INFLUENCE OF CHANGING FOREST HEIGHT ON THE FREQUENCY OF AVALANCHE RELEASE IN AN ALPINE AFFORESTATION IN THE SWISS ALPS

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ABSTRACT: A continuous upward shift of the upper treeline is observed in many mountain regions worldwide. Such forest expansion is causing significant impacts on ecosystem services, especially as it may reduce avalanche hazards. Forests mitigate the release of snow avalanches mainly through snowpack stabilization. Trees prevent the creation of continuous weak layers thus decreasing the probability of slab release. Forest density, size of forest gaps, tree height and tree species are key factors to estimate the forest protective effect against snow avalanches. Field observations indicate that a certain tree height is crucial for the prevention of avalanche release in young forest stands and that tree height should be at least one-and-a-half to two times taller than the snow cover, with required tree height increasing with slope inclination. In this study, we analysed the relationship between avalanche occurrence, tree height and snow height within the long-term afforestation research area Stillberg near Davos, Switzerland. A decreasing number of avalanche releases was observed in relation to changes in tree height in the afforestation during the last 49 years. Furthermore, the spatial distribution of avalanche release areas shifted from covering most of the studied area of Stillberg to three local avalanche release areas within gullies. These gullies were characterized by lower tree densities but larger tree heights and larger snow accumulation. The analysis of all avalanches at Stillberg indicated that the ratio of tree height to snow height had contrasting effects on the release of loose snow avalanches and slab avalanches; a high ratio hindered the formation of slab avalanches, but under certain conditions some loose snow avalanches released. Areas prone to loose snow avalanches typically have few or small *Larix* and lack evergreen trees. Overall, the Stillberg afforestation after almost 50 years, together with local temporary protection measures for the gullies could be effective in mitigating avalanche activity.

KEYWORDS: tree regeneration, snow avalanche, avalanche formation, avalanche release, effective tree height

1. INTRODUCTION

The alpine treeline ecotone is the climatic upper limit (in elevation) of a forest ecosystem forming a transition between subalpine forest and alpine elevation zone. It is characterised by slow and sometimes twisted growth as a response to harsh environmental conditions. The width of a treeline may vary from a narrow treeline with an abrupt change from closed forest to alpine tundra especially on steep slopes, to very wide belt stretching over hundreds of meters typical for gentle topography (Elliott, 2017).

As temperature is one of the limiting factors for forest growth and the treeline, it is assumed that climate change will shift the species elevational optimum and therefore the upper treeline (Vitasse et al., 2021). In some mountainous regions around the world, a continuous upward shift of the upper treeline is already being observed (Arekhi et al., 2018; Hansson et al., 2021; Treml and Migoń, 2015), due to temperature increase and/or abandonment from human management. Remote and less populated places in the Alps have typically higher rates of reforestation (Anselmetto et al., 2024). Such forest expansion will affect biodiversity and ecosystem services through altered species composition, carbon storage, and the frequency of natural hazards like snow avalanches or rockfall. Potential avalanche release zones may be affected by new ingrowth contributing to mitigation of avalanches (Berger et al., 2013). Similarly, also the transition zone for rockfall will be affected and soils stabilized against landslides.

Sparse vegetation at the treeline like shrubs and groups of trees are usually not characterised as forest, even if they affect the release and dynamics of natural hazards (Brožová et al., 2021). Forests may hinder snow avalanche release through altered snow conditions or by stabilizing the snowpack (Bebi et al., 2009b). The presence of forest gaps and forest parameters like forest density, species composition and tree height are important factors for probability of an avalanche release

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(Schneebeli and Bebi, 2004). Small trees in a release area may influence the runout distance of snow avalanches (Teich et al., 2012). They also prevent snow gliding through the anchoring effect of vegetation (Feistl et al., 2014; Höller, 2001, 2013).

