STOPPING BEHAVIOR OF SNOW AVALANCHES IN FORESTS

T. Feistl[1,2,*], P. Bebi[1], Y. Bühler[1], M. Christen[1], M. Teich[1,3], P. Bartelt[1]
[1] WSL Institute for Snow and Avalanche Research SLF, Davos Dorf, Switzerland
[2] Technical University Munich (TUM), Munich, Germany
[3] Swiss Federal Institute of Technology (ETH), Zurich, Switzerland

ABSTRACT: A longstanding problem in avalanche science is to understand how forests stop small and medium sized avalanches. Avalanche dynamics models have traditionally been employed to calculate extreme avalanche runout and have assigned a minor role to forests in dissipating flow energy. In this paper we quantify the important effect of forests in stopping small avalanche events, crucial for road and ski-run safety. We performed field studies of several avalanches where trees affected the runout. We gathered information concerning the starting location, deposition heights, runout distance and forest structure. These studies were made during the 2011/12 winter where many gliding snow avalanches released in forested areas in Switzerland and Germany. Using the field observations as a guide, we hypothesized that mass detrainment due to tree-avalanche interaction led to a significant deceleration of the avalanches. This effect is important for physical based avalanche dynamics models which reveal that avalanche mobility is strongly linked to mass entrainment/detrainment. We tested this hypothesis with a numerical experiment and simulated the documented avalanche events using a velocity dependent detrainment model to reconstruct the braking effect of forests. For the numerical investigations we used high spatial resolution digital terrain models. The results highlight how forests influence mass and energy fluxes at the front and sides of avalanches. Of particular importance is the distribution of velocity across the flow width of the avalanche, as flow mass can be easily stopped at the flow boundaries.

1. INTRODUCTION

Small to medium sized avalanches are able to threaten people and infrastructure as well as large, extreme avalanches do. They can cause frequent problems for road or railroad safety as local authorities must deal with the risk of small avalanches hitting infrastructure, and therefore people, numerous times during a winter season. Forests serve as a natural barrier where meteorological conditions and terrain features enable trees to grow. They do not only prevent avalanches from releasing (Salm, 1978; de Quervain, 1979; Gubler and Rychetnik, 1991; Newesely et al., 2000), but also have an impact on the runout distance of avalanches (Teich et al., accepted). Therefore they can be a cost efficient protection measure, especially against small avalanches.

There is still a need for investigating and quantifying the decelerating effect of forests on small to medium sized avalanches (Bebi et al., 2009; Teich and Bebi, 2009; Takeuchi et al., 2011). As long as trees can withstand dynamic forces, they are valuable obstacles in the flow path and therefore have a decelerating effect on the moving snow (Faug et al., 2010). However, until now there is little knowledge concerning the critical size of an avalanche necessary to destroy forests (de Quervain, 1979; Gubler and Rychetnik, 1991; Bartelt and Stöckli, 2001; Margreth, 2004). Nevertheless the effectiveness of a protective forest depends amongst others on the avalanche size.

In this article, avalanches are classified as small to medium if trees remain standing and therefore provide a protective effect. Bartelt and Stöckli (2001) explained the almost non-existent deceleration of large avalanches, which flow through forest and destroy trees by various mechanisms, including fracturing, overturning and the inclusion of their mass into the flow. There are numerous controlling parameters such as stem diameter (Teich et al., accepted) and velocity distribution within the avalanche (Bartelt and Stöckli, 2001), which are crucial factors to determine if trees break or uproot or withstand the impact pressure. The idea of a single critical limiting volume is perhaps too rigid, as there is a most likely continuous transition from none, to a significant protective effect depending on tree stand, terrain and snow conditions.

