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„Structure and protective function of a mountain forest 23-28 years after a large-scale disturbance caused by the storm Vivian and subsequent bark-beetle infestations"

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Summary

Large-scale disturbances, such as storms and bark beetle infestations, can greatly reduce the protective function of mountain forests and increase the risk of avalanches. The aim of this study was to investigate how the stand structure and protective function of an uncleared bark beetle stand have changed over time. The study area is located at the Gandberg in the Canton of Glarus in Switzerland, where the storm Vivian (1990) and subsequent bark beetle infestations (1992-1997) affected large parts of the forest.

Both live trees and deadwood elements can increase the surface roughness of a stand and thus reduce the likelihood of avalanches. Therefore, in this study, field data were collected on the composition, density, and height of the new tree generation, as well as on the height and degree of decay of deadwood. For trees, a distinction was made between seedlings (0.2m-1.3m) and saplings (>1.3m). A total of 24 sample plots with a radius of 5m were surveyed. Eleven of these sample plots are located in the montane elevational level (1200-1450m.a.s.l.) and 13 in the subalpine level (1450-1600m.a.s.l.). Furthermore, satellite imagery and canopy height models from the years 1985, 1997 and 2016 were analysed and used for RAMMS simulations to assess run out pathways and intensities of potential avalanches.

The field survey showed that, 23-28 years after the bark beetle infestations, 25% of the forest floor was covered with deadwood. Most deadwood elements were either lying or hanging, with only 10% being standing elements. The tallest deadwood elements per survey plot had heights between 1.6-2.5m. The densities, heights, and crown cover of the new tree generation in the montane level exceeded the ones in the subalpine level. Densities of seedlings and saplings together ranged from 1800-2300 per ha, sapling height was 3-4m, and crown cover was 10-30%. Remote sensing data and RAMMS simulations showed that the forest prior to Vivian provided protection from both small avalanches (return period of 10-30 years) and large avalanches (100-300 years). In the year 1990, the storm Vivian caused new potential avalanche release areas, which were visible in the 1997 satellite image. The influence of the new deadwood stands created by bark beetles was not yet visible at that time. Only for the year 2016, did the RAMMS simulations show an increased predisposition for avalanche releases in the bark beetle stands. Those findings suggest that there was a delay between tree death and decline in the protective function.

The field survey, when compared to literature reference values, indicates that the height and crown cover of the saplings were not yet sufficient to provide protection from avalanche formation on Gandberg in 2020. The remote sensing data also suggest that avalanche releases in the bark beetle area would have been possible in 2016, yet no avalanches occurred in recent years. This was surprising given that 2018, 2019, and 2021 were snow rich years in Switzerland. However, local snow heights only reached the value of a scenario with a return period of 30 years in 2021. The fact that no avalanches occurred this year suggests that the lack of avalanche activity can be attributed, at least in part, to other factors than snow height. It is possible that the requirements for protection forests were too strict in this case, or that deadwood played an even more important role than expected.

Zusammenfassung

Grossflächige Störungen, wie Stürme und Borkenkäferbefälle, können die Schutzwirkung von Bergwäldern stark reduzieren und die Gefahr für Lawinen erhöhen. Ziel dieser Studie war es zu untersuchen, wie sich die Bestandesstruktur und die Schutzfunktion einer belassenen Borkenkäferfläche im Laufe der Zeit verändert haben. Das Untersuchungsgebiet befindet sich am Gandberg im Kanton Glarus in der Schweiz, wo der Sturm Vivian (1990) und nachfolgende Borkenkäferbefälle (1992-1997) grosse Teile des Waldes zerstörten.

Sowohl lebende Bäume als auch Totholzelemente können die Oberflächenrauigkeit eines Bestandes erhöhen und damit die Wahrscheinlichkeit von Lawinenabgängen verringern. In dieser Studie wurden daher sowohl Felddaten über die Zusammensetzung, die Dichte und die Höhe der neuen Baumgeneration, als auch über die Höhe und den Zersetzungsgrad des Totholzes erhoben. Bei Bäumen wurde zwischen Anwuchs (0.2m-1.3m) und Aufwuchs (>1.3m) unterschieden. Insgesamt wurden 24 Probeflächen mit einem Radius von 5m untersucht. Von diesen Probeflächen lagen elf in der montanen Höhenstufe (1200-1450m.ü.M) und 13 in der subalpinen Höhenstufe (1450-1600m.ü.M). Des Weiteren wurden Satellitenbilder und Vegetationshöhenmodelle aus den Jahren 1985, 1997 und 2016 ausgewertet und für RAMMS-Simulationen verwendet, um die Intensitäten und Auslaufstrecken von potenziellen Lawinen zu modellieren.

Die Felderhebungen zeigen, dass 23-28 Jahre nach dem Borkenkäferbefall 25% des Waldbodens mit Totholz bedeckt waren. Die meisten Totholzelemente waren entweder liegend oder hängend, nur 10% waren stehende Elemente. Das höchste Element pro Untersuchungsfläche war zwischen 1.6-2.5m hoch. Die Dichten, Höhen und der Kronendeckungsgrad der neuen Baumgeneration waren in der montanen Höhenstufe grösser als in der subalpinen. Die Dichten von An- und Aufwuchs zusammen lagen zwischen 1800-2300 pro ha, die Höhe des Aufwuchses zwischen 3-4m und der Kronendeckungsgrad bei 10-30%. Die Fernerkundungsdaten und RAMMS-Simulationen veranschaulichen, dass der Wald vor Vivian sowohl vor kleinen Lawinen (Wiederkehrperiode 10-30 Jahre) als auch vor grossen Lawinen (100-300 Jahre) Schutz bot. Der Sturm Vivian verursachte neue potenzielle Lawinenanrissflächen, die in den Satellitenbildern von 1997 sichtbar sind. Der Einfluss, der damals neu durch die Borkenkäfer entstandenen Totholzflächen, war noch nicht erkennbar. Nur im Jahr 2016 zeigten die RAMMS-Simulationen eine erhöhte Lawinenaktivität im Borkenkäfergebiet. Das deutet darauf hin, dass es eine Verzögerung zwischen dem Absterben der Bäume und der Abnahme der Schutzfunktion gab.

Die Felddaten zeigen, im Vergleich mit Literaturreferenzwerten, dass die Höhe und der Kronendeckungsgrad des Aufwuchses am Gandberg im Jahr 2020 noch nicht ausreichten, um Schutz vor Lawinenbildung zu bieten. Die Fernerkundungsdaten deuten ebenfalls darauf hin, dass 2016 Lawinenanrisse in den Borkenkäferbeständen möglich gewesen wären, dennoch traten in den letzten Jahren keine Lawinen auf. Das ist überraschend, da 2018, 2019 und 2021, in der Schweiz schneereiche Jahre waren. Lokale Schneehöhen erreichten jedoch nur im Jahr 2021 den Wert eines 30 jährlichen Szenarios. Die Tatsache, dass auch in diesem Jahr keine Lawinen vorgekommen sind, legt nahe, dass die Ursache der geringen Lawinenaktivität anderen Faktoren zuzuschreiben ist. Es ist möglich, dass die Anforderungen an Schutzwälder in diesem Fall zu streng waren, oder dass Totholz eine wichtigere Rolle spielte, als erwartet.

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Abbreviations

CHM	Canopy Height Model
dbh	diameter at breast height (e.g. 1.3m)
DEM	Digital Elevation Model
DSM	Digital Surface Model
DTM	Digital Terrain Model
EVA+	Online tool for extreme value statistics (eva.zamg.ac.at/evaplus)
FOEN	Federal Office for Environment, Bern, Switzerland
GIS	Geographical Information System
GNSS	Global Navigation Satellite System
Mu	Friction parameter of the Voellmy friction law. The variable Mu dominates when the flow is close to stopping (also see Xi).
n	sample size
NA value	Value that was not measured
PRAs	Potential Avalanche Release Areas
RAMMS	Rapid Mass Movement Simulation
SLF	WSL Institute for Snow and Avalanche Research, Davos, Switzerland
swisstopo	Swiss Federal Office of Topography
Transect US	upper subalpine transect
Transect LS	lower subalpine transect
Transect UM	upper montane transect
Transect LM	lower montane transect
VHM	Vegetation Height Model
WSL	Swiss federal institute for forest, snow and landscape research, Birmensdorf, Switzerland
Xi	Friction parameter of the Voellmy friction law. The variable Xi dominates when the flow is running quickly (also see Mu).
30y scenario	Scenario for avalanches with the return period of 30 years (frequent, small avalanches)
300y scenario	Scenario for avalanches with the return period of 300 years (infrequent, extreme avalanches)

1 Introduction

1.1 The Growing Importance of Windthrows and Bark Beetles

Storms and bark beetle infestations are among the most severe forest disturbances in Europe. Together they accounted for 61% of all forest damages between 1950 and 2000 (Schelhaas et al., 2003). According to the fourth Swiss National Forest Inventory (2009-2017) sanitary fellings took place in over 25% of the managed forest area of Switzerland and caused 14% of harvested wood volume. The main causes for sanitary fellings were insects accounting for 51%, while windthrows caused 22% of total damages (Brändli et al., 2020). In recent decades, forest disturbance regimes have intensified markedly, as the susceptibility of forests increased due to a warmer climate and changes in forest structure and composition (Seidl et al., 2011). Although some montane and subalpine forest stands tend to be homogenous by nature, past management and clear-cuts in the 19th century have often favoured the development of dense even-aged stands of *Picea abies* (L.) Karst. (Norway spruce), with high intraspecific competition and low stability, making them heavily predisposed for damages (Brang et al., 2006; Honkaniemi et al., 2018).