If the vegetation height is 1.5 to 2 times greater than the snow cover, it should be enough to prevent an avalanche to release, according to observations and practical guidelines (Frey, 1978). As snow depth and slope inclination increase, taller and more trees are required (Saeki and Matsuoka, 1970; Perzl, 2005). Furthermore, this critical snow-height ratio is species dependent and varies for evergreen and deciduous trees (Dellagiovanna, 2011). There are estimations for young broadleaved forests in Japan, when those are considered effective as mitigation against avalanche release (Saeki and Matsuoka, 1970). While these individual observations exist, there is a notable lack of a systematic analysis on growing trees, their increasing height and the relation to snow height and avalanche activity. We used a unique dataset from Stillberg study area (Lechler et al., 2024) that dates back to the 1950's with first snow observations and first plans for afforestation in avalanche release zones at the treeline. The aim of this study was to analyse the growing forest, compare tree and snow heights and relate these to the changing avalanche activity at Stillberg.

2. METHODS

2.1 Study area and datasets

The Stillberg afforestation is located at the treeline ecotone close to Davos (GR, Switzerland; Fig. 1) on a north-eastern slope with average inclination of 38°, between 1980 and 2230 m a.s.l. (elevational gradient of 150 m). Mean annual precipitation at the local climate station at 2090 m a.s.l. is 1150 mm, the July mean daily temperature is 9.4°C, while the mean daily temperature in January is -5.8°C (1975-2005). Average maximum snow depth is 146 cm, with 60 cm on wind-exposed ridges and 420 cm in leeward gullies (1975-2005). Stillberg is a unique area for its long-term monitoring for about 50 years (Lechler et al., 2024), with the main experiment established in 1975: 92000 trees were systematically planted in a gridded scheme. The planted tree species were European larch (*Larix decidua*), Swiss stone pine (*Pinus cembra*) and mountain pine (*Pinus mugo* subsp. *uncinata*).

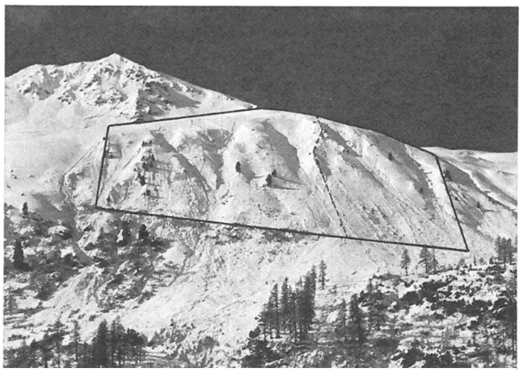

Figure 2: Study area of Stillberg, from de Quervain et al., 1972 (Photo H. R. in der Gand, 1957)

Survival, growth and damage of trees were intensely monitored in 1975, 1979, 1982, 1985, 1990, 1995, 2005, 2010 and 2015. In 1985 and 1995, height, survival and damage were recorded for all trees, whereas in 2005 and 2015 these parameters were only recorded for a subset of trees (7181 trees in 2005 and 6781 trees in 2015; Frei et al., 2023). Snow conditions and avalanche activity were observed from the winter 1959/1960 (de Quervain et al., 1972). Over 400 snow laths with the distance of 14 m from each other were set within Stillberg area to monitor snow height (Bebi et al., 2009a). The available dataset records snow heights from the winter of 1973/1974 to 1991/1992 from 254 snow laths, and from 1992/1993 to 2006/2007 and from 2009/2010 to 2013/2014 at 14 snow laths. Avalanches from 1976 to 2003 were outlined by hand on 1:500 topographic maps and then digitised. The avalanches from 2003 were mapped by SLF staff, rescue services and staff of the mountain railways/cableways. All slab avalanches with a minimum size of 50 m in one direction and loose snow avalanches with a minimum length of 100 m, were recorded. For the purpose of this study, we selected only the left part of Stillberg without the presence of avalanche snow bridges. We analysed only those avalanches, where the data on snow heights were available no earlier than 5 days before the avalanche event. The data on snow height was assigned if an avalanche part covered at least ten percent of the plot (19.6 m^2) of the corresponding snow lath. To assign the control areas we selected plots adjacent to the release areas without any avalanche releases. These comparison areas were selected mostly above and sideways of the original release area.