Small avalanches are especially sensitive to local topography, terrain roughness, forest structure and snow conditions (Bebi et al., 2009; Bühler et al., 2011). The documentation of forest avalanches is demanding and there is limited quantitative information available (Schneebeli and Meyer-Grass, 1993; Teich and Bebi,

* *Corresponding author address:* Thomas Feistl,
WSL Institute for Snow and Avalanche Research SLF,
Davos, Switzerland;
email: thomas.feistl@slf.ch

2009; Viglietti et al., 2010). To extend the current database on forest avalanches in Switzerland (collected between 1985 and 1990 in the region of Davos), we carried out several new field studies. In the winter 2011/12 we recorded data of six forest avalanches around Davos and the Bavarian Prealps (Section 2). The focus of this data collection was on release area and fracture depth, snow conditions, forest structure, deposition area and its characteristic distribution. The aim of these studies was to back calculate the recorded events with a numerical avalanche dynamics model in order to ascertain the role of protective forests in stopping small avalanches.

Numerical avalanche dynamics models have become an important tool for practitioners to forecast pressure and potential runout distances of avalanches (Christen et al., 2010). As physical models improve and high resolution digital terrain models become available (Bühler et al., 2012), it is possible to investigate how small and frequent avalanches reach houses, roads and railroads. At present, however, there is no reliable characterization of forests in avalanche models (Casteller et al., 2008; Christen et al., 2010; Anderson and McClung, 2012).

The purpose of this work is to identify and qualitatively describe the cause of the deceleration and runout shortening of avalanches flowing through forests. 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). We hypothesize that forests extract mass from avalanches (detrainment), which causes them to stop in forests. We test this hypothesis by applying a forest detrainment model that is embedded within the avalanche dynamics program **RAMMS** (Christen et al., 2010). In Section 4 we present the results of a numerical experiment, carried out on an ideal parabolic shaped slope and the back calculation of one of the documented forest avalanche events of the winter 2011/12.

2. OBSERVATIONS

Between 1985 and 1990 a forest avalanche research project in the Swiss Alps collected data on avalanche formation in forests with the goal of improving silvicultural decision making (Schneebeli and Meyer-Grass, 1993). This project revealed that small to medium sized avalanches release in forest clearings after heavy snowfall (more than 40 cm in three days) with cold temperatures or during warm periods with strong temperature increase, usually associated with high radiation (Teich et al., 2012). We supplemented this data with more detailed information obtained from the region of Davos, Switzerland and the Bavarian Alps in the winter 2011/12. Runout area, release area, fracture depth, snow density, mass distribution of the deposition and forest structure of six avalanches were documented. The aim of this field campaign was to collect detailed information of the release and deposition zones and forest structure such that it could be used to develop numerical models for avalanche flow in forests.

For the mapping of release areas, fracture depths and runout areas we used a hand-held differential GPS (DGPS) device. Of particular importance was to reach the site as soon as possible, before weather conditions affected the deposits (melting, rain, snowfall, settlement). Where the measurement of release depths with probes was not possible, we analyzed the snow structure of corresponding slopes and searched for the snow slab and the corresponding weak layer, on which the snow started to move. The determination of an average fracture depth was thereby possible. The mapping of the runout area was done by DGPS measurements along the boundary of the avalanche deposition. This allowed us to compare model simulation results with the precise dimension of the real avalanche. Densities could be picked out of snow profiles, regularly collected all over the Alps. We took photographs of the deposition (Figure 1), to document the influence of forest, its structure and stem distribution on snow detrainment. Several depth measurements with snow probes were performed, but quantitative measurements over the whole deposition area is a target for further studies. We focused on snow depositions behind trees, measured their length and height and therefore their volume to get a rough estimation about the deposited mass of avalanches due to forest. Forest structures could be determined by analyzing high-resolution orthophotos (Bebi et al., 2001). Detailed information about age and density of forest stands can also be gained by site inspections in summer.

Figure 1: Deposition of avalanche snow behind a tree.

One avalanche, released near Filisur (Switzerland) in February 2012, is a typical example case. The avalanche released in a forest opening above the railroad and road from Filisur in direction to Bergün. The railroad was protected by a fence, whereas the road was hit by the avalanche, which stopped there. Before the avalanche hit the road, it flowed through a dense forest, with a four meter wide clearing not visible on aerial photographs (Figure 2). The runout area was mapped by a DGPS device. For this case, a mapping of the release area with GPS was impossible due to steep, unaccessible terrain. Photographs of the deposition were taken and its upper level determined.

Figure 2: Track of forest avalanche near Filisur.