According to the Federal Office for Environment (FOEN) severe storms such as Vivian (1990), Lothar (1999) and more recently Burglind (2018) caused substantial damage to Swiss forests. Vivian caused 5.1 million m^3 damaged growing stock, Lothar 14 million m^3 and Burglind 1.3 million m^3 (FOEN, 2020; Usbeck et al., 2012), which are large amounts, considering that the annual harvest is 7.6 million m^3 (Brändli et al., 2020). Several studies have observed an upward trend of storm damages in forests since 1850 (Gregow et al., 2017; Schelhaas et al., 2003; Seidl et al., 2014). Schelhaas et al. (2003) and Seidl et al. (2014) have concluded that this effect has likely been caused by changes in forest management and structure, which led to an increase in conifer growing stocks and therefore to an increase in damage potential. Unlike other studies Gregow et al. (2014) have attributed the increase in forest losses to an increase in storminess itself, rather than to changes in management, because 85% of all windstorm damages since 1990 have occurred as a result of individual catastrophic storms (Gregow et al., 2017).

The European spruce bark beetle (*Ips typographus*) is the most destructive species affecting Norway spruce forests in Europe and has the potential to influence large-scale forest dynamics (Jakoby et al., 2019). A recent report by Stroheker et al. (2020) has addressed the bark beetle development in 2019 in Switzerlandand and found the highest amount of bark beetle invested wood since 2003, with a total of 1.4 million m^3 damaged wood. These high numbers were likely caused by the extremely hot and dry summer of 2018 (Stroheker et al., 2020).

Disturbances can cause cascading effects in forests (Honkaniemi et al., 2018). Normally weakened trees with low resistance are required for breeding when bark beetle populations are low. However, if the number of bark beetles increases rapidly - as is often the case after storms which increase the available breeding material (Jakoby et al., 2019), or after severe droughts which lower the tree resistance (Netherer et al., 2019) - bark beetles can attack in high numbers and overcome the defence mechanisms of healthy trees (Honkaniemi et al., 2018). This situation is expected to exacerbate in the future due to climate change, which will likely cause more frequent and severe storms, more forest droughts and a warmer climate that favours the development of bark beetle populations (IPCC, 2014; Jakoby et al., 2019).

A recent study of Jakoby et al. (2019) has simulated bark beetle populations in Switzerland under different climate scenarios (figure 1). The study has predicted an increase in the number of generations per year and earlier swarming times of 15-35 days before the end of the century (Jakoby et al., 2019). They have used the Swiss climate scenario A1B, which assumes a temperature rise between 2.3-4.5°C (van der Linden & Mitchell, 2009). Under current climate conditions usually two generations occur at low elevations (Central Plateau and alpine valleys) and one generation at higher altitudes (Alps and Pre-Alps). Under the A1B scenario up to three generations are expected at lower and 1.5 generations at higher elevations (Jakoby et al., 2019).

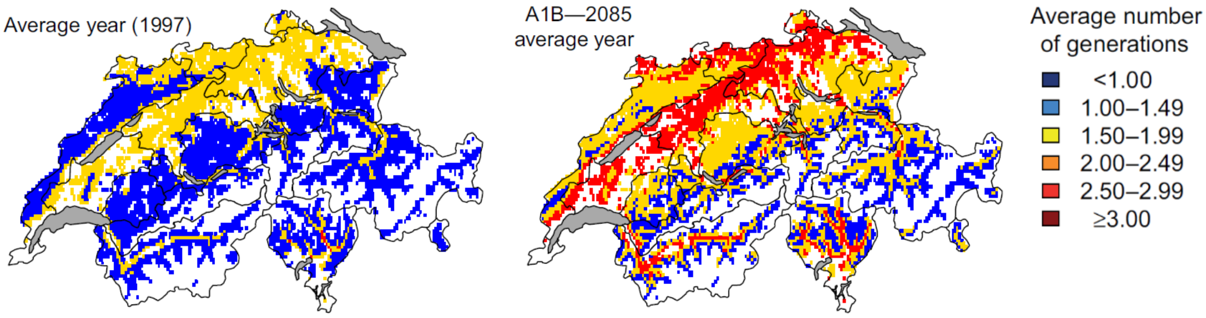

Figure 1: Figure by Jakoby et al. (2019) showing the average number of bark beetle generations under the current climate (with the year 1997 as an example of a year with average temperatures) on the left, compared to a simulation of the expected number of generations in an average year in 2085 on the right.

Jackoby et al. (2019) have stressed that the number of populations per year can have a crucial impact on the likelihood of mass propagations. After large storm events or severe droughts, population sizes of bark beetles can increase by a factor of 50 with each additional generation (Baier et al., 2007). These growing population densities could have far reaching impacts on Swiss forests and the services they provide. In mountain regions one of the most important forest functions is the protection against natural hazards. Large-scale disturbances, such as windstorms and bark beetle infestations, can lead to a rapid change in the forest structure and reduce the densities of the living trees, lowering the ability of a forest to fulfill its protective function. Therefore, it is important to know how such forests develop over time.

1.2 The Role of Forests as a Protection Against Natural Hazards

Mountain regions have experienced a strong increase of human infrastructure, caused by population growth, expansion of settlements and a growing tourist industry and a main function of mountain forests is to protect these often highly exposed infrastructures, as well as human lives (Sebald et al., 2019). In Switzerland a protection forest is defined as:

> *"A protection forest is a forest that can protect a recognised damage potential against an existing natural hazard or reduce the associated risks (Losey & Wehrli, 2013, p. 5, translated)."*

According to this definition almost half of the Swiss forests are protection forests (586`000 ha), protecting streets, railways, buildings and human lives where they intersect areas with hazard potential. Almost a fifth of this infrastructure is at a risk from natural hazards, such as avalanches, rockfalls, shallow landslides, debris flows, surface erosion or channel processes (Losey & Wehrli, 2013). The natural hazard, which is relevant to this study - avalanches - will be explained in the following paragraphs.

In non-forested areas avalanches can occur on slopes with inclinations of less than 30°, whereas in forested areas avalanches are limited to steeper slopes (Bebi et al., 2009). In conifer stands of high altitudes avalanches predominantly occur on north facing slopes in the form of slab avalanches (Frehner et al., 2005). Important factors influencing the formation of forest avalanches are the amount of recent snow, the snow characteristics, temperature, wind, topography, surface roughness and the forest structure (Bebi et al., 2001; Margreth, 2004).

Forests can offer no protection if the avalanche starting zone is located above the treeline. After a distance of about 50-150m even small avalanches can develop forces which are strong enough to break tree stems (Bebi et al., 2009). Margreth (2008) has estimated that, depending on the tree diameter, a snow pressure of 10-50kN/m^2 is necessary to break trees. Furthermore, a slowing effect can only be expected for avalanches of less than 10`000m^3 (Margreth, 2004). If the avalanche starting zone is located within a forest, trees can reduce the likelihood of avalanche formation, as well as their size and run out distances. It is recommended that subalpine and high-montane forests have a large percentage of coniferous trees, crown covers over 30-50% and gaps smaller than 15-40m (Bebi et al., 2009; Frehner et al., 2005; Margreth, 2004). Additionally, trees should be at least twice the height of the snowpack (Frehner et al., 2005). However, ideal values strongly depend on local characteristics such as the forest type and the topography.

Forests influence the structure of the snowpack and the formation of weak snow layers through following mechanisms; 1) interception reducing the amount of snow in forests compared to non-forested areas, 2) lumps of snow falling from branches and causing a more heterogenous layering of the snowpack, 3) reducing temperature fluctuations and the formation of surface hoar, 4) reducing the wind speed and subsequent snow accumulations, 5) directly supporting the snow pack and 6) enhancing surface roughness through deadwood elements (Bebi et al., 2009; Frehner et al., 2005; Frey & Thee, 2002; Margreth, 2004).

1.3 Effects of Disturbances on the Protective Function of Forests

Storms and bark beetle infestations have the potential to destroy entire stands. After such disturbances the protective function of a forest may be reduced for several decades. The loss of living trees can partially be compensated by the remaining deadwood elements, which increase the surface roughness of the forest floor and thereby impede the release of avalanches or act as obstacles for rockfall (Ammann, 2006; Fuhr et al., 2015). However, with an advancing wood decay this protective function declines over time. If tree regeneration does not grow fast enough to regain sufficient densities and heights before the deadwood decays, a gap in the protective function might occur (Wohlgemuth et al., 2017). It is important to consider the implications such a “protection gap” could have, when taking management decisions in protection forests after large-scale disturbances (FOEN, 2008).