2.2 Analysis

We analysed the trend of avalanche activity at Stillberg using the whole dataset of mapped avalanches (n = 214) and calculated Spearman correlation between the number of avalanches and time. We determined the annual maxima for snow height using the data of the weather station Stillberg. To visualize the spatial distribution of the centroids of avalanche releases from our dataset, we employed Kernel Density Estimation (KDE), using the R package "spatstat" (Baddeley et al., 2015). For the analysis on avalanche occurrence, we used only a complete set of data on avalanches, snow height and tree height – missing data were eliminated.

The last match of data was in the avalanche year 1998, which was paired with tree data from 1995. The total number of analysed avalanches counted for 80 and we used logistic regression to estimate the probability of avalanche occurrence. We divided the avalanches into groups per avalanche type: loose (n = 33) and slab (n = 47) and checked for collinearity. We performed a binomial regression analysis (generalised linear mixed model – GLMM). The response variable *avalanche occurrence* (binary 1/0) was set with the predictor variables describing topography and ratio between tree height and snow height: *curvature* (factor, classification of plan and profile curvature: convex (-) or concave (+)), *aspect* (continuous from 27 to 127 i.e., from NE, E to SE), *slope inclination* (continuous from 25 to 50, in degrees), H_T/H_S (the ratio between the tree height and snow height, continuous from 0.005 to 35); and *avalanche number* was set as a random variable. We tested the relationship between release area size and release height in time using Spearman correlation. For the differences between avalanche release and control areas we used Wilcoxon tests. We calculated mean and median values of tree-to-snow height ratios at different time steps within Stillberg, using the snow height data from the laths. The respective years from laths were coupled with the closest years of tree measurement.

To perform all statistical analyses, we used R software version 4.2.1 (R Core Team, 2022) paired with RStudio version 2022.7.2.576 (RStudio, 2022). The data visualisation was done using the R package “ggplot2” (Wickham, 2016).

3. RESULTS

The total of 214 avalanche releases were observed at the left part of Stillberg (around 60% of area without snow avalanche bridges) in the last 46 years (from 1976 to 2022, Fig. 2). The most avalanches happened in 1991, counting for 25 avalanches (from which 10 loose and 15 slab avalanches). The number of avalanches was decreasing since the observation in 1976 ($p < 0.001$), i.e., one year after the afforestation until present. In the first years of the afforestation from 1976 to 1979, 22 avalanches released at the left part of Stillberg. The number of avalanches releasing per decade was higher until the 1990’s, when 106 avalanches release per decade. After the year 2000, avalanche release decreased to 5 avalanches per decade in the 2000’s and 2010’s. After 2020, only two avalanches released in 2021.

No significant changes in snow height between years were observed, thus the influence of changing weather conditions may be ruled out. Trees at Stillberg grew taller with the highest tree of more than 8 m measured in 2015 (Fig. 3). Tree density decreased with time, but was in average still very high in 2015 with tree density of more than 800 trees/ha to places with more than 9000 trees/ha. Lower densities were found especially within the three gullies compared to the ridges ($p < 0.05$).

