td>
<td>1</td>
</tr>
<tr>
<td>bw</td>
<td>1</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ls</td>
<td>1</td>
</tr>
<tr>
<td>La</td>
<td>1</td>
</tr>
<tr>
<td>Mt_{min}</td>
<td>0.5</td>
</tr>
<tr>
<td>seedGerm</td>
<td>0.48</td>
</tr>
<tr>
<td>seedLoss</td>
<td>0.8</td>
</tr>
<tr>
<td>seedMaxage</td>
<td>7.7</td>
</tr>
<tr>
<td>period</td>
<td>1</td>
</tr>
<tr>
<td>SD_{max}</td>
<td>50000</td>
</tr>
<tr>
<td>dispFac</td>
<td>0.99</td>
</tr>
<tr>
<td>alfa1</td>
<td>25</td>
</tr>
<tr>
<td>alfa2</td>
<td>200</td>
</tr>
</tbody>
</table>

B.4 Snow-induced mortality of mountain forest conifers

To further improve simulations of mountain forests and treelines, we added a snow-induced mortality for all coniferous species to represent the negative effects of delays in snow melt and of snow fungus infections. We analyzed the effects of snow melt timing on mortality rates of Larix decidua L., Pinus mugo ssp. uncinata Ramond, and Pinus cembra L., using data (described by Barbeito et al., 2012) from a plantation in the same geographic area as the study described here (Stillberg, Davos, Switzerland). In the plantation, 92'000 seedlings were planted in 1975. We used proportions of trees alive in each census year (6 measurement censuses between 1979-1995), and the average day of snow melt for each tree location in 10 snow melt classes (class width 5 days), to obtain species-specific survival rates for each snow melt day class. Mortality rates were estimated from the survival proportion \( p_{end}/p_{start} \) assuming an exponential decay:

\[
\begin{align*}
    p_{end} &= p_{start} \cdot e^{-M_{app} \cdot \Delta t} \\
    M_{app} &= -\ln(p_{end}/p_{start}) \cdot 1/\Delta t
\end{align*}
\] (B1)

where \( M_{app} \) is the species-specific mortality rate, \( p_{end} \) the proportion of survivors at the last census, \( p_{start} \) the proportion of survivors at the first census, and \( \Delta t \) 16 years (1979-1995).

Because survival data were not available for all conifers simulated in TreeMig 1.0mf, \( M_{app} \) of \( P. mugo \) and \( P. cembra \) were combined (‘Pines’) and used as snow-induced mortality in all evergreen coniferous species simulated in TreeMig 1.0mf. Hence one mean \( M_{app} \) value was available for each of the two species groups and ten snow melt day classes. A quadratic regression equation was then established to predict the snow-induced mortality \( M_{app} \) from the snow melt day \( smday \):

\[
M_{snow} = a \cdot smday^2 + b \cdot smday + c
\] (B2)

with \( smday \) as the snow melt day-of-year ranging 120-170 days after 1. Jan, and \( a, b, \) and \( c \) as the regression parameters (Table B4). The resulting predictions for snow-induced mortality follow a non-linear increase with increasing length of snow cover, assuming increased risk of snow fungus infection especially for evergreen coniferous species, but also for \( L. decidua \). The resulting significance levels of the parameters were high for \( L. decidua \), but lower for the pine species, likely due to the lower mean mortality found for the snow melt class of day 170 (Fig. B2). However, this data point was not considered an outlier but part of the natural variability of the data and was therefore kept for the analysis. In the TreeMig 1.0mf mortality subroutine, a vitality-related mortality is derived from
B. Changes from TreeMig 1.0 to TreeMig 1.0mf

Table B3: Variable names and definitions. For more information see the online appendix of Lischke et al. (2006).

<table>
<thead>
<tr>
<th>Variable</th>
<th>Definition</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>sType/B</td>
<td>Species type: coniferous [C] or deciduous [D]</td>
<td></td>
</tr>
<tr>
<td>sType/N</td>
<td>Species type: shading capability low [1] to high [5]</td>
<td></td>
</tr>
<tr>
<td>$D_{max}$</td>
<td>Max. diameter at breast height (DBH)</td>
<td>cm</td>
</tr>
<tr>
<td>$H_{max}$</td>
<td>Max. height</td>
<td>m</td>
</tr>
<tr>
<td>$A_{max}$</td>
<td>Max. age</td>
<td>year</td>
</tr>
<tr>
<td>$G$</td>
<td>Max. growth rate</td>
<td>cm/year</td>
</tr>
<tr>
<td>$DD_{min}$</td>
<td>Min. yearly degree-day sum above 5.5°C</td>
<td>degree-day</td>
</tr>
<tr>
<td>$d75$</td>
<td>Degree-day sum at 75% of maximum growth modifier</td>
<td>degree-day</td>
</tr>
<tr>
<td>$W_{IT}$</td>
<td>Min. mean temperature of winter months (Dec, Jan, Feb)</td>
<td>°C</td>
</tr>
<tr>
<td>$DrT$</td>
<td>Drought tolerance: prop. of evapotranspiration deficit tolerated</td>
<td></td>
</tr>
<tr>
<td>$NT_{tol}$</td>
<td>Low nitrogen concentration tolerance: tolerant [1] to intolerant [3]</td>
<td></td>
</tr>
<tr>
<td>$brow$</td>
<td>Susceptibility to browsing: high [3] to low [1]</td>
<td></td>
</tr>
<tr>
<td>$Ls$</td>
<td>Sapling light parameter: shade-tolerant [1] to shade-intolerant [9]</td>
<td></td>
</tr>
<tr>
<td>$La$</td>
<td>Adult light parameter: shade-tolerant [1] to shade-intolerant [9]</td>
<td></td>
</tr>
<tr>
<td>$Mt_{min}$</td>
<td>Min. height for maturity</td>
<td>m</td>
</tr>
<tr>
<td>$seedGerm$</td>
<td>Seed germination rate</td>
<td>year$^{-1}$</td>
</tr>
<tr>
<td>$seedLoss$</td>
<td>Seed loss rate</td>
<td>year$^{-1}$</td>
</tr>
<tr>
<td>$seedMax_Age$</td>
<td>Max. seed age</td>
<td>year</td>
</tr>
<tr>
<td>$period$</td>
<td>Mast seeding period</td>
<td></td>
</tr>
<tr>
<td>$SD_{max}$</td>
<td>Max. number of seeds</td>
<td></td>
</tr>
<tr>
<td>$dispFrac$</td>
<td>Fraction of long-distance dispersal</td>
<td></td>
</tr>
<tr>
<td>$alfa1$</td>
<td>Mean short-distance dispersal distance</td>
<td>m</td>
</tr>
<tr>
<td>$alfa2$</td>
<td>Mean long-distance dispersal distance</td>
<td>m</td>
</tr>
</tbody>
</table>

Table B4: Parameters and their significance for the two species groups for the regression equation predicting snow-induced mortality based on the snow melt day of the year (see Eq. (B2)). Pines are P. mugo and P. cembra. Significance levels are given as: *** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$; , $p < 0.1$.

<table>
<thead>
<tr>
<th>Species</th>
<th>a</th>
<th>b</th>
<th>c</th>
</tr>
</thead>
<tbody>
<tr>
<td>L. decidua</td>
<td>6.69E-05</td>
<td>-1.81E-02</td>
<td>1.24 ***</td>
</tr>
<tr>
<td>Pines</td>
<td>1.38E-04</td>
<td>-3.30E-02</td>
<td>1.99</td>
</tr>
</tbody>
</table>

growth and environment. For the lowest height class (tree seedlings), the vitality-related mortality is then compared against the snow-induced mortality, and the more severe of the two is applied.

To calculate the snow melt day based on the monthly mean temperatures which were available for our simulations, we used a previously published linear regression equation (Eq. (B3)) for the prediction of the snow melt day based on May and June mean temperatures (Rammig et al., 2010).

$$s_{mday} = -5.5 \cdot (\mu T_5 + \mu T_6)/2 + 189.0$$  \hspace{1cm} (B3)

where $\mu T_5$ and $\mu T_6$ are mean monthly temperatures of May and June, respectively. Their regression was based on data from 17 climate measurement sites above 1500m a.s.l. in the Swiss Alps from 1997-2005. Accordingly, the mean May-June temperature was used as additional climate input variable into TREEMIG 1.0mf (M.JT). To maintain consistency with the other climate input variables in TREEMIG (Lischke et al., 2006), the mean and standard deviation of the May-June temperature were used to stochastically determine the yearly realization of the snow melt day.

B.5 New variables for avalanche simulations

For the calculations of forest influence on avalanche release probability, new variables were calculated allometrically from the TREEMIG state variable mean number of trees per species and height class, species specific per-tree crown area ($CA_{sp}$), total and coniferous percent crown coverage ($pc_{ctot}$ and $pc_{cnf}$), and maximum gap size ($mgap$) were calculated for each cell and year.
B. Changes from TreeMig 1.0 to TreeMig 1.0mf

\[ CA_{spp,ht} = CR_a \cdot h^2 + CR_b \cdot h \]  \hspace{1cm} \text{(B4)}

with \( h \) as height of the individual trees (in meters), and \( CR_a \) and \( CR_b \) as species-specific parameters (Table B5). Predictions for \( CA_{spp,ht} \) for each species and height are used as constant parameters in TreeMig 1.0mf (Fig. B3). For most species, the parameter estimates were considered reasonable. However, the sample size of the input data ranged widely among the species (0 - > 1400). For species with too few input data, equations for related species were used or combined. Furthermore, for the 5 species where input data did not reach the maximum species specific tree height used in TreeMig 1.0mf (\( P. \ cembra, Pinus montana \) Mill., \( Quercus \ robur \) L., \( Sorbus \ aria \) (L.) Crantz, and \( Ulmus \ scabra \) Huds.), additional data points (max. 5) were added to the data, based on expert knowledge and literature estimates, to extrapolate the regression equation up to the maximum species specific tree height used in TreeMig. Thus the confidence in the parameter estimates for these species is lower, and further research should be conducted to improve the estimates. However, for the heights that \( P. \ cembra \) and \( P. \ montana \) usually reach in the mountain forest ecosystem studied here (\( \leq 20 \) m), enough samples (38 and 25, respectively) were available. The other three species with insufficient data points, \( Q. \ robur, S. \ aria, \) and \( U. \ scabra \), are not common in our simulation area.

The total and coniferous percent crown coverage (\( pc_{tot} \) and \( pc_{con} \)) were based on summed crown areas per cell. Summed crown areas (\( CA_{sum} \)), described in Eq. (B5), are used to distinguish between coniferous and broadleaf/mixed forests in TreeMig 1.0mf. They are calculated for all species (\( CA_{sumall} \)) and coniferous species (\( CA_{sumcon} \)), by summing \( CA_{spp,ht} \) over all trees (coniferous trees) per cell, respectively. For the percentage coniferous trees \( pc_{con} \), described in Eq. (B6), the ratio of the two sums is used. The total percent crown coverage \( pc_{tot} \), described in Eq. (B7), is calculated using a Lambert-Beer type equation (Crookston and Stage, 1999), assuming random spatial distribution of individual trees and accounting for crown overlap.

\[ CA_{sum} = \sum (numin_{spp,htcd} \cdot CA_{spp,htcd}) \]  \hspace{1cm} \text{(B5)}

\[ pc_{con} = CA_{sumcon}/CA_{sumall} \]  \hspace{1cm} \text{(B6)}

\[ pc_{tot} = 1 - e^{-1 \cdot \sum (numin_{spp,htcd,sqm} \cdot CA_{spp,htcd})} \]  \hspace{1cm} \text{(B7)}

with the TreeMig 1.0mf state variable \( numin_{spp,htcd} \) as number of individuals per species and height class per cell, and its transformed value \( numin_{spp,htcd,sqm} \) as number of individuals per species and height class per square meter.

The diameter of the maximum possible gap per cell (\( mgap \)) was calculated based on a fragmentation analysis on \( pc_{tot} \), run with RULE 3.1. (Gergel and Turner, 2002; Klopfake and Gardner, 1999). This
B. Changes from TreeMig 1.0 to TreeMig 1.0mf

Table B5: Species parameters for the allometric calculation of crown area per species and tree size.

<table>
<thead>
<tr>
<th>Species</th>
<th>$CR_a$</th>
<th>$CR_b$</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Abies alba</em></td>
<td>0.0161</td>
<td>0.8038</td>
</tr>
<tr>
<td><em>Larix decidua</em></td>
<td>0.0077</td>
<td>1.2468</td>
</tr>
<tr>
<td><em>Pinus cembra</em></td>
<td>-0.0073</td>
<td>1.579</td>
</tr>
<tr>
<td><em>Pinus montana</em></td>
<td>-0.0054</td>
<td>0.8972</td>
</tr>
<tr>
<td><em>Pinus sylvestris</em></td>
<td>-0.014</td>
<td>1.6888</td>
</tr>
<tr>
<td><em>Taxus baccata</em></td>
<td>-0.014</td>
<td>1.6888</td>
</tr>
<tr>
<td><em>Acer campestre</em></td>
<td>-0.0177</td>
<td>1.8758</td>
</tr>
<tr>
<td><em>Acer platanoides</em></td>
<td>-0.0177</td>
<td>1.8758</td>
</tr>
<tr>
<td><em>Acer pseudoplatanus</em></td>
<td>0.0225</td>
<td>0.8625</td>
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<tr>
<td><em>Alnus glutinosa</em></td>
<td>0.0061</td>
<td>0.8672</td>
</tr>
<tr>
<td><em>Alnus incana</em></td>
<td>0.0061</td>
<td>0.8672</td>
</tr>
<tr>
<td><em>Alnus viridis</em></td>
<td>0.08</td>
<td>0.8672</td>
</tr>
<tr>
<td><em>Betula pendula</em></td>
<td>-0.0197</td>
<td>1.6764</td>
</tr>
<tr>
<td><em>Carpinus betulus</em></td>
<td>0.0052</td>
<td>2.0096</td>
</tr>
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<table>
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<tr>
<th>Species</th>
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<th>$CR_b$</th>
</tr>
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<tbody>
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<td>1.6764</td>
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</tr>
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</tr>
<tr>
<td><em>Populus tremula</em></td>
<td>0</td>
<td>2.432</td>
</tr>
<tr>
<td><em>Quercus petraea</em></td>
<td>0.0532</td>
<td>0.8246</td>
</tr>
<tr>
<td><em>Quercus pubescens</em></td>
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<td>0.8246</td>
</tr>
<tr>
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<tr>
<td><em>Sorbus aucuparia</em></td>
<td>-0.0611</td>
<td>2.7725</td>
</tr>
<tr>
<td><em>Tilia cordata</em></td>
<td>0.0674</td>
<td>0.8341</td>
</tr>
<tr>
<td><em>Tilia platyphyllos</em></td>
<td>0.0674</td>
<td>0.8341</td>
</tr>
<tr>
<td><em>Ulmus scabra</em></td>
<td>-0.0185</td>
<td>1.7834</td>
</tr>
</tbody>
</table>