In the past, post-windthrow management often consisted of salvage logging with the goal to prevent the spread of bark beetles, which in turn made costly technical solutions and plantings necessary to guarantee a continued protection of valuable infrastructure (Brang & Duc, 2002; Schönenberger et al., 2005; Wohlgemuth et al., 2017). Working in steep mountain slopes is often risky and expensive. After Vivian the market was flooded with windthrow timber and wood prices dropped, which made costly interventions even more unattractive (Frey & Thee, 2002). Furthermore, deadwood is an important habitat for many saproxylic species (Brändli et al., 2020). For all these reasons, there has been a tendency to increase the role of close-to-nature silvicultural systems in the past decades (Tsvetanov et al., 2018). However, it was unclear if unharvested stands would constitute a safety hazard and limited human experience with this approach lead to many uncertainties and doubts about the ability of a forest to recover without human assistance and fulfill its protective function (Schönenberger, 2002; Zeppenfeld et al., 2015).

Since the severe storms Vivian and Lothar some short-term studies tried to evaluate how long deadwood elements can reduce the risk of natural hazards and how fast the tree layer recovers. Deadwood decay is a slow process. In the first years after falling, wind-felled trees still lie on their branches, settling closer to the ground as the supporting branches break (Frey & Thee, 2002). Once wood is in contact with the ground, the decay is sped up by greater moisture availability. If a tree is killed by an insect attack, it may remain standing for several decades and decay more slowly since it dries out (Storaunet & Rolstad, 2002). Standing deadwood elements often loose branches before they break. Once they do break, they settle closer to the ground, compared to wind-felled trees, and are then exposed to higher humidity (Kupferschmid Albisetti et al., 2003). Therefore, decay speeds might be similar in bark beetle and windthrow areas.

Studies in windthrow areas have predicted that remaining structural elements, such as standing deadwood and logs offer an effective protection against avalanches and rockfall for 10-30 years (Bebi et al., 2015; Frey & Thee, 2002; Schönenberger et al., 2005; Wohlgemuth et al., 2017). Thereby, avalanches were more likely to occur in cleared areas, than in uncleared forests, which might offer even better protection than the previous forest stand in the first decade after the disturbance (Frey & Thee, 2002; Schönenberger, 2002). This protective function may decline over time, as the height and strength of deadwood elements decrease. Bebi et al. (2015) found that, 20 years after Vivian, deadwood retained only 4% of the strength of healthy living wood. After some years deadwood elements might even move downward with the snowpack causing additional risks, but movements were only recorded in steep slopes >45° (Bebi et al., 2015; Schönenberger, 2002).

It is important that reforestation takes place before deadwood loses its protective function. The recovery of the tree layer in subalpine forest usually takes several decades due to infrequent mast-years, sparse seedling banks and slow tree growth (Schönenberger, 2002). It may take 30-50 years until a seedling has outgrown the average snowpack depth of 1-2m in subalpine spruce forests (Brang & Duc, 2002). The recovery depends on the availability of favourable microsites such as nurse logs (Frehner et al., 2005). Sparse cover of such nurse logs and little advance regeneration, is a serious impediment to a fast recovery (Schwitter et al., 2015). Looking at the numbers given above it becomes obvious that a gap in the protective function of a forest might occur after about 20-50 years, as deadwood decay has progressed and tree regeneration might not yet have reached sufficient heights and densities to take over the protective function (Frey & Thee, 2002).

In the past, forest stands in central Europe have usually been harvested immediately after a disturbance and there is not enough long-term data available, which would allow a reliable estimate on how quickly deadwood decay proceeds and under which conditions forest renewal is able to regain its protective function in time (Brang et al., 2006; Fischer et al., 2015). There are some recent studies which have addressed the structure and recovery of stands which have been killed by bark beetles (furthermore referred to as bark beetle stands) (Červenka et al., 2020; Fischer et al., 2015; Winter et al., 2015; Zeppenfeld et al., 2015). However, most suites addressing the protective function of disturbed forests have focused on windthrow areas and only few studies assessed the protective function of bark beetle stands (Bebi et al., 2015; Teich et al., 2016).

The changes in the protective function of a bark beetle stand might be distinctively different from a windthrow stand, as it undergoes different structural changes. Červenka et al. (2020) have explained that the key difference lies in the fact that bark beetle infested trees do not die at once, but gradually. Therefore, the stand microclimate changes more slowly. Unlike in windthrow stands there is no immediate or severe disruption of soil, vegetation cover, or advance regeneration. This continuity is likely favouring the re-establishment of the dominant tree species from the previous forest stand instead of pioneer species (Fischer et al., 2015). Periods of protection gaps after bark beetle infestations are likely to appear later compared to windthrow stands due to both a delay in tree mortality and wood decay (Bebi et al., 2015; Kupferschmid & Bugmann, 2005b).

Even though some studies have already described the structural changes of bark beetle sites, only very few have studied the influence of those changes on the protective function of the forest against avalanches (Teich et al., 2016) and none have combined those findings with avalanche simulations. Since storm and bark beetle damages are likely to increase in the future (Seidl et al., 2011), it will become even more important for forest managers to know how disturbances affect the protective function of forests, how fast they recover and what the best practices after such events could look like. Studying the speed of deadwood decay and reforestation can provide valuable information about the resilience of spruce ecosystems, giving forest practitioners an idea on sustainable management options for both managed and protected forests (Tsvetanov et al., 2018). Putting such findings in direct relation to requirements for protection forests will allow practitioners to make more reliable management decisions in the future.

1.4 Research Questions

This study analyses uncleared bark beetle stands 23-28 years after the die-back - thus in a critical phase - and will therefore be able to help decision makers in similar cases. The main goal of the study is to address the question of the development of the protective function after a large-scale bark beetle infestation. The bark beetle stands of Gandberg forest in the Canton of Glarus in Switzerland present an ideal study site for several reasons: 1) they are located next to a large windthrow area caused by Vivian in 1990 and suffered some smaller scattered windthrows themselves, 2) they suffered from a large-scale bark beetle infestations between 1992 and 1997 and 3) a considerable amount of data has been collected in the bark beetle stands about tree regeneration (Kupferschmid, 2002; Kupferschmid & Bugmann, 2005a, 2005b; Kupferschmid et al., 2002) and deadwood elements (Ammann, 2006; Hamdan et al., 2005; Kupferschmid & Bugmann, 2005a, 2005b; Kupferschmid Albisetti et al., 2003; Landolt, 2001) and in the surrounding windthrow areas (Bebi et al., 2015; Brang et al., 2015; Frey & Thee, 2002; Schönenberger, 2002; Wohlgemuth & Kramer, 2015). This study explores the regeneration processes and the speed of wood decay after stand-replacing disturbances caused by the storm Vivian and subsequent bark beetle infestations in a spruce mountain forest. It assesses the current and past stand structure with the help of field surveys and remote sensing methods. The main research questions addressed in this study are:

Field survey

- Which plants dominate the ground vegetation on Gandberg?
- How much of the ground is covered by deadwood?
- How large is the percentage of the crown cover?
- Are the highest deadwood elements on Gandberg standing, lying or hanging elements?
- How high are the remaining deadwood elements?
- What is the current stage of decay of the deadwood elements?
- Is stem breakage or uprooting the more important process in spruce decay?
- Is tree regeneration present on the logs, which were created during the disturbances of 1990-1997?
- How high is the deadwood regeneration?
- How large is the density of seedlings and saplings?
- Which tree species are present?
- What are the heights of seedlings and saplings?
- How high is the browsing intensity on seedlins?
- Are the structural parameters of the bark beetle stands fulfilling requirements for protection forests?

Comparison to past surveys

- How did the stand parameters change compared to past studies, in terms of surface cover, deadwood heights, deadwood regeneration, seedlings and saplings?
- Did the predictions of past studies about the development of the protective function of the bark beetle stands come true?

Remote sensing

- How did the protective function of Gandberg forest change after the disturbances?
- Was the protective function worse in 1997 (many deadwood elements but no tall trees) or in 2016 (deadwood more decayed but taller trees)?
- Would avalanches, with return periods of 30 years and 300 years, have been likely in one of the surveyed years (1985, 1997 and 2016), if sufficient snow heights had been reached in those years?
- Would potential avalanches reach the valley and if so, would they still have high intensities when they do?
- Did avalanches occur on Gandberg since 1990?

Evaluating these questions will provide an immediately relevant application of forest disturbance theories and inform management objectives for the reforestation of mountain forests which suffered large-scale disturbances (Zeppenfeld et al., 2015).