3. MODELLING

We applied the numerical avalanche dynamics program **RAMMS** (Christen et al., 2010) to simulate the observed avalanche events. This program solves the depth-averaged mass and momentum balance equations for avalanche flow:

$$\partial_t H + \partial_x (HU_x) + \partial_y (HU_y) = \dot{Q}(x,y,t), \qquad (1)$$

$$\partial_t (HU_x) + \partial_x \left(HU_x^2 + g_z \frac{H^2}{2} \right) + \partial_y (HU_xU_y) = G_x - S_x, \qquad (2)$$

$$\partial_t (HU_y) + \partial_x (HU_xU_y) + \partial_y \left(HU_y^2 + g_z \frac{H^2}{2} \right) = G_y - S_y, \qquad (3)$$

and

$$\partial_t (HR) + \partial_x (HRU_x) + \partial_y (HRU_y) = \alpha (\mathbf{SU}) - \beta (RH). \qquad (4)$$

The unknown field variables are the avalanche flow height $H(x,y,t)$ and the mean avalanche velocities $U_x(x,y,t)$ and $U_y(x,y,t)$ in the local x and y directions, respectively. We introduce an additional depth-averaged energy equation accounting for the kinetic energy $R(x,y,t)$ associated with particle velocity fluctuations (Bartelt et al., 2012). The parameter α controls the production of fluctuation energy R from the mean shear and the parameter β determines the dissipation of fluctuation energy by different mechanisms (collisions, plastic deformations, abrasion, fragmentation). The field variables are a function of time t and thus we solve the equations from avalanche release (t = 0) to avalanche deposition. The force components associated with the gravitational accelerations in the x and y directions are denoted G_x and G_y and given by

$$G_x = g_x H \qquad \text{and} \qquad G_y = g_y H. \qquad (5)$$

Mass uptake (and detrainment) from the snow cover is specified by the volumetric entrainment rate $\dot{Q}(x,y,t)$ per unit area. We use the well-known Voellmy model (Voellmy, 1955; Salm, 1993) by making the Voellmy constitutive parameters μ and ξ functions of R (Bartelt et al., 2012):

$$S_x = \frac{U_x}{\|U\|} \left[\mu(R) g_z H + \frac{g \|U\|^2}{\xi(R)} \right] \qquad (6)$$

and

$$S_y = \frac{U_y}{\|U\|} \left[\mu(R) g_z H + \frac{g \|U\|^2}{\xi(R)} \right]. \qquad (7)$$

The Voellmy approach (Salm, 1993) splits the total basal friction into a velocity independent dry-Coulomb term, which is proportional to the normal stress (friction coefficient μ) and a velocity dependent "viscous" or "turbulent" friction (friction coefficient ξ). These are the Reynold's stresses. When α = 0, we have the standard Voellmy-Salm model (VS-model) with constant friction parameters μ and ξ.

We pursued the hypothesis in the numerical simulations that the trees did not break, acting like obstacles causing mass to stop and be lost from the flow. The underlying idea behind this assumption is that trees affect the avalanche mass flux directly, not via the friction. In the simulations, detrainment was treated as negative entrainment $\dot{Q}_e$ proportional to the inverse velocity and a constant K

$$\dot{Q}_e = -\frac{K}{\|U\|}. \qquad (8)$$

This approach allows the characterization of different forest stand density and age, depending on the parameter K.

4. RESULTS

4.1 Numerical experiment

To begin our analysis, we first carried out a numerical experiment to explore the difference between frictional braking and detrainment. To minimize the influence of small terrain features on the results, we designed a parabolic shaped slope avalanche track, with a 300 meter long runout area in flat terrain (Figure 3).

We simulated avalanches with α = 0 (standard Voellmy model) with and without forest, characterized either by different friction parameters (Bartelt and Stöckli, 2001) or with detrainment. The forest covered the whole avalanche path. In the current **RAMMS** version, forest is characterized by adding 0.02 to the μ value and setting ξ = 400 m/s^2 independent of the forest structure. When using the detrainment approach the possible deposition height and the constant K were varied.