Figure B3: Predicted crown area in TreeMig 1.0mf for the most common species used in our simulations, based on a regression analysis of the Swiss National Forest Health Inventory (Brang, 1998; Dobbertin, 1996).
B. Changes from TreeMig 1.0 to TreeMig 1.0mf

program allows a neutral model analysis of multifractal maps, when proportions of occupied pixels and the distribution type are given. To analyze the spatial distribution of trees and gaps within one cell in TreeMig 1.0mf, stochastic pixel maps were created with random distributions and analyzed for different \( p_{c tot} \) values in a polynomial regression. The program was run for maps representing single cells in TreeMig 1.0mf (therefore representing within-cell heterogeneity), using 256x256 pixels per run (cell), i.e. a within-cell resolution of approximately 1 m\(^2\), and with 10 repetitions. RULE requires input of fractions of different vegetation types, in our case forested and bare ground, for which \( p_{c tot} \) was used in steps of 0.05 resulting in 19 runs (from 0.05 to 0.95). The \( H \) index, representing the amount of spatial clustering, was set to 0.5 for all runs, assuming random spatial distributions. The maximum length of a gap within a cell was used as output, and approximated with a regression equation based on \( p_{c tot} \), as described in Eq. (B8).

\[
\text{GapFrac} = 4.46 \cdot p_{c tot}^4 - 8.00 \cdot p_{c tot}^3 + 3.22 \cdot p_{c tot}^2 - 0.43 \cdot p_{c tot} + 0.836 \quad \text{(B8)}
\]

with \( \text{GapFrac} \) as predicted gap length as a fraction of the cell side length. \( \text{GapFrac} \) was then transformed to maximum gap size per hectare (\( mgap \)) for compatibility with the avalanche calculations in the avalanche module.
C Avalanche release module: additional information

C.1 Representation of $P_{ar}$ in TreeMig-Aval

In TreeMig, within-cell heterogeneity is described by species- and height-specific frequency distributions of tree densities (Lischke et al., 1998), and the state variables represent the means of these distributions. In accordance with this state variable structure, the avalanche release probability $P_{ar}$ represents the mean of a normal distribution. However, the yearly calculation of $P_{ar}$ is not calculated as distribution but directly from the mean values of the TreeMig-Aval state variables to reduce simulation time. A pre-study showed that calculating $P_{ar}$ once using the mean state variable as input is equivalent to the average $P_{ar}$ of 10’000 repetitions drawing from the full distribution range of the state variable as input (data not shown). Deviations introduced with this simplification were small (1% deviation in < 0.5%, and 5% deviation in < 0.3% of all analyzed situations), showed no spatial pattern, and were considered minor compared to other model uncertainties.

C.2 Forest and topography influence on avalanche release

We performed logistic regressions (binomial generalized linear model; GLM) for the three avalanche release situations $i$ (bare ground, $glm_1$; coniferous forests, $glm_2$; mixed and broadleaf forests, $glm_3$) using topographic information and, where applicable, forest information as predictors for presence or absence of avalanches. For each GLM a tenfold cross-validation was run with a stepwise reduction procedure based on the Akaike Information Criterion (AIC). For the final models, predictor terms were chosen based on their occurrence in the tenfold cross-validation, and parameters for each term were based on all available data combined per avalanche situation (Tables C1, C2, Fig. C1, C2). The signs of the estimated parameters reflect influence of the factor on $P_{arTF}$. For example, in $glm_1$ and $glm_2$, a positive estimate for slope steepness (slp) combined with a negative estimate for slp$^2$ leads to a peak-shaped response of $P_{arTF}$ to slope (Table C1, Fig. C1).

For predictor equations based on binomial data, where the prediction is also binomial, thresholds are often used to determine the outcome. These thresholds are usually chosen at the best kappa value, to optimize model performance. For predictor equations where the outcome is continuous and used as a probability which is compared to a random number, the thresholds would lead to non-uniform probability distributions if the threshold is significantly different from 0.5. (For example, for a threshold of 0.7, 50% of the random numbers should be below 0.7, the other 50% above 0.7.) However, in our three models, the thresholds at best kappa were all close to 0.5 (0.46 ($glm_1$), 0.49 ($glm_2$), 0.52 ($glm_3$)) and were therefore not taken into account.

The statistical analyses involved in model building and testing, and their graphical representations here and in the main text were done in R 2.14.0 (R Development Core Team, 2011), using the packages 'dipetest' 0.75-1 (Maechler, 2011), 'lattice' 0.20-0 (Sarkar, 2011), and 'sp' 0.9-91 (Pebesma and Bivand, 2011).

C.3 Spatial and temporal reference factors in GLMs

Due to differences in spatial and temporal configurations of the avalanche input data sets, reference factors were used to translate avalanche release probabilities to the spatial and temporal resolution used in TreeMig-Aval (1-year time steps and 25-m cells). Due to the different data sources for the three avalanche release situations $i$, different reference factors were used in the three GLM equations.

The 50-year avalanche data set (Gruber and Bartelt, 2007; Maggioni and Gruber, 2003) used to build the non-forest GLM equation $glm_1$, described in Eq. (2), contained avalanche areas of different sizes and with different avalanche frequencies over the 50-years. Therefore, to standardize the avalanche release probability over time and space, we analyzed the meta-information given by Maggioni and Gruber (2003), using the 23 defined potential release areas, the release size in ten size classes (10-100% of the total release area affected), and the avalanche frequency. For each release area, the number of avalanches $n_{AR}$ in the 50-year data for each of the 10 release area size classes was multiplied with the release area size class size$^{pRA}$, and summed over all classes. This resulted in an avalanche frequency $AvalFreq^{pRA}$ per release area and per 50 years.
C. Avalanche release module: additional information

![Graph showing avalanche release module]

**Figure C1**: Plotted prediction equation for bare ground (glm1), at north exposition, on a relative scale for $P_{etf}$, illustrating the interaction between slope steepness (sllp) and curvature (crv). The influence of curvature is linear, while the influence of slope steepness is determined by the linear and quadratic terms (Table C1).

![Graph showing coniferous and mixed forest scenarios]

**Figure C2**: Plotted prediction equation for coniferous (glm2) and mixed forests (glm3), for three slope steepness scenarios, on a relative scale for $P_{etf}$. The panels show interactions between percent crown coverage ($pc_{tot}$) and maximum gap size (mgap), and between $pc_{tot}$ and percent coniferous crown coverage ($pc_{con}$), respectively.
C. Avalanche release module: additional information

Table C1: GLM summary table for the three avalanche release situations $i$: bare ground release areas ($glm_1$), release areas in coniferous forests ($glm_2$), and release areas in mixed and broadleaf forests ($glm_3$). Variable abbreviations are: $slp$, slope steepness (in $^\circ$); $crr$, slope curvature (relative measure of channelization calculated as second derivative of the surface); $est$ and $nth$, slope aspect (east = $est$ and west = $nth$, as relative measure calculated as sine and cosine of slope aspect); $pc_{tot}$, percent crown coverage (in %); $pc_{con}$, percent coniferous crown coverage (in %); $mgap$, maximum gap size (in m). Significance levels of parameter estimates are given as: *** $p < 0.001$; ** $p < 0.01$; * $p < 0.05$; $.$ $p < 0.1$. Graphical representations of the predictor equations are given in Fig. C1, C2.

<table>
<thead>
<tr>
<th>$glm_1$</th>
<th>full model</th>
<th>param. estimates</th>
</tr>
</thead>
<tbody>
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<td>$glm_1$ (bare ground)</td>
<td>$slp$</td>
<td>$a_1$</td>
</tr>
<tr>
<td></td>
<td>$slp^2$</td>
<td>$b_1$</td>
</tr>
<tr>
<td></td>
<td>$crr$</td>
<td>$c_1$</td>
</tr>
<tr>
<td></td>
<td>$est$</td>
<td>$d_1$</td>
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<td>$nth$</td>
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<td>$f_1$</td>
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<td></td>
<td>$nth^3$</td>
<td>$g_1$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$glm_2$ (coniferous forest)</th>
<th>full model</th>
<th>param. estimates</th>
</tr>
</thead>
<tbody>
<tr>
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<td>$slp$</td>
<td>$a_2$</td>
</tr>
<tr>
<td></td>
<td>$slp^2$</td>
<td>$b_2$</td>
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<td>$pc_{tot}$</td>
<td>$c_2$</td>
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<td></td>
<td>$pc_{con}$</td>
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<tr>
<td></td>
<td>$mgap$</td>
<td>$e_2$</td>
</tr>
<tr>
<td></td>
<td>$mgap^2$</td>
<td>$f_2$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>$glm_3$ (mixed/ broadleaf forest)</th>
<th>full model</th>
<th>param. estimates</th>
</tr>
</thead>
<tbody>
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<td>$slp$</td>
<td>$a_3$</td>
</tr>
<tr>
<td></td>
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<td></td>
<td>$pc_{con}$</td>
<td>$c_3$</td>
</tr>
<tr>
<td></td>
<td>$pc_{con}^2$</td>
<td>$d_3$</td>
</tr>
</tbody>
</table>

Table C2: Input data properties and GLM quality for the three avalanche release situations $i$. Abbreviations are: $n$, sample size of input data; $\Delta t$, time span covered by input data; TSS, true skill statistic; CCR, correct classification rate; $ref_i$, reference factors as explained in section C.3.

<table>
<thead>
<tr>
<th>$glm_i$</th>
<th>$\Delta t$</th>
<th>kappa</th>
<th>TSS</th>
<th>CCR</th>
<th>$ref_i$</th>
</tr>
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<tr>
<td>$glm_1$ &gt; 24000</td>
<td>1950-2001</td>
<td>0.55</td>
<td>0.55</td>
<td>0.78</td>
<td>$ref_1 = AveFreqPRA_{23} = 0.382$</td>
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<tr>
<td>$glm_2$ 201</td>
<td>1985-1990</td>
<td>0.53</td>
<td>0.53</td>
<td>0.77</td>
<td>$ref_2 = AveFreqPRA_{23} = 0.0432$</td>
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<tr>
<td>$glm_3$ 61</td>
<td>1985-1990</td>
<td>0.50</td>
<td>0.50</td>
<td>0.80</td>
<td>$ref_3 = AveFreqPRA_{23} = 0.2$</td>
</tr>
</tbody>
</table>

AveFreqPRA = $\sum_{i} n_{i}/50 \cdot size_{PRA}$

The maximum AveFreqPRA of the 23 release areas (AveFreqPRA$_{23} = 0.382$) described by Maggioni and Gruber (2003) was used as the maximum possible release probability in the avalanche release module, assuming that lower avalanche frequencies in the other release areas (in the data described by Maggioni and Gruber, 2003) were due to reductions by climate, topography, or vegetation, which are already accounted for in the avalanche release module. The maximum avalanche frequency found in the 50-year data, relative to release area size, was used as the spatial and temporal reference factor ($ref_1 = 0.382$) for non-forest avalanches ($glm_1$).

The 5-year forest avalanche data set (Meyer-Grass and Schneebeli, 1992) used to build the forest GLM equations Eq. (3) and (4), contained avalanche release areas and non-avalanche control areas on different slope exposures. This slope exposition is more important in coniferous forests than in mixed and broadleaf forests, thus an exposition-based reference factor was used in $glm_2$. In the coniferous forest avalanche data subset of the forest avalanche data (Schneebeli and Meyer-Grass, 1992), avalanches in north-exposed slopes (W-NE exposures) were 4.62 times more frequent than in
C. Avalanche release module: additional information

south-exposed slopes (E-SW expositions). Due to the small sample size of avalanches in south-exposed slopes, only avalanche probability in north-exposed slopes \( P_{av\text{North}} \) was explicitly modeled, and avalanche probability in south-exposed slopes \( P_{av\text{South}} \) was approximated as \( P_{av\text{South}} = P_{av\text{North}}/4.62 \) (i.e. with the reference factor \( re_{f\text{South}} = 1/4.62 = 0.216 \)).

As the forest information of the forest avalanche data set was already given relative to space (e.g. percent crown coverage per unit area), no spatial reference factor was necessary for the forest avalanche GLMs \( glm_2 \) and \( glm_3 \).

The time frame of the forest avalanche data (five years) was taken into account in a temporal reference factor \( (re_{f\text{time}} = 0.2) \). Because the avalanche presence and absence was recorded over five years, a 100%-probability of an avalanche release within that time span was translated to a 20%-probability of an avalanche release per year, assuming that each of the five years had an equal avalanche release probability. Accordingly, this reference factor is used in \( glm_2 \) and \( glm_3 \). For \( glm_2 \), the two reference factors for slope exposition and time were multiplied \( (re_{f_2} = re_{f\text{time}} \cdot re_{f\text{South}}) \).

Overall, the reference factors used for the different spatial and temporal configurations are listed in Table C2. The equation for back-transformation of the predictor equations \( glm_i \) from logistic to linear scale is described in Eq. (5) in the main text.

C.4 Climate influence on avalanche release

To aggregate the avalanche simulations to the same temporal scale as the forest simulations, the climatic avalanche release probability \( P_{av\text{C}} \) was approximated in two main steps. First, using Swiss climate data from 11 weather stations over 30 years (Swiss Federal Office of Meteorology and Climatology, MeteoSchweiz) we established an empirical relationship between temperature and the 3-day sum of new snow height \( H N72 \), which is a good approximation for the daily avalanche danger (McClung and Schaerer, 1993; Whiteman, 2011), and is often used in Swiss hazard map assessments (Bianchi Janetti et al., 2008; Bocchiola et al., 2008). The daily values of \( H N72 \) were translated into daily avalanche release probabilities using the information given in Table 5.1 by Schneebeeli et al. (1998). The summed monthly avalanche probabilities of each weather station were then compared among the months (Fig. C3).

Because there was no clear direct relationship between monthly temperature and monthly avalanche release probability, and because the mean monthly probability averaged over stations and years was very similar during November - April, we used the overall averaged probability over stations, years, and the mentioned months as constant (11.99%) monthly avalanche release probability in the simulations to obtain the yearly climate-related avalanche release probability \( P_{av\text{C}} \).

Second, the proportion of each year with potential avalanches (winter length) was approximated. Winter length was defined as the number of months with enough snow for avalanche release in un-forested \( WiLenBar \) and forested areas \( WiLenFor \). Due to the influence of forests on snow interception, and on avalanche release, the threshold values for snow cover differed between bare ground and forested areas. Snow covers of 20 cm and 30 cm are required for avalanche release in bare slopes (Schneebeeli et al., 1998) and forested areas (Teich et al., 2012a), respectively. However, since snow cover input data are not used in TreeMig-Aval, we approximated monthly snow cover with the available monthly temperatures. For this purpose, we tested the climate data for relationships between snow cover and temperature. Due to the different processes involved, years were split into a snow-accumulation phase (until end of Feb) and a snow-melt phase (after Feb).

Polynomial regressions for each phase (Fig. C4) showed moderate relationships between maximum snow cover and monthly minimum temperature \( (R^2 = 0.30 \) for early winter and \( R^2 = 0.39 \) for late winter). The relatively low model fit can be explained by the high variability. This variability was not represented in our simulation model directly. For simulations that used yearly data, the mean winter length is used directly, while for long-term data preparations, a mean and standard deviation is calculated over several years, and the yearly realization of winter length is drawn from this distribution.