2 Study Site

The study site is to the southeast of Schwanden in the Canton of Glarus in Switzerland (figure 2). It is part of the biological region Northern Pre-Alps. This region is characterized by an oceanic climate, with high precipitation, moderate daily and annual temperature changes, relatively cold average temperatures and frequent warm föhn winds (Frehner et al., 2005). The study site is located on the north face of the "Gandstock" mountain at an elevation between 1200-1600m.a.s.l. The study site can be split into a montane and a subalpine level with elevations of 1200-1450m.a.s.l. and 1450-1600m.a.s.l., respectively. The slope angle ranges from 14-36° (30-80%) (Kupferschmid & Bugmann, 2005b), making the area a potential starting zone for avalanches and rockfall (Frehner et al., 2005).

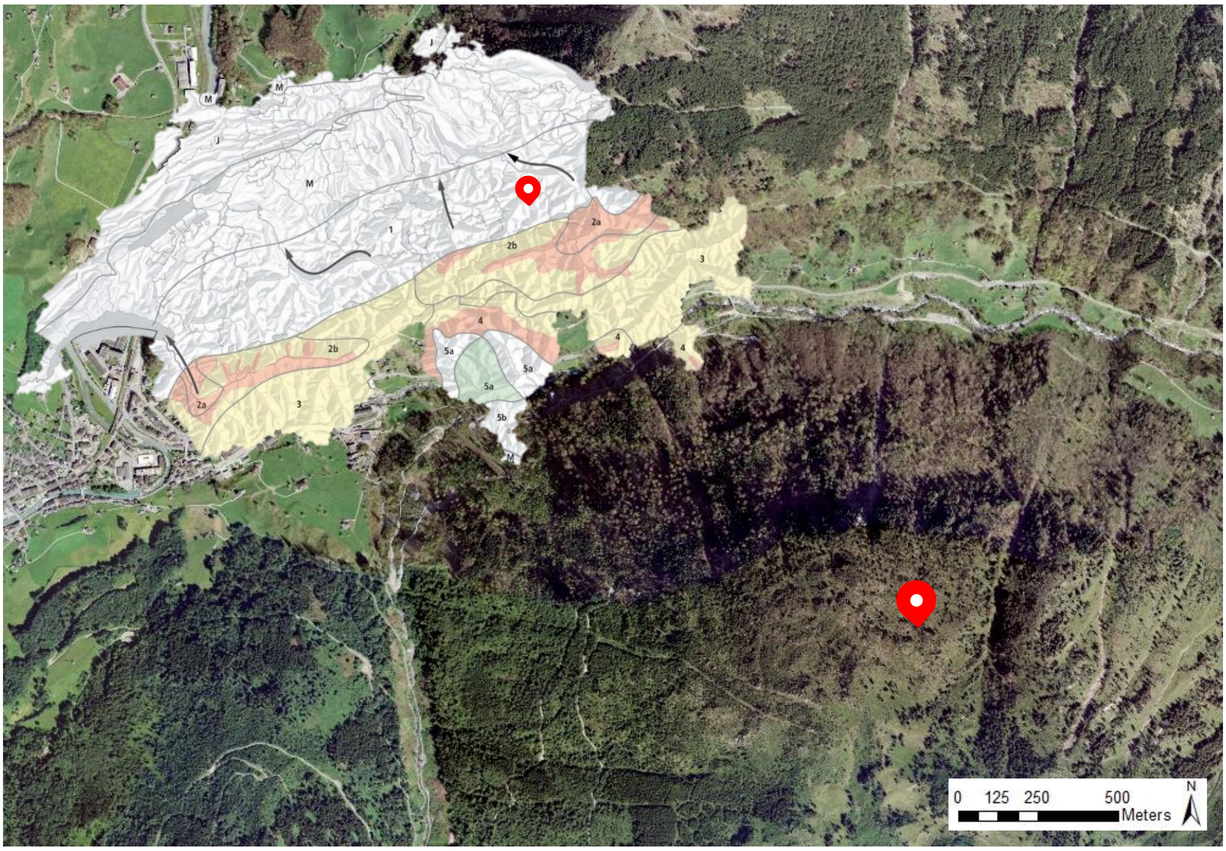

Figure 2: Location of the study site. Top left: map of the biological regions of Switzerland (Frehner et al., 2005). Right: Ortophoto of Gandberg (Swissimage: © swisstopo, 2016).

Kupferschmid et al. (2002) have estimated the mean annual precipitation to be 1600-2000mm and the mean annual temperature 2-3°C. Snow covers the Gandberg from about November to April and maximal snow heights on Gandberg were estimated to be 2.5m at the montane level and 3.2m in the subalpine level (Kupferschmid Albisetti, 2003). The geological composition of the Gandberg is made up by Verrucano (swisstopo, 2020).

The study site is part of the game reserve "Freiberg Kärpf". The reserve was established in 1548 in an area of 106km^2, making it one of the biggest and oldest game reserves in Switzerland, as well as a home to ibex, chamois, deer, roe deer, marmots, eagles, black grouse and many other wild animals (Luftseilbahn Kies-Mettmen AG, 2020).

The stands at the montane level belong to the *Galio-Abieti-Piceetum* association and the stands at the subalpine level to the *Homogyno-Piceetum vaccinietosum myrtilli* association (Kägi, 1992). According to Frehner et al. (2005) the montane *Galio-Abieti-Piceetum* association is characterized by a high productivity and tree heights up to 40m. Limiting factors are bark beetles and dense ground vegetation, as well as snow creeping, snow gliding and erosion (Frehner et al., 2005). Frehner et al. (2015) have described the subalpine *Homogyno-Piceetum vaccinietosum myrtilli* association to be characterized by trees growing in groups on suitable microsites and knee-high blueberry shrubs. Limiting factors are mainly lack of warmth for the regeneration, snow fungi (*Herpotrichia juniperi*), snow creeping, snow gliding and ground vegetation. Elevated deadwood is crucial for the regeneration of spruce in this association, since it offers protection against snow movements as well as ground vegetation (Frehner et al., 2005).

The subalpine level was not managed intensely in the past and was only subject to little high thinning, whereas the montane level was clear-cut between 1842 and 1846, followed by some high thinning in later years (Forstverwaltung Kt. Glarus, 1949, as cited in Kupferschmid Albisetti et al., 2003). This clear-cut lead to very dense and homogenous stands with high growing stocks and little advance regeneration (Kupferschmid et al., 2002). Such forests are known to be prone to disturbances (Seidl et al., 2011) and slower recovery due to the missing advance regeneration (Wohlgemuth et al., 2017). The storm Vivian in 1990 affected many protection forests in Switzerland and caused damages on a total of almost 5000ha (Brang et al., 2015). On Gandberg it caused scattered windthrows and felled 3.4ha of forest (Kupferschmid Albisetti et al., 2003).

Before the storm, the forest was almost entirely made up by spruce, with only 1% *Abies alba* (silver fir) and 3% *Acer pseudoplatanus* (sycamore maple) trees (Kupferschmid et al., 2002). The growing stock ranged from 820 m^3/ha in the montane level to 590 m^3/ha in the subalpine level (Kupferschmid Albisetti et al., 2003). After the storm the forest administration in Glarus was confronted with more wood than the typical annual harvest (Kupferschmid, 2003). The sheer mass of bark beetle invested wood required forest practitioners to focus their resources on the areas with the largest damage potential. Since the Gandberg was no protection forest, they decided not to clear the area and declared it a natural forest reserve, making it into a valuably study area, being one of the largest uncleared forests in Switzerland (Kupferschmid, 2003).

After Vivian, subsequent bark beetle infestations on the Gandberg caused the death of further 30 ha of forest (Kupferschmid, 2002). The infestations took place between 1992 and 1997 (see map in appendix A.1). After the disturbances all silver fir and sycamore maple trees survived, but only about 2% of the spruce trees (Kupferschmid & Bugmann, 2005b).

3 Methods and Materials

3.1 Field Survey

3.1.1 Sampling Design

In order to evaluate the changes in the stand structure on Gandberg the same sampling location as in previous studies was chosen (Kupferschmid Albisetti, 2003; Landolt, 2001). They have surveyed four strip transects with a width of 5m and lengths ranging between 100-160m. Two of their transects were situated in the subalpine level at 1570m.a.s.l. (upper subalpine transect, US) and at 1535m.a.s.l. (lower subalpine transect, LS). The two montane transects were located at 1320m.a.s.l. (upper montane transect, UM) and at 1290m.a.s.l. (lower montane transect, LM) However, in order to be congruent with ongoing studies in nearby windthrow areas, circles with a radius of 5m were surveyed every 20m, instead of surveying the whole strip transect (figure 3). This method resulted in a total of 24 plots, of which 11 were located in the montane and 13 in the subalpine level. A total area of 1885m^2 was surveyed.