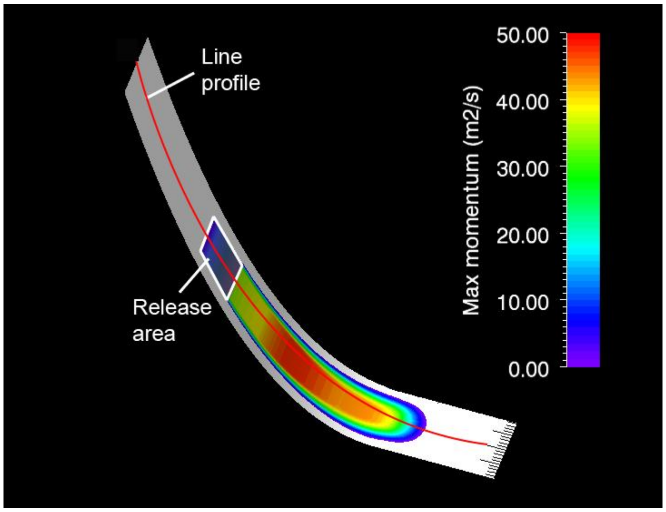

Figure 3: Max-momentum of simulation of avalanche on parabola with a release volume of 19828 m^3 and line profile.

The spatial resolution of the digital elevation model (DEM) was chosen to be 1 meter. For simulations with **RAMMS** the input parameters release area, fracture depth, snow density and the two friction parameters μ and ξ had to be defined. Three different release areas and fracture depths of one meter respectively were tested. The resulting release volumes were 19828 m^3, 5058 m^3 and 1316 m^3. The average elevation of the release areas was set to 380 m above zero and the avalanche density to 300 kg/m^3. The friction parameters were chosen to be constant; μ was 0.26 and ξ = 2000 m/s^2, what, according to the recommended guideline values (Buser1980, Salm1990), fits for small (5 - 25000 m^3), frequent avalanches (10 year return period) in unchannelled terrain above 1500 m.a.s.l.

Simulations with and without forest and with detrainment of maximum 30 cm on the forested area were conducted. The numerical experiments revealed that the detrainment approach had a significant influence on the runout of small volume avalanches. It was barely influenced by changing the friction parameters (Figure 4a). Conversely, the detrainment approach did not alter significantly the runout of the large volume avalanches (Figure 4c); modification of the friction parameters had the largest influence. We tested three different values for the detrainment parameter K (200 m^2/s^2, 300 m^2/s^2, 500 m^2/s^2).

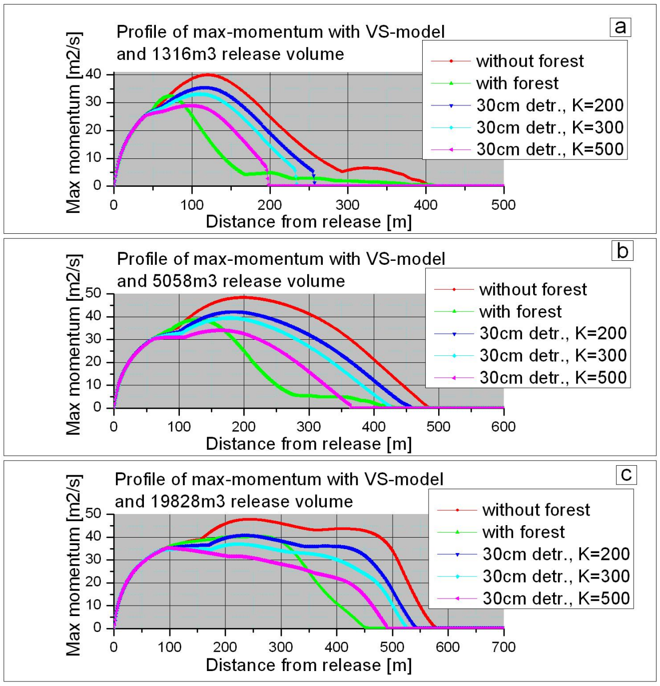

Figure 4: Profiles of max-flow-momentum of simulations of avalanche with different release volumes (1316 m^3, Figure (a); 5058 m^3, Figure (b); 19828 m^3, Figure (c)). The simulations were conducted with the VS-model of **RAMMS** on a parabolic slope with friction parameter and detrainment approach.