In TreeMig-Aval, the minimum temperature is not directly available, but is predicted linearly from the mean temperature which is used in TreeMig (Eq. (C2); \( R^2 = 0.95 \)).

\[
T_{\text{min}} = 1.11 \cdot T_{\text{mean}} - 7.27 \tag{C2}
\]
C. Avalanche release module: additional information

Figure C3: Monthly summed avalanche probability, based on climate data over 30 years and 11 stations above 1500m a.s.l. in Switzerland, and a translation into avalanche release probabilities using the information given by Schneebeeli et al. (1998). No significant differences in mean avalanche probability were found between November and April (mean 11.99%).

Figure C4: Regression of monthly maximum snow cover and minimum temperature, over 30 years and 11 stations above 1500m a.s.l. in Switzerland. Despite high variability, the polynomial regressions for early and late winter months showed some relationship of snow cover with temperature (early winter $R^2 = 0.30$; late winter $R^2 = 0.39$). The threshold values for temperatures required for winter months were taken from the regression predictions at the snow cover required for avalanches.
References

For the calculation of winter length, the average minimum monthly temperatures at the according snow layer thresholds were then used as upper threshold for the minimum monthly temperature of winter months. The resulting thresholds were $-5.0 \, ^\circ{C} \left(-6.1 \, ^\circ{C}\right)$ for early winter on bare (forested) slopes, and $0.6 \, ^\circ{C} \left(-0.5 \, ^\circ{C}\right)$ for late winter on bare (forested) slopes, respectively (Fig. C4). Where temperature thresholds were crossed between two months, the portions of the months below the thresholds were interpolated linearly.

In the TREEMIG-AVAL transect simulations described in the main text, only long-term climate was used, and the winter length was therefore used as distribution described by a mean and standard deviation over a base period. The yearly realizations of winter length were sampled randomly from this distribution for each cell. The calculation of the final climate-related avalanche release probability $P_{arc}$ in each cell and year depended on the state of each cell (forested, unforested), and was calculated as multiplication of the according winter length with the monthly avalanche release probability (11.99%; Fig. C3).

References


References


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Pebsma, E., Bivand, R., 2011. R package ‘sp’ v0.9-91.


Sarkar, D., 2011. R package ‘lattice’ v0.20-0.


Appendix D

Paper X

Performance of alternative disturbance formulations in a spatially explicit avalanche-forest model

Intended for submission

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To Ecological Modeling
Abstract
Spatial and temporal patterns of disturbances strongly influence the structure and dynamics of mountain forests. In the Swiss Alps, snow avalanches are one of the most important disturbances influencing humans and ecosystems. The influence of forests on avalanches, coupled with the influence of avalanches on forests, leads to a positive avalanche-forest feedback and to complex landscape patterns. Dynamic forest models are useful tools to study these processes, their interactions, and their changes under environmental change. The aims of this study were to include an avalanche flow module in a spatially explicit dynamic forest landscape model coupled with an avalanche release module (TREEMIG-AVAL), and to examine if such spatially explicit disturbance simulations improve model performance compared to simplified model versions without disturbances, or with random disturbances.

TREEMIG-AVAL simulates the influence of forests, topography, and climate on avalanches, and the influence of avalanches on forests. These interactions result in a dynamically simulated positive feedback influenced by changes in the environment, and lead to distinct landscape patterns as an emergent model property. Using a study area in the Swiss Alps, we tested if the spatial patterns of simulated avalanches in TREEMIG-AVAL agree with observed avalanche patterns. Then, we compared forest simulation results of the three model versions without disturbances, with random disturbances, and with explicit avalanches, to observed forest density and composition. Avalanche and forest observation data were available for avalanche frequency, forest density, and forest types, and the comparisons were done for each variable on three spatial scales. Additionally, simulation results of the three model versions were compared under a future extreme climate change scenario, to test if the sensitivity of model versions to the disturbance formulations remained under warmer climate.

We found that the areas affected by avalanches corresponded well with observed avalanches. However, within the affected areas, avalanche frequency was overestimated by the model, and the model may need further improvements regarding the speed of forest and avalanche dynamics. In the comparisons of simulated to observed forest density and forest types, the full model version including explicit avalanches performed best. Simulations without disturbances overestimated forest density and underestimated the number of forest types, while simulations with random disturbances improved the resulting forest density and number of forest types but was not able to capture the spatial patterns of the forest patches. The future simulations showed that model sensitivity to disturbance formulations persisted under higher temperatures.

The model version comparisons showed that (a) disturbances in general are necessary to be able to represent all forest types and (b) spatially explicit disturbances, in this case spatially connected avalanches, are necessary to provide the spatial patterns of forest density and types observed in the mountain forest of our study area. We conclude that with potential further improvements of TREEMIG-AVAL, the model is useful for dynamic and spatially explicit simulations of avalanche-forest feedback under environmental change, and is an improvement over model versions without spatially explicit disturbances.

Keywords: spatially explicit simulation, positive feedback, dynamic forest model, Treemig-Aval, snow avalanches, disturbance model

1 Introduction
Disturbances are important structuring processes in forest ecosystems, and snow avalanches are one of the most important disturbances in boreal and temperate mountain forests (Walsh et al., 1994; Tanaka et al., 2008; Bebi et al., 2009). With the expected temperature increase in mountain ecosystems locally and globally (Beniston et al., 1997; Pepin and Seidel, 2005), forests will experience changes in environmental drivers, tree population dynamics, and in disturbance frequency and intensity (Bugmann et al., 2005; Nogues-Bravo et al., 2007; Trujillo et al., 2012). In Europe, even though snow and weather conditions associated with avalanche releases in forests show decreasing trends (Teich et al., 2012a), high elevation avalanches have remained important over the past century (Martin et al., 2001; Laternser and Schneebeli, 2003; Eckert, 2009).

Forest mortality caused by snow avalanches, coupled with the forests’ capability to reduce the probability of avalanche release (Bebi et al., 2009), leads to a positive feedback (sensu
Wilson and Agnew, 1992) between avalanches and forests: when forest gaps are created in steep terrain and tree density falls below a certain threshold, the probability of avalanche release increases, which can lead to a further reduction in tree density and a subsequent increase in avalanche release probability. Spatial patterns of spatially connected disturbances such as avalanches influence forest landscape patterns (Hiebeler and Michaud, 2012), and avalanche-forest feedbacks can lead to complex landscape patterns in time and space (Peterson, 2002; Loehle, 2004), thereby challenging projections of future forest development.

To improve the process knowledge of potential future forest development, experimental or observational studies are often impossible due to the large temporal and spatial scales involved. Therefore, dynamic forest models have become increasingly important tools in forest and landscape scenario analysis under environmental change. However, despite recent developments in forest models, disturbances are rarely simulated explicitly, i.e. as a spatially explicit and emergent model property (Marston, 2010; Reinhardt et al., 2010; Seidl et al., 2011). Spatially explicit landscape properties may be spatially “distributed”, in the case of cell-specific data (e.g. climate or topography), or additionally spatially “linked”, in the case of cell-specific processes which influence neighboring cells (such as described as ‘spatially linked spatio-temporal’ (SLST) processes by Lischke et al., 2007). In this paper, we use the term “spatially explicit disturbances” as a spatially linked process influenced by spatially distributed driving factors, and our disturbance simulations include the criteria spatial interactions and dynamic communities from the classification of Scheller and Mladenoff (2007) and Xi et al. (2009).

Some examples of spatially explicit disturbances in forest landscape models are the simulation of fire in LANDIS (Wimberly, 2004), windthrow in LPJ-Guess (Lagergren et al., 2012), windthrow and fire in LandClim (Elkin et al., 2012), and insects in LPJ-Guess (Jönsson et al., 2012). However, in many forest models, disturbances are neglected or represented as a spatially averaged random parameter. Despite the importance of avalanches in the forests of many mountain regions worldwide, until recently avalanches have not been included explicitly in dynamic forest models. To our knowledge TREEMig-AVAL (Zurbriggsen et al., 2014) is the first spatially explicit forest model that includes the effect of both forests on avalanches and avalanches on forests, and that therefore allows for spatially explicit and dynamic simulations of the avalanche-forest feedback.

TREEMig-AVAL consists of the forest landscape model TREEmig (Lischke et al., 2006) coupled with an avalanche release module (Zurbrigggen et al., 2014) and a new module for avalanche flow direction and length (described here). TREEmig-AVAL allows simulations of forest and avalanche dynamics in yearly time steps. TREEMig-AVAL is sensitive to environmental factors (Zurbrigggen et al., 2014), and has the advantages that it runs on a sufficiently high spatial resolution for avalanche simulation (25 m-cells) and can simulate long time spans (centuries to millennia). In each year, the model simulates avalanches as an emergent spatial pattern, without prescribed avalanche release areas.

A wide range of questions regarding for example climate change impacts or interactions with land use can be answered with TREEMig-AVAL, but the simulations should be compared to observation data first. Because “absolute” validations are considered impossible due to limitations of models, observation data, and validation procedures (Oreskes et al. 1994; Beven 2006; Xi et al. 2009; Kirchner 2006; but see Rykkel 1996), it has been suggested that the relative model performance, compared to other models or model versions, can provide more valuable information (Oreskes et al., 1994; Kirchner et al., 1996; Loehle, 1997). Specifically, by comparing model versions with different levels of process resolution to observation data, the differences in model performance among the model versions can be used to test if model performance is increased by the proposed increase in process resolution. Therefore, the objective of this study is a comparison of TREEMig-AVAL simulation results with observation data, as well as comparisons of results of two simplified model versions with observation data. To study if it is necessary to spatially explicitly simulate avalanches, the two simplified model versions used disturbance formulations where the avalanche simulation was removed, or replaced by a spatially averaged random parameter. Furthermore, we compared all three model versions under an extreme future climate warming scenario, to test whether the effects of
simplified disturbance simulations remain with changes in environmental drivers. Davos in the eastern Swiss Alps was chosen as case study area, due to the importance of avalanches and protection forest, and the availability of forest and avalanche observation data. Three available data sets, for avalanche frequency, forest density, and forest composition, were used for the comparisons. Our research questions were:

(1) Is TREEMIG-AVAL consistent with observations and scientific knowledge in the study area Davos in Switzerland?
(2) Is it necessary to simulate avalanches spatially explicitly, or could they be omitted or approximated by a spatially averaged random disturbance parameter?
(3) How do the differences among model versions with different disturbance simulations change under an extreme future climate scenario?

2 Model description

The forest and avalanche release simulation of TREEMIG-AVAL (Fig. 1) has been described before (forest model in Lischke et al. 1998, 2006 and avalanche release module in Zurbriggen et al., 2014). Here, we provide a summary of these two components and introduce a new avalanche flow module.

2.1 Forest and avalanche release simulation

Yearly forest dynamics are simulated as species-specific seed dispersal, seed bank dynamics, germination, growth, maturation, seed production, and mortality, driven by temperature, precipitation, and competition for light (Lischke et al., 2006). Tree growth is calculated for height classes and applied as transition probabilities between these classes (Lischke et al., 1998). A detailed description of the forest dynamics model can be found in earlier publications (Lischke et al., 1998, 2006; Rickebusch et al., 2007). The input data required for forest dynamics are spatially explicit maps of bioclimatic variables (Lischke et al., 2006), and additional variables specifically included for better representation of treelines (Zurbriggen et al., 2014).

The avalanche release probability is influenced by climate, topography, and forest density and type in each cell and time step (Zurbriggen et al., 2014). Therefore, in addition to the bioclimatic input variables required for the yearly forest dynamic simulations (Lischke et al., 2006), TREEMIG-AVAL requires spatially explicit input maps for winter length, slope steepness, curvature, and aspect. While TREEMIG is spatially linked due to the explicit simulation of seed dispersal, TREEMIG-AVAL is additionally linked by spatially connected

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**Fig. 1.** Schematic structure of TREEMIG-AVAL simulation sequence. Each simulation step (one year) updates the climate information, determines avalanche release based on the previous year avalanche release probability, and determines avalanche flow direction and length if an avalanche is released. The flow length results from an iterative application of stopping probabilities in each cell along the flow path. Within all cells affected by avalanches, an avalanche-induced mortality is applied to the forest. Forest dynamics are then calculated as in TREEMIG (Lischke et al., 2006). At the end of each simulation step, the avalanche release probability is calculated based on the current year forest, climate, and (static) topography, after which the simulation of the next time step starts. Optionally, output can be written for pre-defined years or intervals, for avalanche probability, flow frequency, and several forest density and composition variables.
avalanches affecting several cells during their flow. Thus in TREEMIG-AVAL cells can have a higher disturbance frequency than estimated from the local cell properties (topography, climate, forest) alone, due to contributing areas further upslope. An avalanche is released if a number drawn from a pseudo-random number (prn) stream uniformly distributed within [0,1] is lower than the avalanche release probability in the current cell and one adjacent cell (within the von Neumann neighborhood).

2.2 Spatially explicit avalanche flow

After the release of an avalanche, its flow path is simulated iteratively with a probabilistic flow direction and flow stop in each cell. The avalanche flow path and length are thus stochastic emergent properties influenced by topography, avalanche release type, forest structure, and forest type. In each cell along the flow path, the avalanche stopping probability \( p_{\text{stop}} \) is determined with an empirically derived set of rules (see section 2.2.1). For the flow direction, flow angles calculated with a hydrological flow model are used as input into TREEMIG-AVAL, and converted to flow probabilities into separate neighboring cells (in the Moore neighborhood; see section 2.2.2). To keep the flow module complexity to a minimum, the snow mass entrainment, kinetic flow energy, and snow deposition are not explicitly simulated. Instead, each simulated avalanche only flows from one cell into a single neighboring cell without spreading to further cells, and snow mass is not considered.

2.2.1 Flow length

Avalanche flow length results from the simulation of flow stopping probability \( p_{\text{stop}} \) in each cell along the flow path, and is influenced by slope steepness, forest release type, and forest flow type. The influence of slope steepness is simplified such that avalanches always stop in cells that are \( \leq 10^\circ \) steep (Delparte et al., 2008; Anderson and McClung, 2012). On steeper slopes, the avalanche stopping probability \( p_{\text{stop}} \) is approximated by an empirical set of rules derived from Swiss and Bavarian avalanche flow length data (Teich et al., 2012b).

Teich et al. (2012b) showed that avalanche flow could be classified according to the forest type of the release area, and the position of the current cell along the cumulative flow length. The classification of release area forest types is also used in TREEMIG-AVAL (see Zurbrüggen et al., 2014, and Table 1), where we define four forest classes of no forest (\( \leq 30\% \) total crown coverage), evergreen coniferous forest (\( \geq 60\% \) coniferous crown coverage), larch forest (\( \geq 60\% \) larch crown coverage), and mixed forest (\( \geq 40\% \) broadleaf deciduous crown coverage). The classification analysis further showed that two classes of cumulative flow length, separated at 400 m flow length, describe the data well. The resulting eight classes (4 forest types x 2 cumulative flow lengths) are then used to determine the probability of stopping \( (p_{\text{stop}}) \) in each cell along the flow path. This probability was calculated in advance for each class, by performing a survival analysis on the available flow length data. For each of the eight classes, the proportion of avalanches flowing through each meter ("survival") was calculated, and a stopping probability per meter ("mortality") was derived. This probability was then converted to a 25-m probability for avalanche flow to direct neighbor cells and to a 35-m probability for avalanche flow to diagonal neighbor cells, resulting in 16 pre-defined values for \( p_{\text{stop}} \) (see the supplementary material A), which are applied in each cell depending on the forest type of the avalanche release area, the cumulative flow length, and the local flow direction (direct or diagonal).