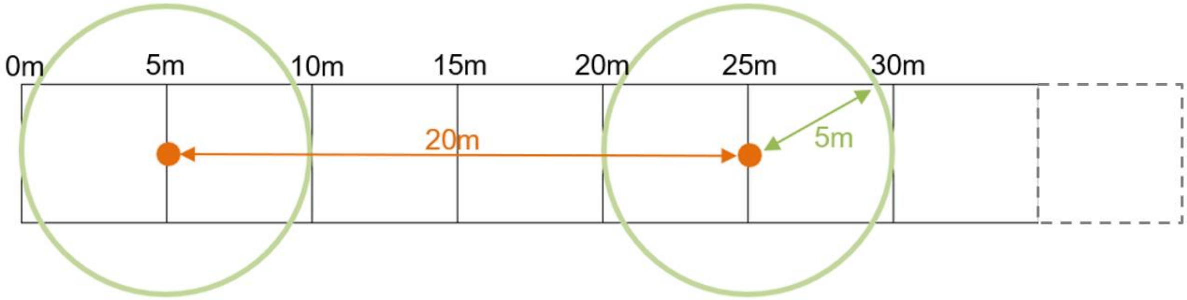

Figure 3: Experimental setup: The black lines show the strip transect. The first survey plot per transect was located at the centre of the 5m line. From this point a circle with a radius of 5m was sampled. The next sample plot was located 20m from the first and so on.

No precise GPS coordinates of the transects were available. Therefore, the location of the transects was reconstructed with the help of: 1) a map which showed the location of the transects in relation to a path, 2) measurements of the distance from the path and the start of the transect (A.D. Kupferschmid, not published), 3) information about the height above sea level (Landolt, 2001), 4) drawings of the location of standing deadwood elements and logs within the transect (Landolt, 2001) and 5) old pictures (A.D. Kupferschmid, not published).

In some cases, the poles, that had been used 20 years ago to mark the transects, were still visible. This was the case in the two subalpine transects and in the lower montane transect. However, none of those poles could be found in the upper montane transect. This was also the transect were the map drawn by Kupferschmid and the elevation given by Landolt (2001) did not agree. According to the map the location should have been at about 1370m.a.s.l. and according to Landolt it should have been at 1320m.a.s.l. The map seemed to be more reliable, as it agreed with pictures taken within the transect during past surveys. Once the start of a transect was identified, the azimuth given by Landolt (2001) was used to identify the correct direction and wooden poles were set every 20m, to mark the sample plots. Coordinates were recorded using the Stonex S800 GNSS Receiver and visualized in a Geographical Information System GIS (figure 4).

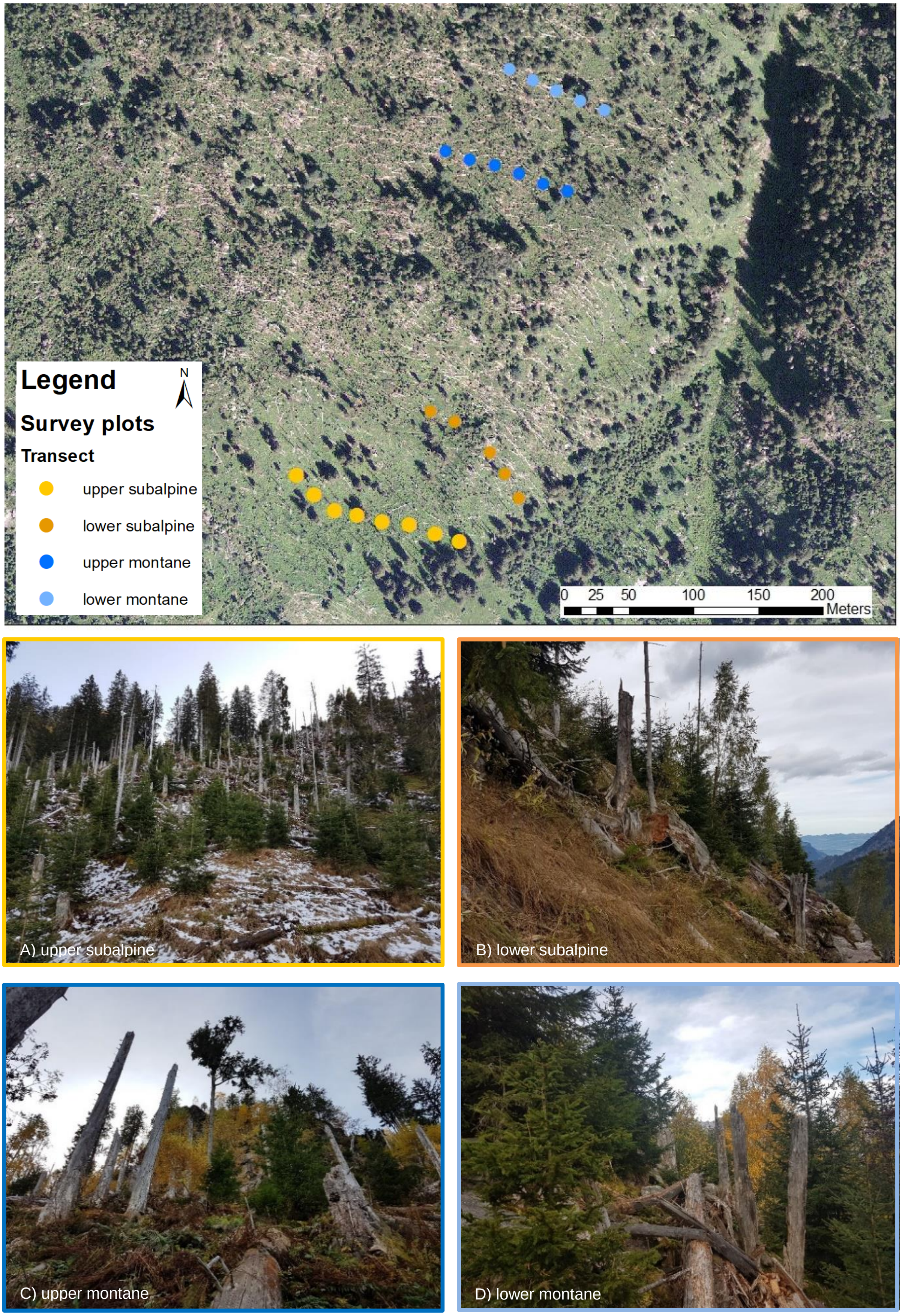

Figure 4: The map on top shows the location of the 24 survey plots, of which 13 are located in the subalpine level and 11 in the montane level (Swissimage: © swisstopo, 2016). The colours of the plots are the same as the frames of the corresponding picture: A) upper subalpine transect, facing south (yellow), B) lower subalpine transect, facing west (orange), C) upper montane transect, facing south (dark blue), D) lower montane transect, facing west (light blue).

3.1.2 Sampling Method

The field campaign took place in October 2020, on 14 days in total. The protocol used for data collection (see protocol in appendix B.1) was derived from a bachelor thesis, which evaluated the avalanche protection and forest development on a Vivian site in Disentis (Marty, 2019). Most variables were assessed within a plot with a 5m radius. Deadwood was an exception because there were not always enough deadwood elements located within a plot (see below). Data on the following variables was collected in each of the 24 plots:

- **Surface cover:** percentage of vegetation, deadwood and crown cover and gap dimensions
- **Deadwood**: composition, height, diameter, decay stage and movability
- **Regeneration on deadwood**: species, number and height of the tallest element
- **Seedlings and saplings**: density, species, height, diameter at breast height (dbh), browsing, other damages, severity of damages and growing on deadwood

In every plot the surface cover by ground vegetation, deadwood and tree crowns was estimated by eye. The three main types of ground vegetation were identified, in order to compare them to past studies. The observed types were (examples in brackets): moss (*Polytrichum formosum*), ferns (*Dryopteris* sp.), grass (*Calamagrostis villosa*), dwarf shrubs (*Vaccinum myrtillis*), tall forb (*Senecio vulgaris*), raspberries (*Rubus idaeus*) and no vegetation (deadwood, soil, rocks). Vegetation cover could exceed 100%, if for example a moss layer was covered by ferns. For the deadwood cover it was estimated how many percent were standing, hanging or lying. Root plates were counted as lying deadwood. Standing, hanging and lying elements were assigned to the height classes: <50cm, 50-100cm, 100-150cm, 150-200cm, and >200cm. For the estimation of crown cover only trees taller than 1.3m were included. If a plot was intersected by a gap, its length and width was measured using a measuring tape. A gap was defined as being longer than 10m, wider than 5m and as neither having elements taller than 50cm, nor trees with a dbh above 8cm (Marty, 2019).