4.2 Simulations of forest avalanche near Filisur

We then compared simulation results with the friction approach and the detrainment approach with the documented avalanches of our field campaign. The avalanche released on 24th February 2012 near Filisur, Switzerland is used to exemplify the procedure.

Figure 5 illustrates the results of the two simulations using the friction parameter approach (recommended guideline value for μ + 0.02 and ξ = 400 m/s^2) and detrainment approach (max detrainment = 10 cm, K = 200 m^2/s^2) for the forest area. On the orthophoto the slope with the forest cover, the railroad (middle part of the slope), the road from Filisur to Bergün (which

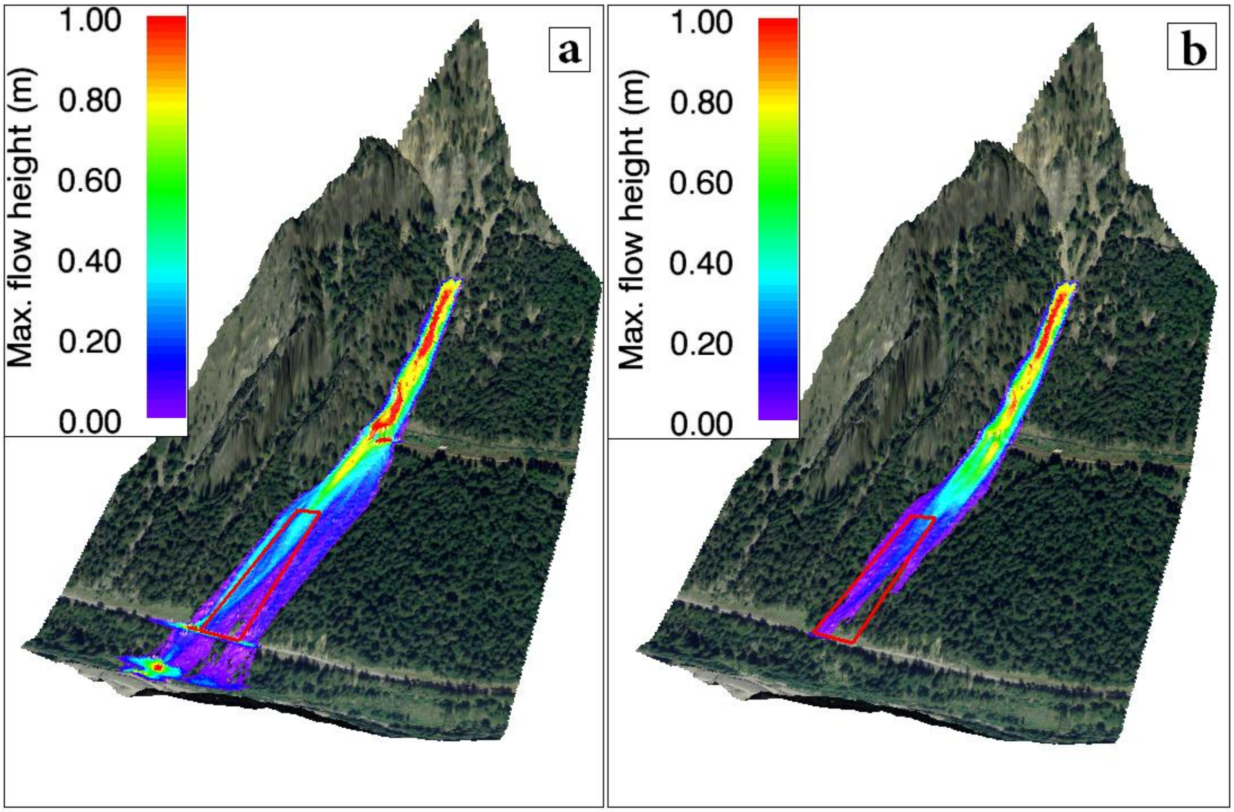

Figure 5: Simulation of forest avalanche near Filisur with the VS-model with the friction parameter approach (a) and the detrainment approach (b).

was hit by the avalanche) and the calculated maximum flow height are shown. The actual deposition area, measured with the DGPS device is marked with a red frame and shows the avalanche stopping on the road. The deposition zone of the friction approach reached the valley floor, whereas with the detrainment approach the lower boundary of the deposition is on the road. Another difference between the two simulations is the lateral spreading of the maximum flow height in the lower part of the avalanche track. The friction parameter approach overestimates the spreading of the avalanche flow.