In addition to the forest type of the release area, the forest type of the flow path showed influences on the stopping probability of avalanches (Teich et al., 2012b). We approximated the increase in \( p_{\text{stop}} \) caused by forest in the flow path by a second rule-based classification. For avalanches that flow through at least four continuously forested cells (i.e. \( \geq 100 \) m), a predetermined increase in \( p_{\text{stop}} \), empirically derived from the available data (Teich et al., 2012b), is used for the different forest classes.

For each released avalanche, an iteration through the cells in the flow path is used, in which the initial \( p_{\text{stop}} \) is determined based on the release type, and the cumulative \( p_{\text{stop}} \) is summed as the avalanche flows through different cells. In each cell along the flow path, the avalanche stops if a uniform random number (prn, drawn from [0,1]) is smaller than the cumulative \( p_{\text{stop}} \). Otherwise, the avalanche flows into the next cell, and the corresponding increase in stopping probability based on conditions in the new cell is added to \( p_{\text{stop}} \).
2.2.2 Flow direction

The simulation of avalanche flow direction is based on output from the hydrological model TauDEM v4.0 (Tarboton, 2009). The continuous $D_{af}$ flow direction described by Tarboton (1997) specifies the angle of the steepest downward slope from the center cell to the center points of cells in the Moore neighborhood, and is used as input for TREEMIG-AVAL. This continuous angle can point between two neighboring cells within the Moore neighborhood (see Fig. 2 in Tarboton, 1997), and in TauDEM it specifies the proportions of hydrological flows between these two neighboring cells. In TREEMIG-AVAL, the proportions are used as probabilities of the flow of the whole avalanche into one of the two neighboring cells. The decision of the flow direction is influenced by an independent prn stream, and is repeated in each cell along the flow path of the avalanche, until the avalanche stops (see above).

3 Simulation experiments

3.1 Model versions

We compared TREEMIG-AVAL with two model versions with simplified disturbance simulations. The full model TREEMIG-AVAL uses the spatially explicit avalanche simulation described above. The forest in cells affected by avalanches is subjected to an avalanche mortality of 80% for all height classes and all species except Alnus viridis (Chaix) DC. (20% mortality), due to this species’ high elasticity (Stokes et al., 2012), and ground vegetation which is assumed to have no avalanche mortality. Despite avalanche mortality being species- and size-specific (e.g. Johnson, 1987; Bebi et al., 2009), the estimated 80% mortality provides a plausible first estimate, which may be specified further if species- and size-specific mortality data compatible with the model structure become available. Additionally, all forested cells are subject to low-intensity random “background” disturbances (with 5% probability of occurrence per year and cell and 5% mortality), which are often used in forest gap models (e.g. reviewed in Bugmann et al., 2001; Keane et al., 2001). In the first simplified model version, abbreviated as TMA-hiR, the explicit avalanche simulation was replaced by a disturbance parameter calculated as the spatially and temporally averaged avalanche frequency of TREEMIG-AVAL over 600 years, i.e. a 16.8% disturbance probability per cell and year with the same avalanche mortality as described above. In the second simplified model version, abbreviated as TMA-loR and equivalent to TREEMIG 1.0b, avalanches were removed completely, and only the random “background” disturbance was used. Because the focus of this study is on large disturbances with higher mortality, this model version represents a “no disturbance” model version.

In all three model versions non-avalanche disturbances were simulated stochastically based on their probabilities of occurrence per cell and year. The same set of 30 prn streams and the same climate sequence was used for the three model versions. The model was implemented to use independent prn streams for each simulation step that includes stochasticity (climate sequence, avalanche release, avalanche flow, other disturbances). Therefore, differences in simulations among model versions can be attributed to differences in disturbance formulations, and the effect of stochastic environmental influences on model version differences is minimal.

3.2 Study area

Simulations were run for a 4.6 km x 3.4 km area of the Dischma Valley in Davos, in the eastern Swiss Alps (Fig. 2), on a grid of 25-m cells. This area is characterized by an inner alpine climate, and the most dominant tree species are Picea abies L., Larix decidua L., and Pinus cembra L.. The altitude in the simulation area ranges from 1540 to 2560 m asl, with the current treeline at ca. 2100 m asl. (Barbeito et al., 2012). The NE-facing slope in the study area is very steep, while the SW-facing slopes are less steep (Fig. 2). All slopes, especially the NE-facing slope, are characterized by gullies and ridges, which influence the release and flow of avalanches.

The climate input files required for the simulations were derived from monthly temperature and precipitation data, based on CRU climate data (University of East Anglia, Norwich, UK) interpolated with DAYMET (Thornton et al., 1997). The topographical input files for altitude, slope, aspect, and the derived variable flow direction were based on a Swiss digital elevation model with 25 m resolution (DHM25(c)1994 Federal Office of Topography). Settlement areas (Davos) and bare rock areas were excluded for forest dynamics simulations but not for avalanche release or flow simulations.
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Fig. 2. Location and topography of the simulation area in the eastern Swiss Alps (Dischma Valley, Davos, Switzerland). The topography is shown as hillshade (ESRI ArcMap 9.3), and altitudinal contour lines (200-m steps) in the 4.6 km x 3.4 km simulation area (inset). The altitudinal range of the simulation is 1540-2560 m asl. Gullies and ridges characteristic for this region are mainly visible on the NE-facing slope, but occur throughout the simulation area. The hillshade and contour lines are based on a digital elevation model with 25 m resolution (DHM25©1994 Swiss Federal Office of Topography).

3.3 Observation data

For the comparison of simulations with observations, observation data sets were available for avalanche frequency, forest density, and forest types. The avalanche frequency data were used to assess the accuracy of avalanche simulations in TREEMIG-AVAL, while the forest density and type data were used to examine the influence of different disturbance formulations on the model version performance in terms of forest simulations. The forest type data were available as forest classes, while the avalanche frequency and forest density were available as continuous data. Simulation results were compared to each of the three data sets on a cell-by-cell level, patch level, and whole landscape level. The patches are defined here as groups of contiguous cells of the same landscape class (such as used by Urban et al., 1987, to describe landscape patterns), and are not related to forest patches within cells as the term is commonly used in forest gap models (e.g. reviewed by Bugmann et al., 2001; Xi et al., 2009). To be able to compare the simulations and observations on the patch level, class data were necessary, and the avalanche frequency and forest density were therefore also used as class data. The three data sets were also used in classes for the comparisons on the cell-by-cell and landscape levels, to enable comparisons among the three spatial scales.

The avalanche frequency observation data were used as maps of the percentage of years with avalanches during 1955/56-2011/12, which were combined from two data sets (1955-2005 and 2006-2012) from the Updated Internal SLF-Avalanche Database of the area around Davos (see also Maggioni and Gruber, 2003; Bühler et al., 2013). For the map comparisons, the avalanche data were divided into three classes (Table 1), of low frequency (<5%), mid frequency (<30%) and high frequency (≥30%).

Table 1. Avalanche frequency, forest density, and forest type classification criteria for observation and simulation data. For avalanche frequency and forest density, the criteria were applied to both observation and simulation data, while for forest classes the observation data were assembled according to MAB forest classes given. Simulated tree species compositions were classified according to the listed criteria, based on the total percent crown coverage ($pc_{tot}$), coniferous percent crown coverage ($pc_{cnf}$), and species-specific percent crown coverage ($pc_{larch}$ and $pc_{Bp,Sa}$), for each cell and year. The classes are applied rule-based, top-down as listed here, i.e. a forest is compared to the classes until a class is assigned. Abbreviations: Av, *Alnus viridis*; Sa, *Sorbus aucuparia*; Bp, *Betula pendula*.

<table>
<thead>
<tr>
<th>Avalanche frequency (observation &amp; simulation data)</th>
<th>Obs. data years</th>
<th>Classes</th>
<th>Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>low frequency</td>
<td>1955-2012</td>
<td>&lt;5% avalanche years</td>
<td>&lt;5% avalanche years</td>
</tr>
<tr>
<td>mid frequency</td>
<td></td>
<td>&lt;30% avalanche years</td>
<td>≥30% avalanche years</td>
</tr>
<tr>
<td>high frequency</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| Forest density (observation & simulation data)       | 2003            | low density (=no forest) | <30% $pc_{td}$ |
|                                                     |                 | mid density               | ≥60% $pc_{td}$ |
|                                                     |                 | high density              |                      |

| Forest types (simulation data)                       | 1980            | no forest                 | <30% $pc_{td}$ |
|                                                     |                 | larch forest              | ≥60% $pc_{td}$ |
|                                                     |                 | pioneer forest            | ≥30% $pc_{td}$ |
|                                                     |                 | deciduous forest          | <60% $pc_{td}$ |
|                                                     |                 | coniferous forest         | ≥60% $pc_{td}$ |

The percent crown coverage observation data were derived from LiDAR vegetation height data (2003 ALS data) at a resolution of 2.5 m, available up to a maximum altitude of 2000 m asl. Each 2.5-m pixel was classified as ‘forest’ if vegetation height was >1.37 m. This height threshold constitutes the minimum tree height in TREEMIG, and therefore ensures comparability.
between simulated and observed data. The 2.5-m LiDAR pixels were then aggregated to 25-m cells by calculating the percentage of LiDar pixels classified as forest within each 25-m cell. The percentage data were then divided into three classes of low density (<30%; 'no forest'), mid density (<60%) and high density (≥60%) forest (Table 1).

The forest type observation data were based on the Davos project of the UNESCO program 'Man And Biosphere' (MAB) (Wildi and Ewald, 1986), available at a 50-m resolution. The highly detailed vegetation types (62 classes) surveyed in 1980 were aggregated into 5 classes relevant for this study and compatible with TREEMig simulation results. In addition to the same four forest classes used to distinguish avalanche release types (no forest, coniferous forest, larch forest, mixed forest; see Table 1), a separate class for broadleaf deciduous pioneer forest (abbreviated here as 'pioneer forest') was used due to its relevance in avalanche-prone areas. This class was defined as forests with high proportions of *Alnus viridis* (Chaix.) DC., *Betula pendula* Roth, or *Sorbus aucuparia* L.. All preparations of observation data were done in ESRI ArcMap 9.3.

### 3.4 Simulations and output data

The simulations with each model version were repeated 30 times with the same set of 30 prn streams, as preliminary analyses had shown that 30 repetitions cover a large range of variability in the output. Each simulation was run for 600 years, with a model spin-up from 1500 to 1900 AD using extrapolated climate data from 1900-1920. The simulations from 1900 to 2100 used yearly climate data, based on observational climate data for the period 1900-2000, and on yearly SRES A2 projections for the period 2000-2100. During the first 100 years (1500-1600) the simulations were initialized by making seeds available everywhere. For this initialization seed dispersal and disturbances were switched off to save computing time. Explicit seed dispersal and disturbances were switched on in 1600 AD for the rest of the simulation.

The output variables from the simulations were transformed equivalent to the observation data available, and were recorded for each cell in the same years as the observation data were available. Additionally, all variables were recorded for 2100 AD for the future scenario assessment. The percentage of years with avalanches per cell was calculated for 1955-2012 and 2050-2100 in the TREEMig-AVAL simulations, and reported in the same three classes used in the observation data, with low frequency (<5%), mid frequency (<30%) and high frequency (≥30%) avalanches (Table 1).

Total percent crown coverage (\(p_{c_{tot}}\)) per cell was calculated from the sum of individual crowns, specific for each species and tree height, while accounting for crown overlap (Zurbriggen et al., 2014), and was reported for the years of the observation data (2003) and future scenario (2100) in all three model versions. In accordance with the forest density observation data, \(p_{c_{tot}}\) was also divided into three classes of low density (<30%; 'no forest'), mid density (<60%) and high density (≥60%) forest (Table 1). The forest type in each cell was classified based on species-specific summed crown area as a percentage of total summed crown area (Table 1) and reported as one of five classes for the years of the observation data (1980) and future scenario (2100) in all three model versions. The threshold values for the class distinctions were estimated based on the forest class information available in the MAB forest type observation data. The forest type simulation results were then aggregated to 50-m cells by nearest-neighbor interpolation to accommodate the lower resolution of the MAB data.

Land-use effects are implicitly included in the observed data, but are not included in the simulations. To obtain comparable maps, the areas affected by land use were therefore excluded from the forest structure and composition comparisons to avoid biases. Independent land use information was used, based on the Swiss Land Use Statistics (1979/85 revised data BFS GEOFONT, Federal Statistical Office), which were available at a resolution of 100-m cells. Furthermore, because the forest density observation data were available only up to 2000 m asl, only the area below that elevation was compared. For the comparisons of the avalanche frequency maps, no areas were excluded.

### 3.5 Evaluation of simulation results

Output maps were produced for each combination of the three model versions, two forest output variables, two output time points, and 30 repetitions, resulting in 360 maps. Additionally, avalanche frequency maps were simulated with TREEMig-AVAL for the observation data years (1955-2012) and the
future scenario years (2050-2100), with 30 repetitions, resulting in a total of 420 maps. Each set of 30 maps per model and output variable was compared to the corresponding observation data map. Within each set of 30 repetitions, each simulated map was individually compared to the observation data map to account for variability in the simulation results, and the comparisons were made on the spatial levels of cells, patches, and the whole landscape.

3.5.1 Cell by cell comparisons

Cell by cell comparisons between observation and simulation maps were run with the Map Comparison Kit 3.2.2 (Visser and de Nijs, 2006), and the fraction of correct classifications is reported for each simulation map. However, this measure of agreement is biased when classes show uneven distributions, and we also report Cohen’s kappa statistic (Cohen, 1960) as a measure of agreement that takes into account agreement occurring by chance based on the rates of occurrence of each class (Foody, 2002; Visser and de Nijs, 2006). Kappa ranges from 0 to 1, for map pairs ranging from completely different to identical. The performance of model versions can thus be said to increase with increasing kappa. Kappa may be interpreted in classes, such as suggested by Monserud and Leemans (1992), but it has also been argued that “correct” values of kappa may not always be determined, especially with low numbers of classes and high variability (Bakeman et al., 1997). Therefore, we base our assessment of model performance on the relative ranking of the kappa values among model versions.

The calculation of kappa allows fuzzy-based map comparison, applying fuzziness either to location or to category (Hagen, 2003; Hagen-Zanker et al., 2005; Visser and de Nijs, 2006). The fuzziness of category is intended as tolerance levels for misclassification rates between different classes and thus allows partial class membership. Due to a known overestimation of successsion speed (Lischke et al., 1998), avalanche frequency was overestimated during the calibration of the feedback strength in the model. Therefore, a higher tolerance was set for misclassification between the classes intermediate and high avalanche frequency (category similarity was set to 0.2). Similarly, a category similarity of 0.2 was used for the intermediate and high forest density. For the forest types, no prior knowledge about model performance was available, and category similarity levels between all pairs of forest types except the 'no forest' class were set to 0.1. We assumed that a category fuzziness makes sense for ordinal categories that are based on continuous variables (e.g. avalanche frequency and forest density), and for nominal categories that are based on continuous compositions of species percentages. The fuzziness of location, i.e. tolerance of location errors, was not applied in this study due to a generally high spatial autocorrelation, which can bias kappa values (Hagen-Zanker, 2009).