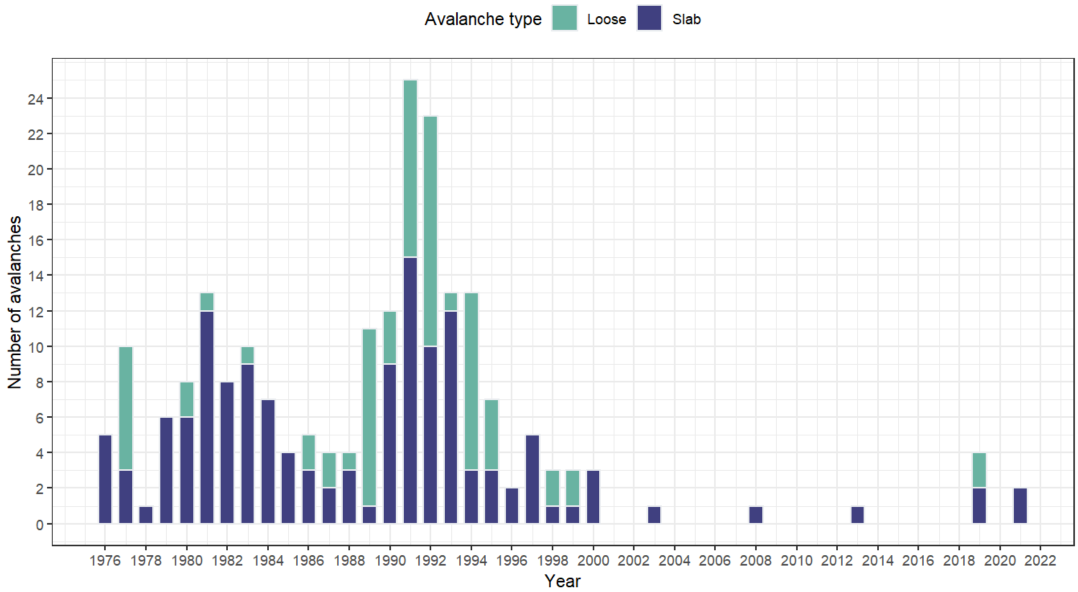

Figure 2: Avalanche activity observed at Stillberg from 1976 to 2022. In the 1970’s the total number of avalanches released was 22, in the 1980’s it was 74, the highest number of avalanche releases was in the 1990’s with 106 avalanches. Whereas after that the number of avalanches was only 5 in 2000’s as well as in 2010’s and 2 avalanches after 2020.

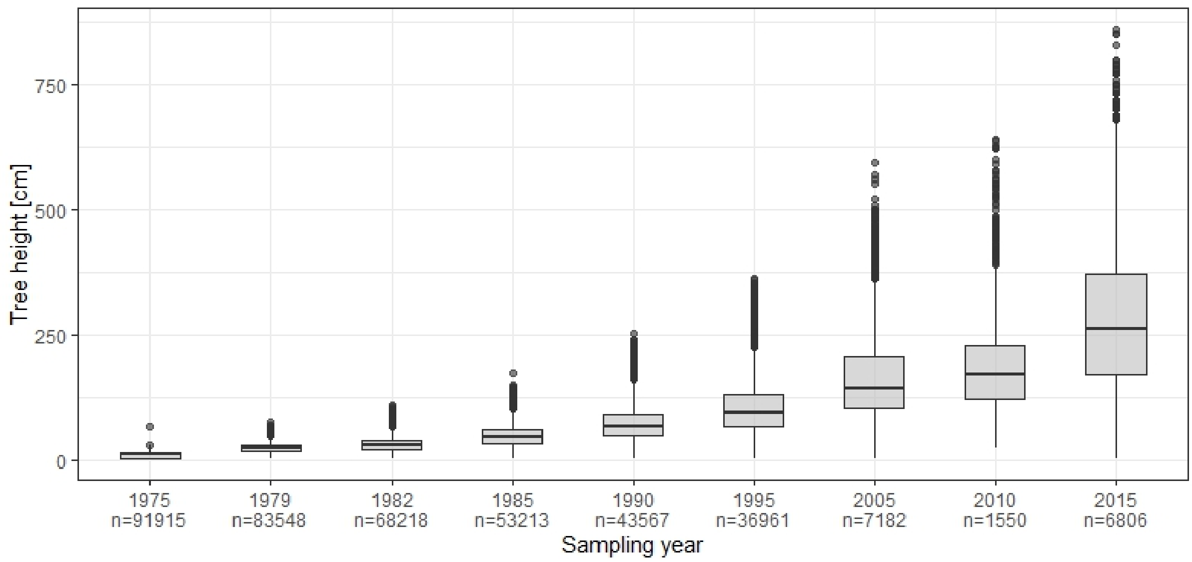

Figure 3: The tree height increased with time with the highest trees reaching over 8 m in 2015.