The release area was determined performing a terrain analysis, which leaves room for speculations about the release volume. Therefore we performed several simulations using different release volumes (677 m^3, 1083 m^3, 1624 m^3). Concerning the runout distance, the results were qualitatively the same: With the friction parameter approach, the simulated avalanche reached the valley floor 20 m below the road, whereas using the detrainment approach the avalanche reached the road and stopped there or shortly below, what corresponds to the observations.

5. CONCLUSIONS

The inclusion of forest effects in avalanche dynamics simulations is an important feature for avalanche hazard analysis, especially for small and frequent avalanches. For these avalanches, forest plays a crucial protective role. 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); the second is to directly extract mass from the flow that has been stopped by the trees. Of course, 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 second approach is more direct and appears to account for physical processes, such as jamming, that cannot be modeled by the friction parameters alone.

We systematically tested both approaches on an ideal, parabolic 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 the same mass will have greater effect on smaller avalanches, which qualitatively agrees with observations. There is almost no effect of detrainment on large avalanches which also agrees with observations. The statement that large avalanches are unaffected by forests is therefore implemented in this approach.

To demonstrate the applicability of the detrainment approach we tested it on avalanche events, documented in winter 2011/12. As an example case we presented the simulation of the forest avalanche, released in February 2012 near Filisur (Switzerland). The observation of this avalanche reveals that the snow was deposited along the lower part of the avalanche track reaching the road and on the road itself. The comparison of the numerical model calculations with the observed deposition area, using the adapted forest friction parameters and the detrainment approach reveals an improvement of the simulation results of the runout distance with the latter approach. The largest part of the avalanche mass stopped on the steep slope above the road or on the road itself, whereas with the friction parameter approach the avalanche did not stop before the valley floor, where almost all the mass deposited. Lateral spreading in the detrainment approach is highly reduced, what could also be observed in the field, with deposited snow behind trees at the outer boundary of the avalanche track. In the test version of **RAMMS**, detrainment depends inversely on velocity, which leads to effective deceleration and stopping at the slower moving parts of the avalanche.

What other parameters than velocity, detrainment depends on, remains an unanswered question so far. More real avalanche events will be used in future studies to fill this gap. An extensive validation of the input parameters detrainment height and constant K is necessary for the implementation in current simulation models, but the general applicability of this approach has been tested and confirmed. The specification of a maximum detrainment height enables the implementation of an approximate avalanche size, where forests still have an effect on the stopping behavior. The constant K could stand for forest structure or snow conditions, two important factors appropriate for being included in current model simulations.

6. ACKNOWLEDGEMENTS

The authors thank Armin Fischer and Irene Vassella for their help on data collection and evaluation.

7. REFERENCES

Anderson, G., and D. McClung, 2012: Snow avalanche penetration into mature forest from timber-harvested terrain. *Canadian Geotechnical Journal*, **49**, 477–484.

Bartelt, P., Y. Bühler, O. Buser, M. Christen, and L. Meier, 2012: Modeling mass-dependent flow regime transitions to predict the stopping and depositional behavior of snow avalanches. *Journal of Geophysical Research-earth Surface*, **117**, F01015.

Bartelt, P., and O. Buser, 2010: Frictional relaxation in avalanches. *Annals of Glaciology*, **51**, 98–104.

Bartelt, P., and V. Stöckli, 2001: The influence of tree and branch fracture, overturning and debris on snow avalanche flow. *Annals of Glaciology*, **32**, 209–216.

Bebi, P., F. Kienast, and W. Schönenberger, 2001: Assessing structures in mountain forests as a basis for investigating the forests dynamics and protective function. *Forest Ecology and Management*, **145**, 3–14.