3.5.2 Patch level comparisons

At the patch level, we compared landscape properties without taking into account the exact locations of the patches. We calculated three landscape metrics that are useful for analyses of the clustered and elongated spatial structures expected from forests influenced by avalanches. First, the largest patch index (lpi, in percent of the landscape) was calculated for each class. The absolute value of lpi is a measure of class connectivity in the landscape, which is useful to distinguish forests that are fragmented by avalanche tracks from other forest patterns. Further, the comparison of the lpi values across classes provides a measure of class dominance. Second, a shape index (shape, no units) was calculated as patch shape complexity relative to a square shape. Shape has a value of one for square patches, and increases with increasing patch shape complexity, without an upper limit. This index is useful to distinguish between linear elements such as avalanche tracks, and random patterns as they would be expected from random disturbances. Third, we calculated an index describing the spatial aggregation of patches (clumpy, no units). The clumpy index ranges from -1 for disaggregation to 1 for full aggregation, with the advantage that the value reaches 0 for random distributions of patches. This provides information on the texture of the landscape, but also on the overall dispersion and connectivity of classes within the landscape. Thus this index should allow for distinctions between the effects of no disturbances (high connectivity expected), random disturbances (random distribution expected), and avalanches (intermediate aggregation expected).

The shape index is calculated for each patch, and subsequently averaged per class, while lpi and clumpy are calculated directly from the landscape for each class. The distribution of each landscape metric over the maps of the 30
repetitions was then compared to the landscape metric of the corresponding observation data map, i.e. for each class in avalanche frequency, forest density, and forest type. All landscape metrics on the patch level were calculated in Fragstats 4.0 (McGarigal et al., 2012).

3.5.3 Landscape level comparisons

For the direct landscape-level comparisons, we created maps in ESRI ArcMap 9.3, and compared them visually between simulated and observed data. Visual comparisons are often considered more informative than automated quantitative comparison methods (Hagen, 2003; Visser and de Nijs, 2006), because they provide more information on the explicit spatial patterns than the comparisons on the patch and cell levels do. For these comparisons, the map with the best fuzzy kappa agreement was chosen from the 30 repetitions for each variable and model version, respectively. However, the variability among the 30 repetitions was very low for all model versions and output variables (see the supplementary material B).

3.5.4 Model version rankings

For the two variables forest density and forest type, the three model versions were each compared to the observation data. In the cell-by-cell and landscape level comparisons, one comparison was done with each model version with forest density and type observation data. On the patch level, comparisons were done for each class (three forest density classes and five forest type classes) and each model version. For forest density, 11 comparisons between model versions and observation data were done, with one each on the whole landscape and cell-by-cell levels, and nine (3 classes x 3 metrics) on the patch level. For forest types, 17 comparisons were done, again with one each on the whole landscape and cell-by-cell levels, and 15 (5 classes x 3 metrics) on the patch level. The best model version was determined in each comparison, and the number of best performances was summed for each model version. Model versions were then ranked depending on how many times each version performed best in the comparisons with the observation data, to assess their overall relative quality in terms of the forest simulations.

4 Results

4.1 Simulation results in observation data years

In a first step, the avalanche frequency resulting from TREEmig-AVAL simulations were compared to the observation data during 1955-2012 AD. In a second step, results from all three model versions were compared to observation data for forest density (in 2003 AD) and forest type data (in 1980 AD). All comparisons were done on three spatial scales, and are described in detail in the following sections.

4.1.1 Avalanche frequency

Over the 30 TREEmig-AVAL maps of avalanche frequency resulting from the simulations, the fraction of cells with correctly classified avalanche frequency between 1955-2012 in the simulations was above 0.63 for each of the 30 repetitions. The mean kappa agreement between each simulated map and the observed map was 0.322 (Table 2), and among the 30 repetitions kappa ranged from 0.310 to 0.338. The simulations of avalanche presence or absence, based on a threshold of 5% avalanche frequency, showed a correct classification of at least 0.77 in all cases, and a mean kappa of 0.527 (Table 2). Kappa values tended to be lower than the correct classification rate, because chance agreement between cells is accounted for in (and thus removed from) kappa. The model performance was considerably higher when two classes were used for avalanche frequency (i.e. avalanche presence and absence) instead of three classes, suggesting that the areas affected by avalanches were simulated more accurately than the avalanche frequency within them.

On the patch level, the comparison of the three avalanche frequency landscape metrics in the maps of the 30 repetitions with the observed avalanche frequency map shows that the largest deviations between simulated and observed maps are in the aggregation (clumpy) of the mid avalanche frequency class (Fig. 3). Both the low and high avalanche frequency classes showed strong agreement between observed and simulated results in terms of patch shape and aggregation (i.e. observed value within or very close to 95% confidence interval (CI) of simulated values). All three classes showed moderate deviations in the largest patch size (lpi), whereas the simulated shape agreed well with the observed values.
Table 2. Fraction of correct cell-by-cell classifications and fuzzy kappa values resulting from the comparisons of simulation results to the observation data, for avalanche frequency, avalanche presence or absence, forest density, and forest type. The lowest, mean, and highest values are shown for sets of 30 repetitions run for each output variable (first column) and each model version (second column). For the forest type and density comparisons, the best performing model version is labeled (“#”).

<table>
<thead>
<tr>
<th>output variable</th>
<th>model</th>
<th>min</th>
<th>mean</th>
<th>max</th>
<th>min</th>
<th>mean</th>
<th>max</th>
</tr>
</thead>
<tbody>
<tr>
<td>avalanche freq.</td>
<td>T-REE</td>
<td>0.636</td>
<td>0.644</td>
<td>0.655</td>
<td>0.310</td>
<td>0.322</td>
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Fig. 3. Landscape metrics of avalanche frequency on the patch level: observed data (single maps; obs. data) compared with the distributions of the 30 repetitions (TREEMIG-AVAL). The distributions show the mean and 95% confidence interval. The landscape metrics (panel rows) are calculated for the three classes low, mid, and high avalanche frequency (panel columns). The landscape metrics represent the percentage of the landscape comprised by the largest patch per map (largest patch index \(l_{pi}\)), a shape complexity index averaged over all patches per map (shape; no units; lower limit 1 for square shapes, increasing with shape complexity, no upper limit), and a measure of spatial aggregation per map (clumpiness index clumpy; no units; ranges -1 disaggregated, 0 random, +1 aggregated).

On the landscape level, the map of the observed avalanche frequency of 1955-2012 shows that avalanches were observed mainly on the NE-facing slope of the Dischmawalley, and above 2300 m asl in the SW of the study area (Fig. 4A, see also Fig. 2). One relatively large gully on the SW-facing slope of the valley showed moderate avalanche activity. The highest frequencies of simulated avalanches were seen in steep areas, at high altitudes (i.e. at low temperature), and in areas with low forest densities or low proportions of coniferous trees. For the visual map comparison of observed and simulated avalanche frequency, the simulation run with the best fit according to cell-based comparisons (kappa; Table 2) was used. The TREEMIG-AVAL results of this simulation showed higher avalanche frequencies than observed, but largely confined to the same areas as the observed avalanches. An additional cell-by-cell comparison showed that avalanche frequency was overestimated more often than underestimated (Fig. 4C), and that the overestimations were largely within the areas of observed avalanches (Fig. 4D). The variability in the spatial patterns of the avalanche frequency among the 30 repetitions was relatively low (see the supplementary material B).

4.1.2 Forest density

The fraction of correct cell-by-cell classifications for forest density \(p_{cd}\) was close to 0.6 for TREEMIG-AVAL, around 0.5 for TMA-LOR, and between 0.41-0.43 for TMA-HIR (Table 2), suggesting similar performance of TREEMIG-AVAL and TMA-LOR when comparing the simulated to the observed forest density classes. However, when accounting for chance agreement, the cell-by-cell kappa value between observed and simulated forest density classification was between 0.22-0.27 for TREEMIG-AVAL, but much lower (0.02) for the two other model versions. While the
performance of all model versions was relatively low, TREEMIG-AVAL performed significantly better than the two other model versions. In the simplified model versions, the kappa values close to zero indicate that the correct classifications were caused mostly by chance agreement.

Fig. 4. Observed avalanche frequency during 1955-2012 (A), simulation for the same period with TREEMIG-AVAL (B), and their differences on a cell-by-cell level (TREEMIG-AVAL minus observed data) as density distribution (C), and spatially explicitly (D). The black contour lines in D show the observed extent of the areas affected by avalanches (observed avalanche frequency >5%). Of the 30 repetitions, the map with the best agreement with the observed data (based on kappa, see Table 1), is shown (B), and compared to the observed data (C, D). The variability among simulation results was low (see the supplementary material B).

On the patch level, the landscape metrics of TREEMIG-AVAL showed mostly similar patch size, shape, and aggregation as the observed patches (Fig. 5). While TREEMIG-AVAL overestimated patch shape and aggregation indices of the lowest forest density class, the TREEMIG-AVAL results for the mid and high density classes were closer to the observed values (i.e. the observed values were within or very close to the 95% CI of the TREEMIG-AVAL simulations). The simulations of TMA-LOR resulted only in high density forest, and therefore no variability was present (Table 2) and no metrics for the low and mid forest density classes were calculated (Fig. 5). TMA-hiR simulations showed higher variability in patch aggregation (clumpy), an underestimation of patch aggregation, and patch size (lpi) and shape relatively close to the observed values.

Fig. 5. Landscape metrics of forest density ($p_{cv}$) on the patch level: observed data (single maps; obs. data) compared with the distributions of the 30 repetitions with the different model versions (TREEMIG-AVAL, TMA-LOR, TMA-hiR). The distributions show the mean and 95% confidence interval. The landscape metrics (panel rows) are calculated for the three classes low, mid, and high forest density (panel columns). The landscape metrics represent the percentage of the landscape comprised by the largest patch per map (largest patch index lpi), a shape complexity index averaged over all patches per map (shape; no units; lower limit 1 for square shapes, increasing with shape complexity, no upper limit), and a measure of spatial aggregation per map (clumpiness index clumpy; no units; ranges -1 disaggregated, 0 random, +1 aggregated). The best performing model version is labeled ("#").

On the landscape level, the map of observed forest density (Fig. 6A) corresponded well with the observed avalanche patterns (Fig. 4A), showing the influence of past and recent avalanche-induced mortality and succession in the forest. Accordingly, most avalanche tracks were present in the forest of the NE-facing slope. A visual comparison with the simulated forest density maps (Fig. 6) showed similar avalanche tracks on the same slope in the forest simulated in TREEMIG-AVAL. The forest density simulated with the two alternative model versions however was not consistent with the patterns seen in the observed forest density (Fig. 6A): a uniformly high forest density was simulated without disturbances (TMA-LOR; Fig. 6C) and intermediate forest density with random patterns...
was simulated with random disturbances (TMA-HiR; Fig. 6D).

On the patch level, the comparison of the patch size, shape, and aggregation of the five forest classes (Fig. 7) revealed further differences among model versions. While TREEMIG-AVAL simulations of unforested areas matched the observed unforested patch sizes and shapes relatively well, they overestimated patch aggregation slightly. In the observation data, the patches of pioneer forest showed small size, intermediate shape complexity, and relatively high aggregation. TREEMIG-AVAL simulations underestimated all three metrics, while TMA-LOR and TMA-HiR overestimated pioneer patch shape complexity and aggregation. The coniferous patches simulated with TREEMIG-AVAL were similar to the observations, although none of the three observed metrics were within the 95% CI of the TREEMIG-AVAL simulations. On the other hand, TMA-LOR simulations strongly overestimated coniferous patch size, and TMA-HiR strongly underestimated coniferous patch aggregation. No mixed forest was seen in the observation data, however all three model versions simulated small patches of mixed forest; the smallest patches of mixed forest being simulated with TMA-HiR. Larch forest was present in the observation data but was not in TMA-LOR simulations. TREEMIG-AVAL simulations and especially TMA-HiR simulations both underestimated the three metrics for larch forest.

On the landscape level, the map of observed forest types (Fig. 8A) showed large patches of coniferous forest, and some pioneer and larch forest patches. The avalanche tracks are visible as strips of unforested areas on the NE-facing slope, and partly on the SW-facing slope. The TREEMIG-AVAL simulation that had the best cell-by-cell agreement (kappa) with the observed data (Fig. 8B) showed similar coniferous forest and unforested patches, but underestimated the larch forest on the SW-facing slope. In TREEMIG-AVAL simulations, the forested areas in general reached higher altitudes in areas not affected by avalanches, and small areas of mixed forest were simulated along the valley bottom. The best TMA-LOR simulation (Fig. 8C) overestimated the coniferous forest area, and within the simulation area did not show any unforested or larch forest areas. Where land use did not determine the forest edges, the coniferous forest simulated in TMA-LOR extended to high altitudes (ca. 2300 m asl). In the best TMA-HiR simulation (Fig. 8D) unforested and larch forest patches occurred, but their spatial patterns did...
not resemble the observed patterns. Furthermore, the pioneer forest patches were overestimated. The altitude of the highest forest patches was lower than in both other model versions, and closer to the observed treeline, but did not resemble the observed spatial patterns.

**Fig. 7.** Landscape metrics of forest types on the patch level: observed data (single maps; obs. data) compared with the distributions of the maps of the 30 repetitions with the different model versions (TREEMIG-AVAL, TMA-LOR, TMA-HIR). The distributions show the mean and 95% confidence interval. The landscape metrics (panel rows) are calculated for the five forest type classes (panel columns) pioneer forest, coniferous forest, mixed forest, larch forest, and no forest. The landscape metrics represent the percentage of the landscape comprised by the largest patch per map (largest patch index \(lpi\)), a shape complexity index averaged over all patches per map (shape; no units; lower limit 1 for square shapes, increasing with shape complexity, no upper limit), and a measure of spatial aggregation per map (clumpiness index \(clumpy\); no units; ranges -1 disaggregated, 0 random, +1 aggregated). The best performing model version is labeled ("#").

### 4.1.4 Model version rankings

In each comparison of simulated with observed forest data, the best model version was marked ("#" symbol in Figs. 5, 6, 7, 8, and Table 2). Each model version was compared to observation data once on the cell-by-cell level, once on the landscape level, and several times on the patch level. The summed number of best performances of each model version is given in Table 3. On the cell-by-cell level, the correct classification rates and kappa values were highest for TREEMIG-AVAL in all cases (Table 2). On the patch level, the simplified model versions performed better than TREEMIG-AVAL in a minority of cases (Figs. 5, 7). Despite deviations in the landscape metrics, such as an overestimation of mixed forest, TREEMIG-AVAL performed best in most comparisons on the patch level. On the landscape level, TREEMIG-AVAL was considered best in both comparisons. Overall, TREEMIG-AVAL performed best for both forest density (9 of 11 times best) and forest types (12 of 17 times best), and thus the model performance was significantly improved with the explicit simulation of avalanches.