Together with the number of avalanches per year, also the size of release areas was decreasing with time ($p < 0.001$). Even though the release height of an avalanche was correlated to the avalanche size ($p < 0.001$), no decrease in release height in time was observed. The spatial distribution of avalanche release areas changed with time and became more aggregated compared to the first three decades after planting, where the spatial distribution was more random (Fig. 4). Most of the release areas from the last two decades aggregated within the gullies. The analysis on topographical parameters and the ratio between the tree height and snow height indicated that both loose and slab avalanches were more likely to occur on steeper slopes with east or north-east expositions (Table 1). Avalanche activity was reduced on south-east facing slopes. Further we found that the probability of avalanche release decreased on slopes with convex-concave, concave-convex or concave-concave combinations of plan and profile curvature compared to concave-concave. Slab avalanche releases differed from loose avalanche releases in relation to tree-to-snow height ratio. Slab avalanche probability decreased with a higher tree-to-snow height ratio, compared to loose snow avalanches. The ratio between the tree height and snow height (TS ratio) is lower in the avalanche release areas compared to control areas (Wilcoxon test, $p < 0.001$). The only exception was in 1990, where the mean H_T/H_S was lower in control areas. However, looking at the median values, the ratio was always larger compared to the avalanche release areas. The ratio between height of the trees and snow is increasing with time, as trees grow. Interestingly, the snow height was always higher within the avalanche release areas compared to the control areas (Wilcoxon test, $p < 0.001$).

Table 1: The results of a generalized linear mixed model (GLMM) of the occurrence of loose and slab avalanches. The probability of an avalanche release is influenced by topography and the ratio between tree and snow height. We use the significant level of 0.05 to determine the predictors for the occurrence of loose and slab avalanches.

	Loose avalanche					*Slab avalanche*				
	Estimate	***Std. Error***	***z value***	***Pr(>|z|)***		***Estimate***	***Std. Error***	***z value***	***Pr(>|z|)***	
(Intercept)	-0,728	0,139	-5,240	0,00	***	0,103	0,039	2,659	0,01	***
Aspect	-0,001	0,000	-1,490	0,14	***	-0,003	0,000	-14,227	< 2e-16	***
Slope	0,025	0,003	7,693	0,00	***	0,000	0,001	0,113	0,91	***
Curvature -+	-0,733	0,023	-31,902	< 2e-16	***	-0,173	0,010	-17,655	< 2e-16	***
Curvature +-	-1,294	0,028	-46,358	< 2e-16	***	-0,231	0,012	-18,780	< 2e-16	***
Curvature ++	-0,903	0,022	-40,464	< 2e-16	***	-0,617	0,010	-60,462	< 2e-16	***
H_T/H_S	0,046	0,014	3,281	0,00	***	-0,172	0,010	-16,462	< 2e-16	***

Significance code: * $p < 0.05$, ** $p < 0.01$, *** $p < 0.001$

Curvature: combination of plan and profile curvature, + concave, - convex

H_T - tree height. H_S – snow height

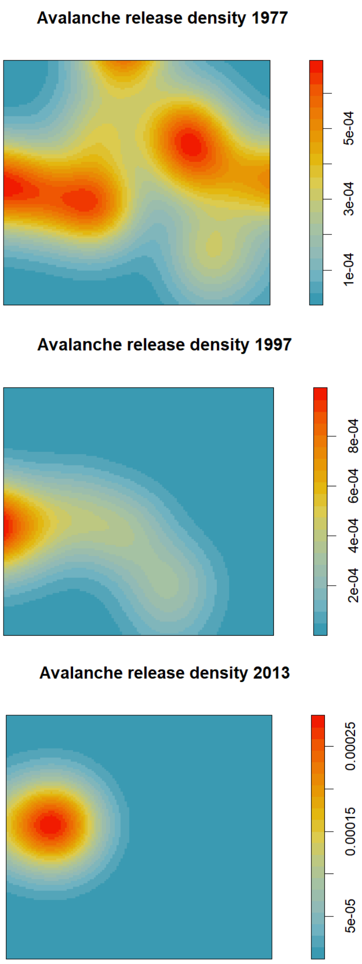

Figure 4: The spatial distribution of avalanche release areas at Stillberg at three different time steps: 1977, 1997 and 2013. The density of central points of release areas has decreased with time and becomes more aggregated.

4. DISCUSSION

The Stillberg study area had been chosen already in the 1950s to observe and characterise snow cover and avalanches. The measurements included numerous snow profiles, measuring snow depths and also more than 500 mapped avalanches (de Quervain et al., 1972).