In every plot the highest deadwood element, as well as the three logs and the three standing deadwood elements, which were closest to the plot centre, were identified and measured (figure 5). This resulted in a total of seven deadwood elements per plot and 168 elements in total. The highest element could either be a log, a standing deadwood element or a root plate. Logs were further split up into lying (more than half of the stem touching the ground) or hanging (less than half of the stem touching the ground). There were not always three logs and standing deadwood elements within a 5m radius; thus, they were measured within a maximal distance of 12m. The horizontal distance from the plot centre to each of the seven deadwood elements was obtained using a laser distance meter (Leica DISTOTM X310) or a measuring tape. For every plot the height of the highest element and the six other deadwood elements was measured using a folding meter for small objects and a Vertex (Haglöf Vertex III) for tall objects. The height and diameter of logs was assessed at the closest point to the plot centre. All measurements were done uphill of the object. For standing elements the dbh was measured at 1.3m, e.g. diameter at breast height (dbh). If stems were broken lower than 1.3m, the diameter was measured just beneath the fracture. The diameter was measured with a sliding calliper. The volume of standing deadwood elements was calculated using the formulas given by Landolt (2001) and the “K-tree method” (Kupferschmid & Gmür, 2020).

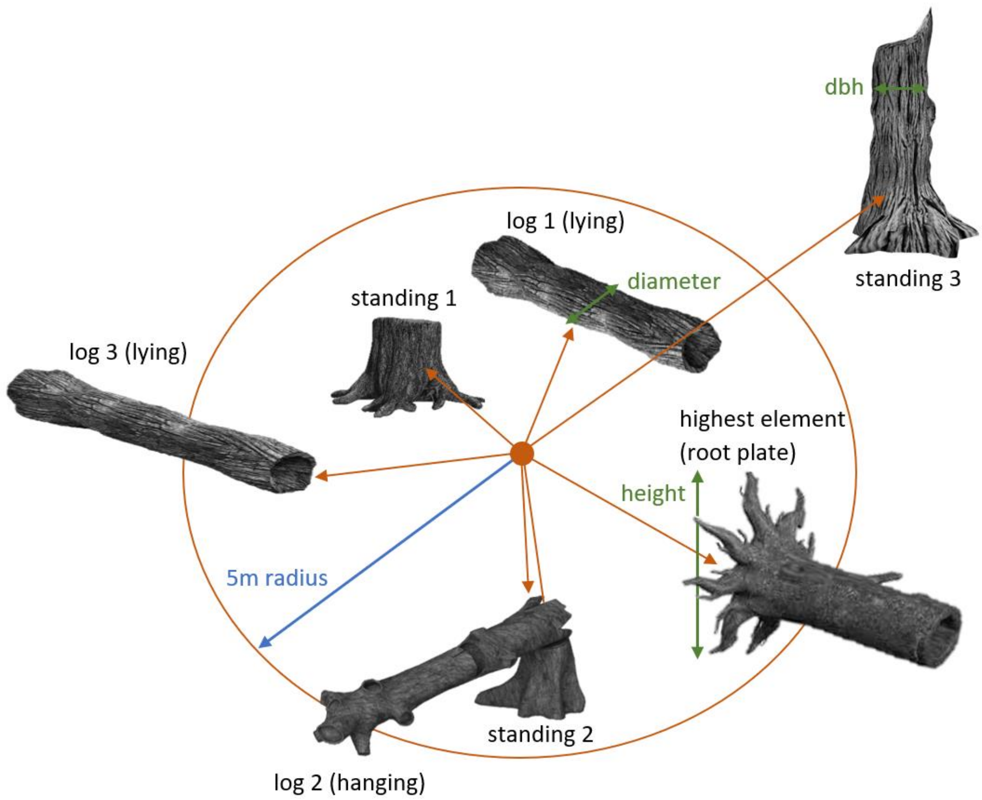

Figure 5: Illustration of the sampling method for standing, hanging and lying deadwood elements as well as for root plates.

The stage of decay was assessed at the closest point of the object to the plot centre, as well as next to seedlings, if present. The same method was used to determine the stage of decay as in other studies (Lachat et al., 2019). Five stages of decay were distinguished depending on how far a knife penetrated the wood (figure 6). Lastly, the movability of logs and stems was tested, by trying to roll or push over the deadwood elements by hand, as an indicator if they could be moved by avalanches.

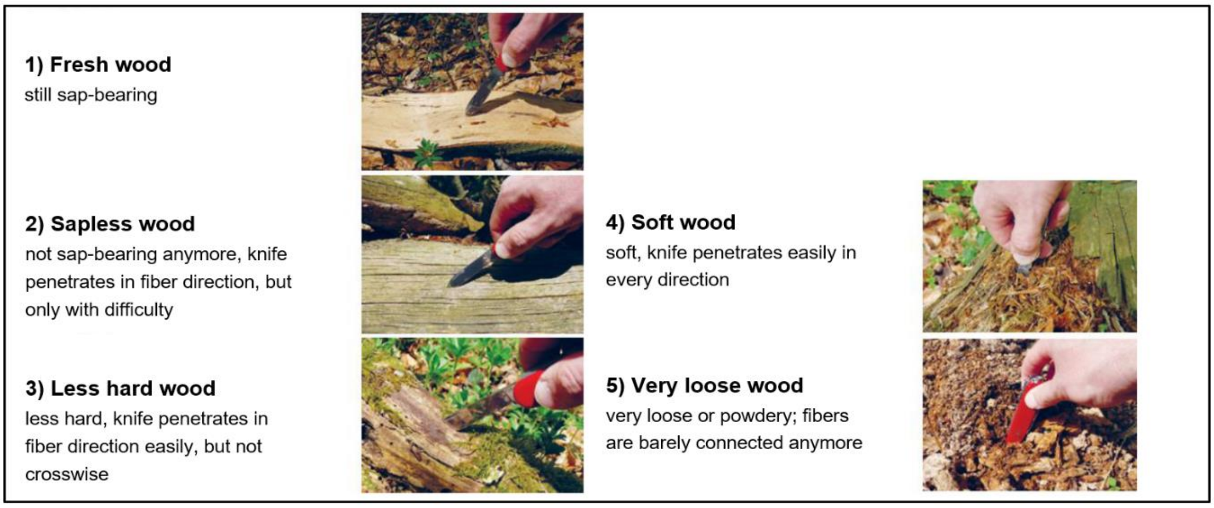

Figure 6: Method used to estimate the stage of decay of deadwood (translated from Lachat et al. (2019)).

The deadwood regeneration on each of the seven deadwood elements was identified and counted, in order to decide if deadwood had become a suitable growing substrate in the years after the disturbances. For each of the occurring species the height of the tallest regeneration was measured using a folding meter. All seedlings on a log were counted, even if most of its length was outside of the 5m radius. For deadwood regeneration it was not differentiated between hight classes and all individuals were counted, independent of their size.

The trees were split into two groups; seedlings taller than 0.2m but smaller than 1.3m and saplings taller than 1.3m. For both groups the height was measured using a folding meter or a Vertex (Haglöf Vertex III). The diameter was only measured for saplings. It was noted if trees were browsed or not. For browsing it was differentiated between not browsed (none), browsing on lateral shoots (L), browsing on lateral and terminal shoots (TL), or browsing on terminal shoots (T). As only very few individuals showed browsing on terminal shoots (T), the category was grouped with TL resulting in the new category TTL. For convenience, TTL will be described as having been browsed on the lateral and terminal shoots. If a tree had other damages such as for example galls, broken branches or snow fungi this was also noted. The severity of the damage was classified using the following categories: 1 = damage on 1/3rd of the tree (small), 2 = damage on 2/3rd of the tree (medium), 3 = whole tree damaged (severe), or 4 = tree dead (dead). If it was clearly visible that trees had grown on deadwood this was noted.

3.1.3 Data Analysis of Field Data

The statistical analysis of the data was performed using Excel (version 2008) and R Studio (version 4.0.2), including the following extensions: tidyverse (version 1.3.0), psych (version 2.0.9), dplyr (version 1.0.2), tidyr (version 1.1.2), reshape (version 0.8.8), emmeans (version 1.5.2-1) and stargazer (version 5.2.2.). Descriptive data were generated for all variables. Shapiro tests were used to evaluate if the data had a normal distribution (shapiro.test function). Most data did not have a normal distribution or values were not metrical. Thus, nonparametric two-sided tests were used for data analysis, such as the Wilcoxon rank-sum test (wilcox.test function), or the Kruskal–Wallis test (kruskal.test function) for tests with more than two variables. If the Kruskal–Wallis test detected a difference between groups, it was determined between which pairs this difference occurred using the Benjamini–Hochberg method (pairwise.wilcox.test function). The used adjustment method was the Bonferroni correction. If no analysis of variance was possible, a Chi-square test (chisqu.test function) accompanied by a Fisher`s exact test (fisher.test function) was used, to generate exact p-values. However, the small sample size of some variables in the dataset meant that it was not always possible to generate a reliable p-value. For some metric variables regression analyses were conducted using the lm function in R Studio. P-values higher than 0.05 were regarded as not being statistically significant. P-values smaller than 0.05 were regarded as showing a trend (*), values smaller than 0.01 (**) as significant and values smaller than 0.001 as highly significant (***).