Bebi, P., D. Kulakowski, and C. Rixen, 2009: Snow avalanche disturbances in forest ecosystems–State of research and implications for management. *Forest Ecology and Management*, **257**, 1883–1892.

Bühler, Y., M. Christen, J. Kowalski, and P. Bartelt, 2011: Sensitivity of snow avalanche simulations to digital elevation model quality and resolution. *Annals of Glaciology*, **52(58)**, 72–80.

Bühler, Y., M. Marty, and C. Ginzler, 2012: High resolution DEM generation in high-alpine terrain using airborne remote sensing techniques. *Transactions in GIS*, **(in press)**, –.

Casteller, A., M. Christen, R. Villalba, H. Martinez, V. Stöckli, J.C. Leiva, and P. Bartelt, 2008: Validating numerical simulations of snow avalanches using dendrochronology: the Cerro Ventana event in Northern Patagonia, Argentina. *Natural Hazards and Earth System Sciences*, **8**, 433–443.

Christen, M., J. Kowalski, and P. Bartelt, 2010: RAMMS: Numerical simulation of dense snow avalanches in three-dimensional terrain. *Cold Regions Science and Technology*, **63**, 1–14.

de Quervain, M., 1979: Wald und Lawinen. In: *Mountain Forests and Avalanches*, pp. 219–239.

Faug, T., B. Chanut, R. Beguin, M. Naaim, E. Thibert, and D. Baroudi, 2010: A simple analytical model for pressure on obstacles induced by snow avalanches. *Annals of Glaciology*, **51**, 1–8.

Gubler, H., and J. Rychetnik, 1991: Effects of forests near timberline on avalanche formation. *Snow, Hydrology and Forests in High Alpine Areas*, **205**, 19–38.

Margreth, S., 2004: Die Wirkung des Waldes bei Lawinen. In: *Forum für Wissen*, pp. 21–26.

Newesely, C., E. Tasser, P. Spadinger, and A. Cernusca, 2000: Effects of land-use changes on snow gliding processes in alpine ecosystems. *Basic and Applied Ecology*, **1**, 61–67.

Salm, B., 1978: Snow forces on forest plants. In: *Mountain Forests and Avalanches*, pp. 157–181.

Salm, B., 1993: Flow, flow transition and runout distances of flowing avalanches. *Annals of Glaciology*, **18**, 221–221.

Schneebeli, M., and M. Meyer-Grass, 1993: Avalanche starting zones below the timberline-structure of forest. In: *Proceedings of the International Snow Science Workshop*, Breckenridge, CO, pp. 176–181.

Takeuchi, Y., H. Torita, K. Nishimura, and H. Hirashima, 2011: Study of a large-scale dry slab avalanche and the extent of damage to a cedar forest in the Makunosawa valley, Myoko, Japan. *Annals of Glaciology*, **52**, 119–128.

Teich, M., P. Bartelt, A. Grêt-Regamey, and P. Bebi, accepted: Snow avalanches in forested terrain: influence of forest parameters, topography and avalanche characteristics on runout distance. *Arctic, Antarctic, and Alpine Research*.

Teich, M., and P. Bebi, 2009: Evaluating the benefit of avalanche protection forest with GIS-based risk analyses–A case study in Switzerland. *Forest Ecology and Management*, **257**, 1910–1919.

Teich, M., C. Marty, C. Gollut, A. Grêt-Regamey, and P. Bebi, 2012: Snow and weather conditions associated with avalanche releases in forests: Rare situations with decreasing trends during the last 41 years. *Cold Regions Science and Technology*, **(in press)**, –.

Viglietti, D., S. Letey, R. Motta, M. Maggioni, and M. Freppaz, 2010: Snow avalanche release in forest ecosystems: A case study in the Aosta Valley Region (NW-Italy). *Cold Regions Science and Technology*, **64**, 167–173.

Voellmy, A., 1955: Über die Zerstörungskraft von Lawinen. *Schweizer Bauzeitung*, **73(12/15/17/19)**, 159–162, 212–217, 246–249.