The Stillberg afforestation was set up in 1975 and 92000 trees were planted in order to study next to the tree growth and mortality, also the different snow distribution and avalanche activity. From the beginning of the Stillberg afforestation, 214 of avalanches released at the studied left part of Stillberg. From the long-term observation it is clear that the avalanche activity decreased with time. The number of avalanches and the size was lower in the last years compared to the beginning of the observation. The spatial distribution of avalanche release areas changed in time. In the first thirty years of the afforestation, avalanche release areas were randomly distributed across the area of Stillberg. However, after the 2000, avalanche release areas became more clustered mainly in the area of gullies in the upper part of Stillberg (Fig. 5). This could be attributed to generally larger snow accumulations within the gullies, but also lower tree density. As most of the afforestation of Stillberg became increasingly effective as protection against avalanche releases, implementing technical measures specifically within potential release areas in gullies may be a cost-efficient method to further enhance avalanche protection across the whole area.

One of the controlling factors for avalanche release was the ratio between tree height and snow height. With increasing tree height this ratio increased and was found to be higher already 20 years after the afforestation. In 1975 this ratio for avalanche release areas was 0.08, compared to control areas without release in 1995 it increased to 0.95. After that the trees became almost as high as the snow cover, the avalanche activity decreased substantially. Young growing trees affect the snowpack by preventing the development of weak layers and therefore influencing avalanche formation (Schweizer et al., 2003). However, to

Figure 5: The whole area of Stillberg reduced to three potential areas for avalanche release within the gullies. Photographed in October 2023 (Photo Natalie Piazza).

completely hinder the avalanche release it has been found that trees with at least 1.5 to 2 times greater height than the snow cover are necessary (Perzl, 2005; Saeki and Matsouka, 1970) and on slopes above 30 degrees with buried trees, glide-snow (full-depth) avalanches may occur. With further increase in the height of trees, even fewer avalanches were observed at Stillberg. The afforestation at Stillberg became efficient in decreasing an avalanche formation with some gaps. Forest growth above the treeline is a slow process, where young trees are being continuously damaged by avalanches, snow gliding and creeping (McClung and Schaerer, 2006). At Stillberg, snowmelt was found to be an important environmental factor for tree mortality. Furthermore, the tree growth was driven by elevation and most of the trees survived rather in the lower part of Stillberg (Barbeito et al., 2012). Within the forest gaps in the upper part, few avalanches may still release as during the snow-rich winter in 2021. However, with further growth of trees the avalanche activity could be reduced completely (Giacona et al., 2018).

Forest plays a significant role in preventing avalanche formation and release. However, deciduous trees with gaps may have a limited effect (McClung and Schaerer, 2006). The mechanical support of snowpack and an interception by growing tree crowns will increase in the future. A dense conifer forest intercepts larger amounts of snow precipitation compared to deciduous forest (Schneebeli and Bebi, 2004). In the Southern Andes deciduous Nothofagus forest intercepts on average 23% of snow per year, with a maximum measured interception value of 13.8 mm snow water equivalent (Huerta et al., 2019). The interception rates at Stillberg may be reduced since the dominant tree species is the deciduous larch. However, areas influenced by crowns of larch trees were found to have higher snowpack stability (Schweizer et al., 1995).

Aspect was found to be a significant parameter for loose snow avalanches as well as slab avalanches, where the NE-exposed slopes were more prone to the avalanche release compared to the aspects of E and SE. Loose snow avalanches require generally steeper slopes to release compared to slab avalanches. Our results showed that slope was significant for both avalanche types and the probability of release increased with slope inclination. Loose snow avalanche usually forms on very steep slopes (above 35 to 40°) compared to slab avalanches, which release already above 28 to 30° (Haegeli et al., 2010). However, this lower threshold is reduced by surface roughness as e.g., the forest. We expected that the shape of the slope would influence the avalanche activity. It is known that convex slopes are generally more prone for avalanche release compared to concave ones. In our analysis the combination of plan and profile curvature showed that most of both slab and loose avalanches happened on convex-convex slopes, where the snowpack is usually less stable and promotes failure initiation and crack propagation in the case of slab avalanches (Gaume et al., 2018, 2017).