3.2 Remote Sensing and Avalanche Hazard

3.2.1 Avalanche Protection Forest

A useful remote sensing tool to evaluate the structure and protective function of a forest is an orthophoto. An orthophoto is an aerial photograph or satellite image, which has been geometrically corrected with a digital elevation model (DEM) to create an accurate representation of the Earth's surface and a uniform scale, which allows measurements of true distances between objects, unlike aerial photographs which have not been corrected for topographic relief, lens distortion, or camera tilt (United States Geological Survey, 2021). For this study orthophotos by swisstopo were used. The black and white orthophotos from 1985 and 1997 have a resolution of 0.5m and ones from 2016 and 2020 have a resolution of 0.25m.

Another useful tool to get a better understanding of the forest structure are canopy height models (CHM), also called vegetation height models (VHM). A CHM/VHM is created by subtracting a digital terrain model (DTM) from a digital surface model (DSM) (left side of figure 7, Meddens et al., 2018). The CHMs which were used in this study were created by Mauro Marty and Christian Ginzler and have a resolution of 0.5m (Ginzler et al., 2020).

The final tool used to evaluate the protective function of the Gandberg forest was a GIS code developed at the WSL Institute for Snow and Avalanche Research (SLF), as described by Bebi et al. (2020) and Bühler et al. (2020). It automatically delineates protection forests for frequent avalanches with a return period of 30 years ("30y scenario") and infrequent extreme avalanches with a return period of 300 years ("300y scenario"). The tool is based on a logistic regression model, which uses the slope angle, crown cover and gap widths as input parameters (right side of figure 7). To account for the fact that only trees taller than a certain height are effective in protecting against avalanches, a forest cover map and gap threshold are also part of the model. Using all those input parameters the tool calculates an avalanche disposition between 0-100%. Furthermore, the tool assigns 10% higher values to areas with considerable terrain roughness and 10% lower values to areas covered by shrubs. Finally, this protection forest index is compared to an iteratively validated threshold for both scenarios, which finally leads to an avalanche protection forest layer (Bebi et al., 2020; Bühler et al., 2020).

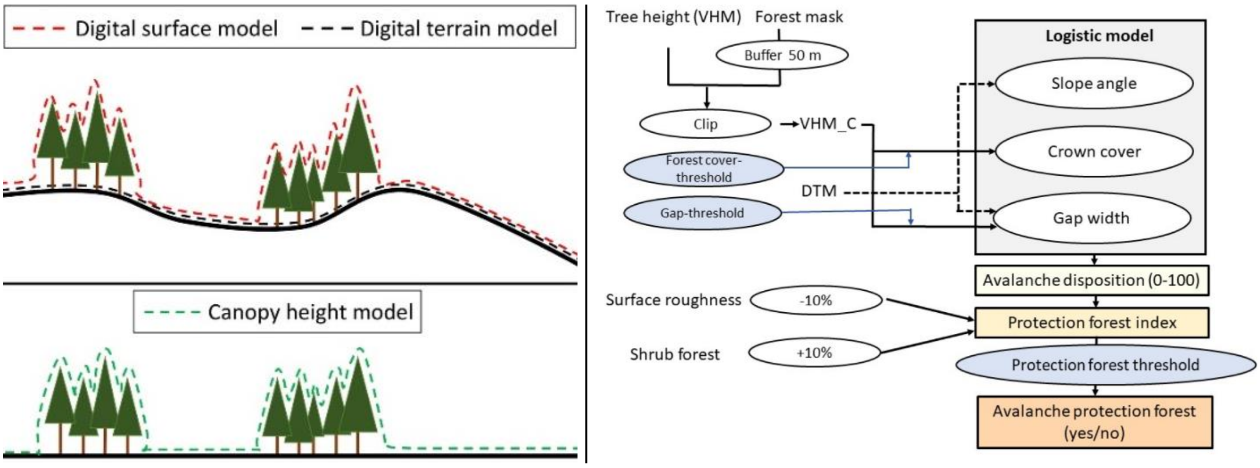

Figure 7: Left: Canopy height models are calculated by subtracting a digital terrain model from a digital surface model (Meddens et al., 2018). Right: Schematic structure of the model developed by Bebi et al. (2020). The core of the model, which calculates the disposition for avalanches, is a logistic model based on input data such as: 1) a vegetation height model (VHM) 2) a terrain model (DTM), 3) a forest mask, 4) a shrub layer and 5) a roughness layer (Bebi et al., 2020).

3.2.2 **Potential Avalanche Release Areas**

If no dense forest is present, avalanches can start in slopes with certain topographic characteristics, as described for example by Maggoni et al (2003). Avalanches occur generally only on slopes with angles between 28° and 50°, because below 28° the gravitational force along the slope is not strong enough to initiate an avalanche and above 50° snow does not accumulate because it slides off continuously (Burkard & Salm, 1992; Maggioni & Gruber, 2003). Other important parameters to define potential avalanche release areas (PRAs) are the curvature and aspect of the terrain. PRAs are often delineated from each other by changes from concave to convex terrain, or by changes in aspect of more than 45° (Maggioni & Gruber, 2003).

For the PRAs in this study, six scenarios were analysed: avalanches with a return period of 30 or 300 years, for the forest before Vivian (1985), after the bark beetle infestations (1996) and recently (2016). Those exact years were chosen because for those years CHMs from Gandberg were available. First, all PRAs were drawn with the help of a slope map and CHMs. For the frequent scenario (return period of 30 years) smaller avalanche areas were drawn, whereas for the infrequent extreme scenario (return period of 300 years) it is likely that some of those small avalanches go off together and that flatter areas are also affected (Margreth, 2021). Therefore, the PRAs for the 300y scenario were drawn larger and sometimes spanned over several PRAs of the 30y scenario. After drawing a first draft of possible PRAs an expert was consulted in order to refine them (Margreth, 2021).

Further refinements were done with the help of the protection forest layer. Compared with the potential avalanche release areas, which are purely defined with the help of the slope and a CHM, the protective forest layer gives a more in-depth view on which parts of the forest actually protect against frequent or extreme avalanches, because it also accounts for parameters such as surface roughness. In a last step the PRAs were therefore adapted to the protection forest layer. Mostly this meant decreasing the size of the previously drawn PRAs where the protective forest layer indicated that the forest offered sufficient protection.

3.2.3 Snow Height Analysis

The intensity of avalanches is determined by the snow volume, the topography and the friction (Margreth et al., 2008). The volume of an avalanche is the product of release area and snow height. To calculate the avalanche volume the cumulative snow height, which falls over a period of three days (“3-day cumulative snow height”), is commonly used (Burkard & Salm, 1992; Margreth et al., 2008). To calculate the extreme value statistics, data from the meteorological station in Braunwald was used. The station is located around 11 kilometres to the southwest of Gandberg at an elevation of 1340m.a.s.l. The observations of the meteorological station Braunwald spanned over 66 years, from 1953 to 2018. A Gumbel distribution was fitted to those observations using an online tool for the determination of extreme values called EVA+ (see Gumble diagrams in appendix B.2). At the station in Braunwald, the values for the 3-day cumulative snow height were 122.3cm for the scenario with return period of 30 years, 144.1cm for 100 years and 163.8cm for 300 years. In this study the snow heights for avalanches with a return period of 30 years and 300 years were used. Several steps are necessary to convert the values from the Gumbel diagram of the meteorological station in Braunwald to values applicable to the study area. Below an overview over the different steps is given. For specific details and formulas see Burkart & Salm (1992).

The values from the Gumble diagrams are only valid for the elevation of the corresponding meteorological station. Thus, the first step is to correct them for the elevation of the PRAs on Gandberg. To simplify the calculations, the snow height was not calculated for every release area separately. Instead, the median heights of all subalpine PRAs and all montane PRAs were used. This median height was 1355m.a.s.l. in the montane and 1565m.a.s.l. in the subalpine level. For every 100m of difference in elevation, between the meteorological station and the elevational level, 5cm of snow height was added to the original value.

The snow height accumulations at the meteorological station are measured on horizontal fields. However, for avalanche calculations values perpendicular to the slope are relevant. Since avalanches can occur on slopes with angles between 28-50 degrees, the second step is to calculate a base value for slopes of an 28° angle, assuming that the same amount of snow can accumulate there as on horizontal terrain. This was done for both elevational levels and return periods. Furthermore, wind can transport snow and substantially add to the snow depth on the lee side of wind exposed areas. On Gandberg this effect was suspected to only occur in the subalpine level. In a third step a snow-drift factor of 20cm for the 300y scenario and 10cm for the 30y scenario was added (Margreth, 2021).

Depending on the inclination of the study area, the snowpack strength can vary. In steep terrain not all the new snow can accumulate, because it continuously slides off. As Gumbel diagrams generally apply to plains, their values were adjusted to the average slope of montane (41°) and subalpine (39°) PRAs, using correction factors, which can be calculated by a formula (see Burkart & Salm, 1992). Finally, the correction factors were multiplied with the snow heights of the subalpine and montane levels for both return periods, resulting in the final estimates of the snow heights for Gandberg.