**Fig. 8.** Forest type maps of observed data in 1980 AD from the MAB UNESCO program (Wildi and Ewald, 1986) (A), and of simulation results of the different model versions in the same simulation year: TREEMIG-AVAL (B), TMA-LOR (C), and TMA-HIR (D). Areas which are currently used by humans (based on Swiss Land Use Statistics, 1979/85 revised data BFS GEOSTAT, Federal Statistical Office) were excluded from the comparisons (white). Of the 30 repetitions, the map with the best agreement with the observed data (based on kappa, see Table 1), is shown for each model version. The variability among simulation results was low (see the supplementary material B). The panel of the best performing model version is labeled ("#").

### 4.2 Simulation results for the future scenario

The TREEMIG-AVAL simulations of the year 2100 under the SRES A2 climate scenario showed decreased avalanche frequency at high elevations in the SW of the study area (Fig. 9A compared to Fig. 4B), but slightly increased avalanche frequency at lower elevations in the NW of the study area and on the SW-facing slope. Forest density was higher in general and specifically on the NE-facing slope, but showed...
several new small avalanche tracks in previously unaffected areas, especially in the NW of the study area, and on the SW-facing slope (Fig. 9B compared to Fig. 6B). The forest types experienced strong shifts: while in 2003 the simulated landscape was dominated by coniferous forest with few larch and broadleaf deciduous pioneer forest patches, the simulated landscape in 2100 was dominated by mixed forest, with larch and pioneer forest only at the high altitudes in the SW of the study area (Fig. 9C compared to Fig. 8B).

The forest density simulated for 2100 with TMA-hiR and TMA-loR showed no difference to the simulations for 2003, at least up to 2000 m asl where simulations were analysed (Fig. 9D, F compared to Fig. 6C, D). The simulation result for the forest types however showed that the simulated treeline in 2100 was higher than the simulated treeline in 2003. The forest type simulations for 2100 with TMA-hiR and TMA-loR showed similar properties to their 2003 simulations in terms of patchiness and simulated proportions of forest types. While TMA-hiR showed high proportions of broadleaf deciduous pioneer forest but no larch at high altitude (Fig. 9E), TMA-loR showed high proportions of larch, but no broadleaf deciduous pioneer forest (Fig. 9G). Furthermore, the coniferous forest showed no strong spatial pattern in TMA-hiR (Fig. 9E), and high aggregation in small patches in TMA-loR (Fig. 9G). For a direct comparison of current and future climate simulation results, see the supplementary material C.

5 Discussion

5.1 TREEMIG-AVAL performance

Within our study area, the presence or absence of simulated avalanches was consistent with the observed avalanches (Table 2, Fig. 4), with the potential avalanche release areas delineated by Maggioni and Gruber (2003), and with expectations based on scientific knowledge on avalanche release and flow (Schneebeli and Bebi, 2004; Gruber and Bartelt, 2007; Bebi et al., 2009; Eckert et al., 2010). The spatial
patterns of the simulated avalanche areas and their changes in the future scenario were also as expected based on the sensitivity of the model to slope steepness, temperature, and forest type and density (Zurbriggen et al., 2014).

On the patch level, the landscape metrics of the simulated avalanche tracks were also similar to the observed avalanche tracks (Fig. 3) for the low and high avalanche frequency classes, suggesting that the simulated avalanche sizes, shapes, and spatial aggregation were mostly accurate. However, the mid frequency class was underestimated in its spatial extent and aggregation (lpi in Fig. 3; Fig. 4), which may be caused by an overestimation of avalanche frequency, i.e. simulations of high frequency avalanches where mid frequency was observed, thus reducing the total area of mid frequency avalanches.

The overestimation of avalanche frequency was mostly within the areas affected by avalanches, i.e. the low avalanche frequency class was most accurate (Fig. 4C, D). This was also reflected in lower kappa values for avalanche frequency than for avalanche presence and absent (Table 2). Due to a known height class discretization problem in TREEMIG (Lischke et al., 1998), the forest succession speed was overestimated. To be able to study the feedback between forests and avalanches and to avoid dominance of a single system state, a realistic balance between avalanche recurrence and forest regeneration time after avalanches (transient form ratio Brunsden and Thornes, 1979; Phillips, 1995) was necessary. Therefore, avalanches were calibrated to a higher than realistic frequency, and both forest succession and avalanche return are hence overestimated in TREEMIG-AVAL. The high agreement between areas affected by simulated and observed avalanches indicates that while the rate of change in the system was overestimated, the balance between avalanche recurrence and forest regeneration time after avalanches was plausible.

The flow length of simulated avalanches was underestimated in areas where observed avalanches flowed into the valley bottom (Fig. 4D). This can be explained by the absence of energy or snow mass simulation for the avalanches. Explicitly simulating the snow amount and energy for each avalanche event may improve the model performance, and could be useful for applications with large proportions of flat avalanche runout zones after steep portions where avalanches gain speed. However, this would lead to high computational costs, and was excluded here.

Given the low process resolution of forest and avalanche dynamics in time, the forest density comparison of observations and TREEMIG-AVAL simulations in 2003 AD showed relatively high agreement on the landscape level (Fig. 6A, B). Because the data was only compared for a single year, which can be influenced by stochastic events both in reality and in the simulations, the location of the simulated avalanche tracks can not be expected to exactly match the observed avalanche tracks. However, the slopes with high avalanche release probability were identified relatively accurately by the model. Therefore, even though on the cell-by-cell level the agreement was low, as indicated by kappa values below 0.3 (Table 2), the spatial patterns of the simulated high and low forest density classes in the landscape were relatively accurate on the patch and landscape levels (Figs. 5, 6A, B). The large simulated patches of high forest density in the NW of the simulation area as well as on the SW-facing slope of the Dischma Valley (Fig. 6A, B) agreed well with the observation data. The slight underrepresentation of the intermediate forest density class (Fig. 6A, B) may be related to the underestimation of the intermediate avalanche frequency class described above.

Conversely, the simulations of the forest types were more prone to errors, especially an underestimation of larch forest on the SW-facing slope, an overestimation of mixed forest in the valley bottom, and an overestimation of coniferous forest at high altitudes (Fig. 8A, B). These inaccuracies may be due to the overestimation of the succession speed, which overestimates the rate at which pioneer species such as larch are replaced by late successional species such as evergreen coniferous species. Further, the data may reflect land-use effects and legacies, which may have influenced forest composition in areas that were not excluded based on the land-use map used here. A further improvement in succession dynamics and therefore in forest composition may be achieved by simulating species-specific and size-specific avalanche mortality rates (Bebi et al., 2009), which was not included in the current version of TREEMIG-AVAL.
5.2 Model version comparison

Spatially explicit model formulations can come at high computational, data, and parametrization costs. We therefore tested if the avalanches in TREEMIG-AVAL need to be simulated explicitly in space, or if they could be approximated by a random global disturbance parameter. We also analyzed simulation results without disturbances.

5.2.1 Forest density

On the cell-by-cell level, the three model versions showed similar results for the fraction of correctly predicted cells but not for kappa (Table 2). The high prevalence of high density forest in TMA-LOR simulations as well as the random distribution of forest density classes in TMA-HiR simulations most likely led to inflated values of the correctly predicted cells, but were accounted for in the kappa values.

On the patch level, strong differences among the model versions became apparent in the simulated forest density. In TMA-LOR, the spatial configuration of the forest density classes was inaccurate in almost all cases (Fig. 5), because these simulations predicted only high density forest throughout the simulated landscape. The spatial configuration of the forest density classes of TMA-HiR was closer to the observed data, however, the accuracy was lower than in TREEMIG-AVAL except in two cases (Fig. 5).

On the landscape level, the visual comparison showed that only TREEMIG-AVAL was able to reflect the observed spatial patterns of forest density in the case study area (Fig. 6). The explicitly simulated avalanche tracks resulted in the elongated forest patches seen in the observation data, while the two alternative model versions overestimated overall forest density and homogeneity.

5.2.2 Forest type

On the cell-by-cell level, the three model versions again showed similar results for the fraction of correctly predicted cells (Table 2). The kappa values showed that while TMA-LoR performance was low, increased disturbance frequency improved model performance both with and without accounting for spatial patterns. This suggests that pioneer forest types were underrepresented when disturbances were omitted.

On the patch level, the relative performance of the model versions depended on the forest types (Fig. 7). The simulation results of TREEMIG-AVAL were closest to the observation data for coniferous and larch forest, and for the unforested class. The high performance of TMA-HiR in the mixed forest class may be due to a general overestimation of mixed forest in high elevation sites simulated with TREEMIG-AVAL, and the random disturbances may have reduced the mixed forest. In the pioneer forest class, the lpi was similar in all three model versions, while shape was best represented in TREEMIG-AVAL and clumpy was best in TMA-LOR. The lower performance of TREEMIG-AVAL compared to TMA-LOR in this case may be explained by the low number of observed patches of pioneer forest. The high spatial aggregation of the pioneer forest in TMA-LOR thus seemed to be an improvement over TREEMIG-AVAL simulations. However, the visual comparison shows that this is caused by an arbitrary line of pioneer forest in TMA-LOR simulations (Fig. 8), and therefore is not a true improvement.

On the landscape level, the simulated forest types were closest to the observed forest types in TREEMIG-AVAL, while the two alternative model versions resulted in different forest types and patterns (Fig. 8). Despite the partly similar results among model versions in the cell-by-cell and patch level comparisons, the visual comparison allowed for a distinction in the perceived plausibility of the patterns. Thus, while the overestimation of mixed forest may be lowest in TMA-HiR, and the spatial aggregation of pioneer forest highest in TMA-LOR, the spatial patterns of these two model versions are less realistic in the visual comparison of the landscape patterns. Some remaining differences between TREEMIG-AVAL simulations and observed forest types may be explained by the low process resolution in the time steps of TREEMIG-AVAL (i.e. the yearly time step), the influence of stochastic effects in the simulated and natural system, and by processes which were not explicitly included in TREEMIG-AVAL, such as effects of human land use.

5.2.3 Relevance of spatially explicit disturbance simulation

Disturbances in general, even when randomly distributed in space, were necessary to prevent early successional forest stages from being replaced by coniferous forest, which is consistent with disturbance ecology and has been shown before for the model LandClim (Elkin et al., 2012). Without disturbances, larch forest was
missing from the simulations, and the patches without forest were underestimated, suggesting that in our case study area, disturbances are an important process that influence succession and forest types, and that they should be included explicitly such as in TREEMIG-AVAL.

Furthermore, the explicit spatial patterns of disturbances were required for correct spatial arrangements of the forest types, and to avoid overestimation of early successional forest stages. A similar requirement for spatially explicit disturbances has also been reported for fire simulation in LANDIS (Wimberly, 2004). Differences in spatial pattern of disturbances also influence the temporal pattern of disturbances, and random disturbances hence have a different effect on the ecosystem than spatially connected avalanches (Hiebeler and Michaud, 2012). In our random disturbance model version, all cells were potential disturbance targets, and the average time between disturbances is similar for all cells. In the spatially explicit avalanche simulations however, a wide range of disturbance probability was simulated among cells, resulting in different disturbance intervals in different cells. While in the random disturbance model version the disturbances thus favored few forest types, the spatially explicit simulation of avalanches favored a larger variety of different forest types in spatially explicit patterns.

An advantage of TREEMIG-AVAL is the spatially explicit simulation of avalanches as an emergent property, resulting from environmental conditions specific to each cell and year, and therefore leading to a dynamically simulated and spatially explicit feedback. To confirm that these spatial patterns were indeed an effect of the feedback (i.e. spatially “linked”), and not merely an effect of the spatially explicit nature of the climate and topography input data (i.e. spatially “distributed”), we performed an additional analysis which compared simulations (a) including only the effects of topography and climate, (b) including the effects of topography, climate, and forests, and (c) including the effects of topography, climate, forests, and the feedback (see the supplementary material D). This analysis confirmed that the spatial patterns of the simulated avalanches were indeed caused by the feedback, which not only confirms the importance of simulating the feedback in TREEMIG-AVAL, but also indicates that the feedback is very important in the natural system studied here. Despite an increase in computational cost, it is therefore crucial to include spatially explicit disturbances as well as the forest-avalanche feedback in TREEMIG-AVAL for an accurate representation of our case study area Davos. Similarly, spatially explicit fires have been simulated as emergent property of LandClim (Schumacher et al., 2006), with the advantage of species-specific effects of fire on tree mortality, but with the disadvantage of simulations in decadal time steps which most likely blurs the effect of feedback between vegetation and disturbances.

5.3 Simulations for the future scenario

In the simulations of 2100 AD under the SRES A2 climate scenario, new combinations of topography, climate, and forest density and composition led to changes in the simulated avalanche patterns according to the model sensitivity described earlier (Zurbriggen et al., 2014). The emerging decrease of avalanches associated with an increase in coniferous forests in high elevations, and the increasing trend of small avalanches associated with an increase in mixed forests in lower elevations, is mostly plausible compared to current expert knowledge (Bebi et al., 2009; Krumm et al., 2011; Marty and Blanchet, 2011; Teich et al., 2012a,c). However, the speed and extent of these changes may be overestimated by the model, especially in terms of the high proportion of mixed forest.

The comparison among the model versions emphasized the influence of the disturbance formulation also under higher temperatures. For the simulations of the forest types, the differences among the model versions were at least as large in the future climate simulations as in the current climate simulations (Figs. 8, 9). The effects of model simplifications in terms of disturbance simulation may change with changes in climate scenarios, but the comparison of the three model versions under two different climatic conditions confirmed that the disturbance formulations had a strong impact, and that this impact did not diminish under climate change.

6 Conclusions

Based on our simulation results for the study area of Davos, in the eastern Swiss Alps, the performance of TREEMIG-AVAL was high in terms of spatial patterns of avalanche tracks. In terms of forest density and composition the simulations revealed a tendency of the model to overestimate treeline elevation and the proportion of deciduous trees. However, the overall performance of TREEMIG-AVAL, in the
comparisons to observation data on three spatial scales (cell, patch, and landscape), was higher than the performance of TREEMIG without the explicit simulation of disturbances. Furthermore, we showed that a simplified representation of disturbances, with a random distribution of disturbances in time and space, was not sufficient. The model version comparisons revealed that model performance could be significantly improved by explicitly accounting for disturbances and their probability in time and space, and that the increased computational cost of the explicit disturbance simulation in TREEMIG-AVAL is justified. Furthermore, the comparisons of model versions under the future climate scenario A2 indicated that the different disturbance formulations have a strong impact also under warmer temperatures.

We suggest that other forest and landscape models may profit from explicitly simulating disturbances as emergent model properties, especially in high altitude forests. To balance the potential gain in model performance with the potential increase in computational cost and complexity, we suggest that different model versions should be compared. In our study area, using only a simplified disturbance simulation would have led to very different conclusions about the model plausibility. Therefore we suggest that model version comparisons should be done more often to assess the influence of differently formulated processes and factors in dynamic forest models.