Loose snow avalanches release as wet avalanches in spring, or as dry after freshly fallen snow or in old surface snow with metamorphosed snow crystals at any time of the season (Haegeli et al., 2010). A localised increase of snow temperature or water content in the snowpack may result in lower cohesion and trigger an avalanche. Such behaviour is often linked to the presence of rocks, which warm the surrounding snowpack increasing the water content in the snowpack (McClung and Schaerer, 2006). Deciduous trees that do not intercept much snow may play a similar role as potential triggering points causing locally higher snow temperatures and a decrease in cohesion. Our analysis showed that, the presence of higher trees increased the probability of loose snow avalanche release. Any objects disturbing the snow surface may act as triggering points for loose avalanches (McClung and Schaerer, 2006). On the contrary, slab avalanches decreased with higher ratio of trees to snow height. Trees support the snowpack mechanically – providing transverse support and increasing the friction, and hindering the formation of slab avalanches by affecting the continuity of weak layers (Meloche et al., 2024; Schneebeli and Bebi, 2004). However, small trees may act as shrubs with both positive and negative effects on avalanche formation and release. By penetrating the snow surface, shrubs may prevent avalanche formation in case of shallow snowpack. On the other hand, shrubs or young trees may hinder settlement of snow and thus create a loose and weak layer (McClung and Schaerer, 2006).

Future environmental changes are expected to significantly alter the interactions between avalanches and forests in mountainous regions. Reduced snow cover and snow cover duration (Marty et al., 2017) and winter rainfall (Knowles et al., 2006) may decrease avalanche activity, particularly in elevations near and below the treeline. Additionally, the increasing tree cover above the actual treeline may decrease frequency of avalanches as it can be observed at the Stillberg example. Another good example is the reforested area in Queyras massif, where the natural ingrowth due to land abandonment and forestry policy enabled trees to grow within potential release areas and decreased the avalanche risk (Zgheib et al., 2023).

Trees are significantly less vulnerable to various abiotic and biotic mortality factors once they grow well above the snowpack. Forest structural and topographical parameters influence snow depth accumulation (Dharmadasa et al., 2023; Fujihara et al., 2017) and reducing snow gliding, habitat for fungal diseases and later snowmelt, thus improving tree health and survival (Barbeito et al., 2012). Swiss stone pine is known for its limits in establishment and growth related to topography, and microsites are important for a successful regeneration. Raised terrain and ridges with short-lasting snow cover are considered to favour the establishment and early growth of Swiss stone pine. At Stillberg, the most common tree species found after 30 years was the deciduous larch and both evergreen pine species were rather sparse (Barbeito et al., 2012), found in lower elevations on ridges. The mixture of larch together with stone pine is typical for inner alpine valleys with lower precipitation. Regions with rather oceanic conditions are dominated by the evergreen Norway spruce (*Picea abies*) instead of the deciduous larch, therefore making the avalanche protection more efficient. In continental regions of the Alps, treeline afforestation for improved avalanche protection should focus on selecting suitable microsites for Swiss stone pine and combining it with other species. Larch, which is able to establish in a larger variety of conditions but offers less avalanche protection, and spruce, which benefits from warming at previously cold-limited sites, both play key roles in enhancing the protective function of the treeline forest. Larch trees were found to effectively prevent avalanche release (Schneebeli and Meyer-Grass, 1992). Evergreen spruce has still a lot of potential to increase the avalanche protection in future, especially if mixed with larch and Swiss stone pine, and as long as the structure is not very homogenous.

5. CONCLUSIONS

Almost 50 years after the afforestation at Stillberg, the avalanche activity decreased significantly. With growing trees, most of the area of Stillberg became effective against avalanche release. However, three gullies in the upper part are still prone for avalanche formation. For avalanche release areas at the treeline that need afforestation under similar conditions as those at Stillberg, and with a potential for damage to be protected below, we recommend combining the afforestation with targeted technical measures within these gullies to ensure avalanche protection throughout the entire area. The mean tree height reached the estimated effective height of 2 times larger than the snow height in 2015. A high ratio of tree height to snow height hindered the formation of slab avalanches. Our study has shown that loose snow avalanches may also occur under certain conditions with a high ratio of tree height to snow height These avalanches typically occurred in areas with few and/or small trees of the genus *Larix*. This long-term dataset is valuable not only for analyzing and better understanding the protective role of forests in mitigating avalanche risks in a climate change context but also for validating physically based models (Védrine et al., 2022).

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