The main advantage of TREEMIG-AVAL is that the spatially explicit avalanche release and flow simulations are an emergent property of the model. A further advantage of the avalanche release and flow modules used here is that they do not have to be adapted for different species, due to their use of forest types. However, the model may be further improved by including species-specific effects of avalanches. Additionally, the approach used in TREEMIG-AVAL is suitable for disturbances that act on small to medium spatial scales, and are spatially connected, and can be applied in simulations over long time periods. Therefore TREEMIG-AVAL is useful for future studies of the influence of environmental change on forest and avalanche dynamics and their feedback.

Acknowledgements

We would like to thank D. Schmatz for help with the climate data, C. Ginzler for providing the LiDAR data, and T. Wuest for help with the computing cluster. NZ was supported by the project Mountland funded by the Competence Centre Environment and Sustainability of the ETH Domain (CCES). JN was supported by the Swiss National Science Foundation Grant 315230-122434.

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Supplementary Material

Performance of alternative disturbance formulations in a spatially explicit avalanche-forest model

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to be submitted to Ecological Modelling

A Avalanche flow: stopping probabilities per cell

We used 16 classes to define avalanche stopping probability per cell ($p_{stop}$; Table A1). These classes were derived from avalanche flow data (Teich et al., 2012), building on their classification analysis which showed that avalanches had different average lengths when released from areas with different forest properties. The four forest types (no forest, larch forest, coniferous forest, and mixed forest) were therefore also used in the classification applied here (see main text Table 1 for forest type definitions). Additionally, in the classification of Teich et al. (2012), the flow behavior of avalanches changed along the flow path (threshold at 400 m; $F_{cumul<400\ m}$ and $F_{cumul>400\ m}$). In a survival analysis (see main text section 2.2.1), we determined the stopping probability per meter as a “mortality” of the avalanche, and then calculated the values for 25 m for avalanche flows from direct neighbor cells ($F_{dir}$), and for 35 m for avalanche flows from diagonal neighbor cells ($F_{diag}$). These four forest types, two cumulative flow path classes, and two flow direction classes, led to the total of 16 classes (Table A1). Avalanches released from larch and coniferous forests showed similar behavior after 400 m cumulative flow length, and therefore they have identical stopping probabilities in the simulations. Because flow length data was only available for forested areas (Teich et al., 2012), but not for avalanches released from unforsted areas, we approximated the stopping probability for avalanches from unforsted areas with a strongly simplified linear dependence on local slope steepness was used ($a$ in Table A1). In the simulations, the cell-wise stopping probability together with the flow direction leads to avalanche flow length as an emergent model property (see main text section 2.2).

Table A1: Avalanche stopping classes and parameterization of the cell-wise avalanche stopping probabilities $p_{stop}$, derived from a statistical analysis of avalanche flow length data (Teich et al., 2012). Abbreviations: $F_{diag}$, flow from diagonal neighbor; $F_{dir}$, flow from direct neighbor; $a$, linear approximation for non-forest avalanche releases.

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<td>$a$</td>
<td>$a$</td>
<td>$a$</td>
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<td>0.1655</td>
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<td>0.0955</td>
<td>0.2216</td>
<td>0.1655</td>
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<td></td>
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<tr>
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<td>0.1346</td>
<td>0.1815</td>
<td>0.1346</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
B. Variability among stochastic simulation results

B Variability among stochastic simulation results

We used a set of 30 different pseudo-random number (prn) streams to repeat the simulations of each of the model versions of our study. Comparisons between simulation and observation data were done for three different variables and on three spatial scales (see main text section 3.4). For the cell-by-cell and the patch level comparisons, each simulation result (30 maps per variable and model version) was compared to the corresponding observational data, for the study area described in Fig. 2 in the main text. Based on the results of the cell-by-cell comparison (see main text Table 2), the map with the best fuzzy kappa agreement was chosen from the 30 repetitions for each variable and model version, respectively, for the visual comparisons on the landscape level (main text Fig. 4, 6, 8). The variability among the 30 simulations was very low for avalanche frequency (Fig. B1), forest density (Fig. B2), as well as forest types (Fig. B3), for all three model versions.

![Image](image_url)

**Figure B1**: Avalanche frequency variability among the 30 repetitions in TreeMig-Aval, showing maps with the best (A), worst (B), and an intermediate (C) agreement with observation data (see main text, Fig. 2), based on fuzzy kappa comparisons (see main text, Table 1).
B. Variability among stochastic simulation results

Figure B2: Forest density variability among the 30 repetitions in the three model versions, showing maps with the best (A, D, G), worst (B, E, H), and an intermediate (C, F, I) agreement with observation data (see main text, Fig. 6), based on fuzzy kappa comparisons (see main text, Table 1).

Figure B3: Forest type variability among the 30 repetitions in the three model versions, showing maps with the best (A, D, G), worst (B, E, H), and an intermediate (C, F, I) agreement with observation data (see main text, Fig. 6), based on fuzzy kappa comparisons (see main text, Table 1).
C. Direct comparison of current and future maps

To allow a direct comparison of the maps shown for current climate simulations with TREE-MIG-AVAL (main text Fig. 4B, 6B, 8B) to future climate simulations with TREE-MIG-AVAL (main text Fig. 9A, B, C), and to emphasize the differences between simulations at the two time points, these figures are assembled in one figure here (Fig C4). The years shown for “current” simulation results are equivalent to the observation data availability (see main text section 3.3), and the future simulation results are shown for 2100 AD.

**Figure C4:** Comparison of TREE-MIG-AVAL “current” (A, years 1955-2012; B, year 2003; C year 1980) and future (D, years 2050-2100; E, F, year 2100) simulation results for avalanche frequency (A, D), forest density (B, E), and forest types (C, F).
D. Spatially explicit effects of the feedback

In a previous study we showed that the effect of the avalanche-forest feedback should be simulated explicitly in time (Zurbrüggen et al., in review), without assessing the spatial patterns of the feedback. Here, we assessed the effects of different spatial patterns of disturbances. In the TMA-HIR simulations (see section 3.1 in the main text), disturbances were purely random, while in the TREEMIG-AVAL simulations, the disturbances were influenced by the spatially explicit factors forest, topography, and climate. Due to forest influences, TMA-HIR and TREEMIG-AVAL not only differed in the spatial patterns of the disturbances, but also by the feedback between the disturbance and the forest in TREEMIG-AVAL. To confirm that the spatially explicit patterns of TREEMIG-AVAL simulations were not only caused by topography and climate, but also influenced by this feedback, effects on the avalanche release probability were compared between forests including the feedback, and forests excluding the feedback.

To disentangle the effects of (a) topography and climate, (b) forests, and (c) the feedback on the spatial patterns of avalanche release probability, three simulation runs were compared in which different combinations of these factors and processes were included (Fig. D5). In the first run, the influence of climate and topography on avalanche release probability was calculated without forest dynamics, and without the influence of forests on avalanches (Fig. D5A). In the second run, the influence of forests (in addition to climate and topography) on avalanche release probability was simulated while the influence of avalanches on forests, and therefore the effect of the feedback, were excluded (Fig. D5B). In the third run, the full feedback was simulated, including the effects of climate, topography, forests, and explicit influences of forests on avalanches as well as of avalanches on forests (Fig. D5C).

The three maps (Fig. D5A, B, C) were then compared pairwise to assess the effect of the different factors and processes. The comparison of maps A (influence of climate, topography) and B (influence of climate, topography, forest) shows the effect of the forest on the spatial patterns of avalanche release probability (Fig. D5D). A strong reduction (green to blue) of avalanche release probability is seen as a result of the forest influence on avalanches. Similarly, the comparison of maps A and C (influence of climate, topography, forest, and the feedback) shows the effect of the forests including the feedback effect (Fig. D5E). Here, the reduction of avalanche release probability caused by the forest is still visible, but within a smaller area. Finally, the comparison of maps B (excluding the feedback) and C (including the feedback) shows the effect of the feedback (Fig. D5F). A strong increase (yellow to red) of avalanche release probability is seen when the feedback is included.

Based on these comparisons, we conclude that the spatial pattern of simulated avalanches is determined not only by climate, topography, and forests, but also by the feedback. For simulations with TREEMIG-AVAL, it is therefore crucial to not only simulate disturbances spatially explicitly, but to also simulate the interactions between forests and disturbances explicitly.
D. Spatially explicit effects of the feedback

Figure D5: Avalanche release probability in the simulation year 1980 AD, with different contributing factors. The left column shows maps of the avalanche release probability (A-C), and the right column shows differences between maps of the left column (D-F). The difference maps in the right column were generated from the two maps referenced (and linked by arrows) in the left column. The difference maps thus show the effect of forests (D), forests including the feedback (E), and the feedback alone (F), with green and blue colors showing reductions in avalanche release probability caused by the according process, and yellow and red colors showing increases in avalanche release probability.
References


Appendix E

Paper XI

Changes in forest cover and ecosystem services in Davos under climate change

Veränderung von Wald und Waldleistungen in der Landschaft Davos im Zuge des Klimawandels

Eingereicht 4. April 2012
Akzeptiert (mit Review) 5. Oktober 2012

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Abstract

The effects of climate change on forests of Davos were examined with field experiments near treeline, analyses of avalanche-forest interactions and with spatially explicit models for the valuation of ecosystem services. Experimental trees at the Stillberg research site showed species-specific responses to elevated CO₂ and soil warming. Growth and mortality of the trees planted in the year 1975 were strongly driven by the duration of snow cover and micro topography. Together with other field studies in the region this suggests that during the next decades the treeline will rise only slowly and mainly on favorable micro sites. Avalanche protection will also in future be the most important forest service in Davos, although critical weather and snow conditions for forest avalanches show a decreasing trend over the last 40 years. The density of forest structures is likely to further increase with potential positive effects on avalanche protection. Decreases of the protective effect against avalanches may however occur by an increase of natural disturbances such as fires or bark beetle outbreaks. Quantification and overlay of five selected ecosystem services (avalanche protection, recreation, CO₂ sequestration and storage, habitats of capercaillie, timber production) suggest in general an increase in the value of most considered ecosystem services.

Keywords: climate change, treeline, forest cover change, avalanche protection, ecosystem services, trade-offs

1 Einleitung

Zum Einfluss des Klimawandels auf kältelimitierte Waldgrenzen und Gebirgswald-ökosysteme gibt es zahlreiche Felduntersuchungen und Modelle auf verschiedenen Skalen und mit zum Teil unterschiedlichen Schlussfolgerungen (Huber et al., 2005). Innerhalb der «Mountland»-Region Davos (Kanton Graubünden) wurden in den letzten Jahren entsprechend dem Grundkonzept des Projektes Experimente und Beobachtungen auf kleinräumiger Skala mit Modellierungen zu Ökosystemleistungen auf grösserer Skala kombiniert, um Hinweise dazu zu erhalten, wie sich Wälder und Waldleistungen in Zukunft verändern könnten. Im Vergleich zu den beiden anderen «Mountland»-Regionen Jura (Kanton Waadt) und Visp (Kanton Wallis) sind die Wälder von Davos stärker durch Kälte und Schnee limitiert und erbringen in erster Linie wichtige Schutzleistungen gegenüber Lawinen und anderen Naturgefahren. Wir fassen einige Aspekte dieser Forschung zusammen und zeigen in diesem Beitrag auf, wie diese Wälder insbesondere an deren oberer Grenze auf eine CO₂-reichere Atmosphäre und ein wärmeres Klima reagieren und wie sich deren Leistungen entsprechend verändern.

2 Material und Methoden

2.1 Untersuchungsgebiet


2.2 Langzeitbeobachtungen und Experimente an der Waldgrenze


2.3 Wechselwirkungen zwischen Wald und Lawinen

Um Bedingungen für Lawinenanrisse im Waldbereich zu studieren, wurden seit den 1980er-Jahren Waldlawinen erfasst und die wesentlichen Standort-, Wald- und Schneeparameter erhoben (Meyer-Grass und Schneebeli, 1992; Bebi et al., 2009). In den letzten Jahren wurden diese Daten ergänzt und im Hinblick auf neue Fragen ausgewertet. Dabei standen bisher vor allem drei Aspekte im Vordergrund: (1) der Einfluss von Waldstruktur, Topografie und Lawineneigenschaften auf die Reichweite einer Lawinlawine (Teich et al., 2012a); (2) die Entwicklung der Bestandesstruktur in ehemaligen Anrissgebieten von Waldlawinen (Ulrich, 2009); (3) die Veränderung der zum Anreissen von Waldlawinen führenden Witterungsbedingungen (Teich et al., 2012b).
2.4 Waldentwicklung und Ökosystemleistungen


3 Ergebnisse

3.1 Ergebnisse der Experimente an der Waldgrenze

Von 92,000 Waldgrenzbäumen am Stillberg (Abb. 2) hatten 30 Jahre nach der Pflanzung rund 30% überlebt. Bei allen drei Arten war die Mortalitätsrate zwischen dem 5. und 15. Lebensjahr am grössten, wobei der Zeitpunkt der Schneeschmelze (gutes Überleben bei Ausaperung vor Mitte Mai) während der ganzen Beobachtungsperiode der bedeutendste Faktor für die Überlebenswahrscheinlichkeit war (Abb. 3). Im Gegensatz dazu wurde das Wachstum der Bäume am stärksten durch die Höhenlage bestimmt, es reagierte aber auch sehr sensibel auf Änderungen des Kleinstandortes und der Schneedecke. Mit zunehmender Grösse der Bäume sank der Einfluss der Einstrahlung, dafür wurden die Bäume mehr durch Wind und mechanische Beschädigungen beeinträchtigt (Barbeito et al., 2012).


Der seit 2001 experimentell simulierte Klimawandel wirkte sich unterschiedlich auf die Baumarten aus. So zeigten bei erhöhtem CO₂-Angebot die Lärchen ein um rund 20% stärkeres Wachstum, während die Bergföhren ihr Wachstum aufgrund von anderen limitierenden Faktoren nicht steigern konnten (Dawes et al., 2011). Hingegen profitierten die Bergföhren vom erwärmten Boden, während die Lärchen nicht darauf reagierten. Einige experimentell behandelte Lärchen wiesen aber unter erhöhten CO₂-Gehalten Frostschäden auf, weil sie im Frühjahr eine Woche früher austrieben (Martin et al., 2010). Bei einer Erwärmung um 3°C setzten die im Boden aktiven Mikroorganismen zusätzliche Mengen CO₂ frei, die nicht durch eine verstärkte CO₂-Aufnahme aufgrund eines erhöhten Pflanzenwachstums ausgeglichen wurden. Eine substanzielle Menge Kohlenstoff gelangt somit aus dem Boden als CO₂ in die Atmosphäre (Hagedorn et al., 2010). Damit würden Waldgrenzenökosysteme wie der Stillberg bei der erwarteten Klimaänderung zumindest anfänglich nicht zu einer CO₂-Senke, sondern zu einer CO₂-Quelle.

ist ein weiterer Hinweis darauf, dass zusätzlich zur Temperatur noch weitere Faktoren wichtig für die Etablierung und das Wachstum von Bäumen an der oberen Baumgrenze sind.

3.2 Wechselwirkungen zwischen Wald und Lawinen

Ob eine bereits angerissene Lawine durch den Wald noch gebremst werden kann, hängt in erster Linie davon ab, wie gross die Beschleunigungsstrecke in einer Waldlücke beziehungsweise oberhalb des Waldes ist. Grössere Lawinen, welche mehr als etwa 150 m oberhalb des Waldes anreissen, gewinnen bis zum Auffolgen auf den Wald so viel Energie, dass die Waldstruktur weiter unten kaum einen Einfluss auf die Auslaufstrecke hat. Bei kleinen Waldlawinen hat hingegen die Stammzahl im Bereich des Anrissgebietes einen signifikanten Einfluss auf die Auslaufstrecke. Interessant ist die Feststellung, dass vor allem die Stammzahl von kleinen Bäumen (<15 cm Brusthöhe, BHD) im Anrissgebiet die Auslaufstrecke und damit das Gefährdungspotenzial einer Lawine reduziert (Teich et al., 2012a). Dies kann vor allem damit erklärt werden, dass kleine Bäume mit Ästen bis zum Boden die Terrainrauigkeit erhöhen und die Lawinenmasse verringern.


Clusteranalysen in zwei Kategorien eingeteilt werden (Teich et al., 2012b): (1) Neuschneewaldlawinen, welche typischerweise während Perioden mit starkem Schneefall, wenig Sonneneinstrahlung, viel Wind und tiefen Temperaturen anreissen, und (2) andere Waldlawinen, die meist nach Perioden mit ergiebiger Sonneneinstrahlung, Erwärmung und nasser Schneedecke beobachtet wurden. Im Vergleich zu Freilandlawinen gehen Waldlawinen meist bei mächtigeren Schneedecken ab, da erst dann der Einfluss der Bodenrauigkeit im Wald verringert ist. In den letzten 41 Jahren (seit genügend zuverlässige Messdaten vorhanden sind) hat die Anzahl von potenziellen Waldlawinentagen, d.h. Tagen, die sich durch Waldlawinen begünstigende Schnee- und Witterungsbedingungen auszeichnen, abgenommen (Abb. 4), und zwar sowohl für Neuschnee-Waldlawinen (an 11 von 14 Messstationen, bedingt durch die Abnahme von kalten Schneefallperioden) als auch für andere Waldlawinen (an 12 von 14 Messstationen, bedingt durch die Abnahme der Schneedeckendicke in tieferen Lagen).

3.3 Waldentwicklung und Ökosystemleistungen

Die Waldfläche in der Landschaft Davos hat zwischen 1954 und 2000 um 13% zugenommen und der Anteil der geschlossenen Wälder (Schlussgrad locker bis gedrängt) ist von rund 33% auf 54% angestiegen (Tabelle 1; Lardelli, 2003). Am stärksten waren die Waldzunahme und -verdichtung im Höhenbereich zwischen 1600 und 2000 m ü. M., also rund 100 bis 500 m unterhalb der aktuellen Waldgrenze (Kulakowski et al., 2011; Abb. 1). In die Zukunft projiziert ergibt sich daraus bis zum Jahr 2050 eine weitere Waldzunahme um 13% im Trendszenario beziehungsweise um 21% im Erwärmungszenario. Beim Trendszenario ist dieser zusätzliche Wald vor allem auf weitere landwirtschaftliche Extensivierungen zurückzuführen, beim Erwärmungszenario ergeben sich insbesondere in den höheren Lagen zusätzliche Waldverdichtungen und Waldausdehnungen.
Der Gesamtwert der fünf für die Landschaft Davos modellierten Ökosystemleistungen (Lawinenschutz, Erholung, C-Speicherung, Auerhuhnhabitate und Holzproduktion) steigt von rund 106 Mio. CHF pro Jahr im Jahr 2000 auf rund 135 Mio. CHF pro Jahr (+27%) beim Erwärmungsszenario (Tabelle 2). Dieser Anstieg ist einerseits auf die Ausdehnung der Waldfläche zurückzuführen (Ökosystemleistungen ausserhalb des Waldes werden hier nicht berücksichtigt). Andererseits tragen auch Waldstrukturveränderungen und erwartete Werterhöhungen einzelner Ökosystemleistungen (z.B. die Erhöhung von CO₂-Emissionsabgaben, des Holzpreises oder des prognostizierten Erholungswerts) zur Erhöhung des Gesamtwertes bei. Diese beiden Faktoren führen zusammen beispielsweise zu einer Erhöhung des Werts der Erholungsleistung um 50%.

Den mit Abstand grössten Wert heute und in Zukunft zeigt die Ökosystemleistung «Lawinenschutz». Die Ökosystemleistung «Holzproduktion» beeinflusst hingegen den Gesamtwert in allen Fällen negativ (Tabelle 2). Dabei reagiert der finanzielle Erfolg dieser Ökosystemleistung sensitiv auf Annahmen bezüglich des Holzpreises. Bei einem heute realistischen durchschnittlichen Holzpreis von CHF 96.–/m³ und bei einem für 2050 prognostizierten Holzpreis von CHF 115.–/m³ ist die Holzproduktion (isoliert betrachtet, ohne Querfinanzierung durch die Bereitstellung von Lawinenschutz und anderen Waldleistungen) in den meisten Davoser Waldbeständen unrentabel, was sich in negative Werten für die Ökosystemleistung «Holzproduktion» ausdrückt (Tabelle 2). Wenn sich der Holzpreis hingegen auf CHF 120.–/m³ erhöhen würde, wäre sie in 80% der Davoser Wälder auch ohne Querfinanzierung gewinnbringend.

Der Wert der einzelnen Ökosystemleistungen unterscheidet sich je nach Topografie, Standort

---


<table>
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<tr>
<th>Schlussgrad</th>
<th>Fläche 1950 (ha)</th>
<th>Fläche 2000 (ha)</th>
<th>Trend-szenario 2050 (ha)</th>
<th>Erwärmungs-szenario 2050 (ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>gedrängt</td>
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<td>2416</td>
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<td>räumig</td>
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<td>1316</td>
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<td>1070</td>
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<td>252</td>
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<td>5085</td>
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</table>

**Tabelle 2.** Bewertung ausgewählter Ökosystemleistungen in der Landschaft Davos für das Jahr 2000 und anhand zweier verschiedener Szenarien für das Jahr 2050.

<table>
<thead>
<tr>
<th></th>
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<td>Auerhuhnhabitate</td>
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<td>151</td>
<td>225</td>
</tr>
<tr>
<td>Holzproduktion</td>
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<td>-299</td>
<td>-355</td>
</tr>
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<td><strong>Summe</strong></td>
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<td><strong>130,448</strong></td>
<td><strong>135,590</strong></td>
</tr>
</tbody>
</table>
und Waldstruktur stark. Auf rund 50% der Davoser Waldfläche ist der Lawinenschutz die wertmässig wichtigste Walddienstleistung (Abb. 5). Im Durchschnitt beläuft sich ihr Wert auf rund CHF 30,000.–/ha. Je nach Topografie und Schadenspotenzial im Einzugsgebiet variiert der berechnete Wert aber zwischen CHF 3.–/ha und CHF 698,000.–/ha. Die potenziellen Auerhuhnhabitate konzentrieren sich wegen spezifischer Ansprüche bezüglich Waldstruktur und Topografie auf eine relativ kleine Fläche von rund 1400 ha, sind aber als Folge der modellierten Waldfächerzunahme eher größer als heute (Tabelle 2). Im Vergleich zu den Leistungen «Lawinenschutz» und «Auerhuhnhabitate» sind die Erholungsleistung und die CO₂-Speicherung gleichmässiger auf alle Wälder verteilt, obwohl auch dort räumliche Unterschiede in der Höhe der Leistungen bestehen (Abb. 5).


4 Diskussion
4.1 Veränderung der Waldfläche und des Waldaufbaus

Sowohl die am Stillberg durchgeführten Experimente als auch die verwendeten Modelle deuten darauf hin, dass in der hochalpinen Region Davos die Waldfläche auch in Zukunft weiter zunehmen wird. Allerdings zeigen die Experimente ebenso, dass an einer grundsätzlich durch die Kälte limitierten Waldgrenze nebst Temperaturerhöhungen auch noch viele andere Faktoren das Baumwachstum und die Mortalität beeinflussen und dass in verschiedenen Stadien der Baumverjüngung unterschiedliche Faktoren wichtig sein können (Barbeito et al., 2012; Moos, 2012). Dazu tragen auch Faktoren bei, welche bei den Versuchen am Stillberg nicht berücksichtigt wurden, wie beispielsweise dichte Zwergstrauchheiden oder Beweidung (Ponge et al., 1998; Motta et al., 2006).


4.2 Veränderung der Ökosystem-leistungen


Zukunftsszenarien mit einwachsendem Schutzwald auf bisher landwirtschaftlich genutzten Flächen weisen zudem auf Potenziale hin, die auf einer besseren Abstimmung der landwirtschaftlichen und forstlichen Förderungsmassnahmen beruhen und die zu einer Verbesserung der Ökosystemleistungen insgesamt führen. Während die Ökosystemleistung «Lawinenschutz» am besten mit einer möglichst dauerhaften Bestockung ohne grosse Lücken erbracht wird, sind für andere Leistungen variablere Bestockungsziele möglich. Im Sinn einer Gesamtoptimierung der Ökosystemleistungen könnten daher auch ein stärkerer Vorratsabbau und eine aktive Verhinderung von Vorratszunahmen in einem Teil der Davoser Wälder ins Auge gefasst werden. Dies wäre insbesondere ein Beitrag zur

4.3 Möglichkeiten und Grenzen der Modellierung

In das hier verwendete Modellsystem lassen sich auch weitere Ökosystemleistungen integrieren und damit bewerten. Darauf aufbauend könnte eine in der Praxis anwendbare Entscheidungshilfe für die multifunktionale Bewirtschaftung von Gebirgsregionen entwickelt werden. Für eine umfassendere Betrachtung wäre es zunächst sicher sinnvoll, auch die Leistungen von Graslandökossystemen (also des Nichtwaldes) zu berücksichtigen. Zudem besteht bei einigen der fünf verwendeten Bewertungsansätze noch Verbesserungspotenzial. So berücksichtigen beispielsweise die Modelle zur C-Speicherung noch nicht die neuen Erkenntnisse der Stillberg-Experimente, wonach die Bodenatmung bei höheren Bodentemperaturen die Biomassenzunahme im Waldgrenzbereich zumindest teilweise kompensieren kann (Hagedorn et al., 2010). Auch deckt das Auerhuhn - wenn auch eine gute Indikatorart für strukturreiche Wälder - nicht sämtliche Habitatbedürfnisse der verschiedenen Pflanzen- und Tierarten im Wald ab, und die Erholungsleistung wurde mit einem einfachen Modell bewertet, welches vor allem auf der Annahme beruht, dass offene und gut zugängliche Wälder für die Erholungsnutzung wertvoller sind.


Dank

Wir danken allen Forschenden und Technikern, die an den Untersuchungen in der Landschaft Davos und insbesondere am Stillberg beteiligt waren, sowie den Experten, welche zur Verbesserung der Modellierung der Ökosystemleistungen beigetragen haben. Für wertvolle Hinweise zum Manuskript danken wir Peter Brang, Georg Leitinger, Andreas Rigling sowie den zuständigen Förstern Hanspeter Hefti und Andreas Kessler.

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Veränderung von Wald und Waldleistungen in der Landschaft Davos im Zuge des Klimawandels


Modification de la forêt et de ses prestations dans le paysage davosien sous l’effet du changement climatique

Les effets du changement climatique sur les forêts de Davos ont été l’objet d’examens sur le terrain à la limite forestière, d’analyses de la fonction protectrice contre les avalanches et de modélisations spatialement explicites des prestations écosystémiques. Des observations à long terme et des expérimentations sur l’aire d’essais de Stillberg révèlent que les arbres situés à la limite forestière réagissent spécifiquement à une atmosphère plus riche en CO₂ et à un environnement plus chaud. Par ailleurs, le manteau neigeux et d’autres facteurs variant à petite échelle ont fortement influencé la croissance et la mortalité des arbres plantés à cette limite en 1975. Il ressort de toutes ces investigations que la limite forestière ne s’élèvera que lentement et d’abord uniquement dans les microstations bénéficiant de conditions favorables. Les modélisations laissent présumer qu’en 2050 encore, la protection contre les avalanches sera la principale fonction de la forêt de Davos, même si les tendances du passé indiquent que les conditions atmosphériques critiques pour le déclenchement d’avalanches vont plutôt se raréfier. Il est en outre probable que quelques forêts, aujourd’hui clairiérées, tendront à se fermer, ce qui favorisera la protection contre les avalanches. Mais l’effet protecteur pourrait être atténué à l’avenir par l’augmentation des perturbations naturelles, comme les incendies de forêt et les fortes pullulations de bostryches. D’après une quantification et une superposition spatiale de cinq prestations forestières importantes pour le paysage davosien (protection contre les avalanches, détente, stockage du CO₂, habitats du grand têtra et production ligneuse), la valeur de ces prestations devrait augmenter à l’avenir.
# Appendix F

## Tables

**Table F.6.1. Avalanche data.**

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<td>Vertical structure</td>
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<td>-0.10</td>
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<td>Surface roughness</td>
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Acknowledgements

I completed this thesis with the encouragement, help and support of many people:

First, I would like to say „Thank you!“ to Peter Bebi from the SLF in Davos. As my direct supervisor, he provided me with thoughtful guidance during my work, and I benefited a lot from his research experience. He helped me in all stages of my studies while allowing me a great deal of independence.

I am grateful to Prof. Adrienne Grêt-Regamey from the ETH Zurich who gave me freedom to develop this thesis and my own ideas, but provided advice whenever I needed directions. Our discussions were always fruitful and very motivating.

I also thank Prof. Johann Stötter from the University of Innsbruck for acting as external reviewer of my thesis.

Many thanks go to all other colleagues, and co-authors namely Perry Bartelt, Marc Christen, Thomas Feistl, Jan-Thomas Fischer, Clotilde Gollut, Christoph Marty, Melanie Ulrich, Irene Vassella who contributed considerably to this research, and especially to Natalie Zurbriggen for our stimulating collaboration within the MOUNTLAND project. I am grateful to my colleagues at the SLF and from PLUS at ETH Zurich for such nice and motivating work environments.

Finally, I would like to thank my family and my friends in Davos, Zurich, Dresden and other places who made the time besides work so enjoyable. My parents Carla and Michael Teich have always encouraged both my academic pursuits and my love for the mountains. I am grateful to them for their endless support – THANK YOU!

„Nur Geduld! Mit der Zeit wird aus Gras Milch.“ (Unbekannt)
Michaela Teich

Curriculum Vitae

Born: 25 June 1980
Nationality: German

**Academic education**

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<tr>
<td>03/2009-10/2013</td>
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<td>10/2006</td>
<td>M. Sc. in Forestry; Technische Universität Dresden TUD, Germany</td>
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<td>Thesis: Der Lawinenschutzwald in GIS-basierten Risikoanalysen - Untersuchung einer Fallstudie: «Der Bannwald von Andermatt»</td>
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<td>ERASMUS foreign exchange, ETH Zurich, Switzerland</td>
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**Scientific and practical work experience**

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