3.2.4 RAMMS Simulations

RAMMS (Rapid Mass Movements Simulation) is a two-dimensional, numerical model which can simulate geophysical mass movements, such as for example snow avalanches or rockslides. It is used to predict the speed and reach of hazardous movements in complex terrain from initiation to runout (Bartelt et al., 2017). For this study the RAMMS version 1.7.20 was used.

RAMMS requires an accurate digital representation of the terrain. For this study the DTM Swissalti3D from the year 2019, with a resolution of 0.5m, was chosen and resampled to a resolution of 1m in RAMMS. Other initial conditions that must be defined in advance are the location and size of the release mass and friction parameters (Bartelt et al., 2017). Friction parameters depend on the terrain (e.g. roughness, vegetation) and material (snow and ice content). They may be kept constant or calculated by an automatic procedure in RAMMS. The automatic procedure is based on 1) topographic data (slope angle, altitude and curvature), 2) forest information and 3) global parameters (return period and avalanche volume). As explained by Bartelt et al. (2017), the output of this automatic procedure are the μ = "Mu" and ξ = "Xi" variables, that are needed in the Voellmy friction law, which is at the heart of the RAMMS simulations. The friction coefficients are responsible for the behaviour of the flow of an avalanche. The variable Mu dominates when the flow is close to stopping and Xi dominates when the flow is running quickly. In addition to the terrain the occurrence of forest is an important determinant for friction values. Forest information was implemented in the form of a separate forest layer for each scenario. The forest polygons were drawn in GIS, based on the protection forest layer and the orthophoto of the corresponding year. Typical friction parameters for forests are Mu = 0.02 and Xi = 400 (Bartelt et al., 2017).

Another possibility to include roughness into RAMMS simulations is to draw MuXi polygons externally, load them into RAMMS and assign friction parameters manually. This method was chosen for areas where there was no forest but visible deadwood elements on the orthophoto. For areas with deadwood, similar friction parameters as for forested areas were chosen, but with values a bit closer to flat (e.g. smoother) areas; Mu = 0.08 and Xi = 800.

Next to the friction parameters Mu and Xi, cohesion also plays an important role in the Voellmy friction law (Bartelt et al., 2017). Generally, larger values are chosen for wet snow avalanches and smaller values for dry snow avalanches. Since on Gandberg dry snow avalanches should be of main interest, a cohesion factor of 50Pa was chosen, based on an expert suggestion (Margreth, 2021). For all other input variables, the standard RAMMS parameters were used (Bartelt et al., 2017).

4 Results

4.1 Field Survey

4.1.1 Surface Cover

The bark beetle stands on Gandberg were characterized by 115% vegetation cover, 25% deadwood cover and 10% crown cover, in the year 2020 (e.g. 23-28 years after the die-back caused by bark beetles). The montane and subalpine levels were similar in terms of vegetation and deadwood cover, only the percentage of crown cover was lower at the subalpine level (figure 8). The median of the vegetation cover was 100% in the montane and 120% in the subalpine level. The median of the deadwood cover was 25% in the montane and 20% in the subalpine level. Neither of those differences between elevational levels was significant (Wilcoxon test, $p > 0.05$). However, the Wilcoxon test revealed a trend towards a smaller crown cover in the subalpine level compared to the montane level (p-value < 0.05). The median of the crown cover was 10% in the subalpine level and 30% in the montane level.

There were more gaps in the subalpine level. Out of the total 24 plots, 13 were intersected by a gap (54%), but only four of those gaps were located in the montane level, the rest in the subalpine level. Gap lengths varied between 20-100m and gap widths between 5-20m (see picture in appendix C.1).

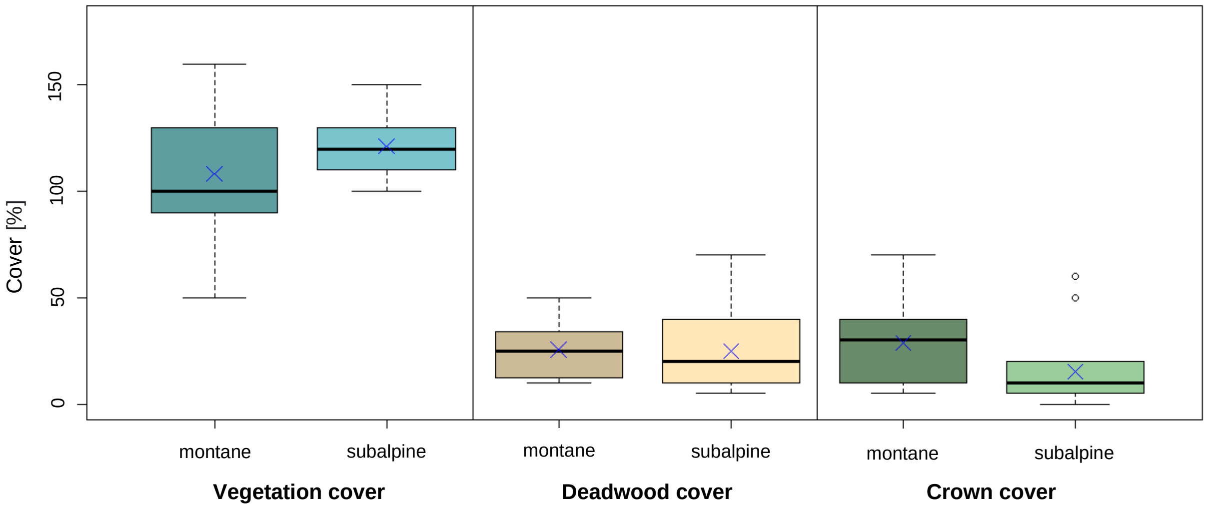

Figure 8: Boxplots of the vegetation cover (left), deadwood cover (middle) and crown cover (right) for the montane level (11 survey plots) and the subalpine level (13 survey plots). All boxplots in this study are the standard boxplots of the R version 4.0.2. The horizontal line in the boxplot indicates the median, the blue cross the mean, the box width reflects the sample size, the length of the box the interquartile range and the points the outliers.

Composition of vegetation cover

The most frequent vegetation types differed between the montane and subalpine level (figure 9). The most common vegetation type in the montane level was fern, followed by grass, raspberry (*Rubus idaeus*) and a very small amount of tall forb. In the subalpine level grass dominated the ground vegetation, followed by fern and dwarf shrubs. No raspberry was found in the subalpine level and no dwarf shrubs in the montane level. Tall shrubs were not among the three most common vegetation types. In total there were 34 holder, two hazel and one honeysuckle shrub within the 24 plots. All but three holder shrubs, were located in the montane level.

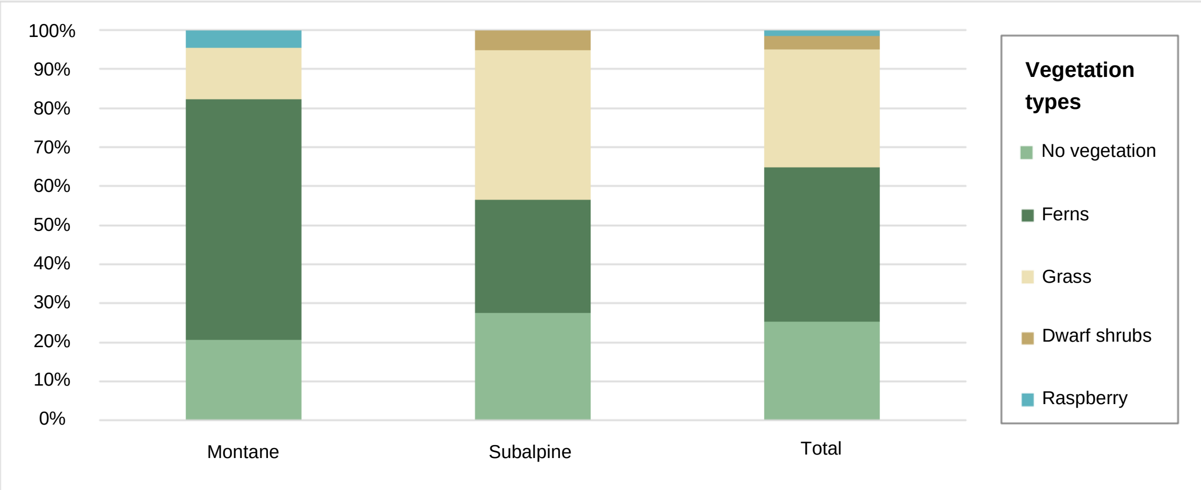

Figure 9: Relative percentage of the different types of vegetation cover for the montane and subalpine level, as well as for the whole study area (total).

Deadwood cover types

Lying deadwood was the most frequent type of deadwood in the study area, hanging and standing elements were rarer (table 1, also see pictures in appendix C.1). In the montane level the deadwood was composed of 79.5% lying, 9.5% hanging and 11.0% standing deadwood. In the subalpine level lying deadwood accounted for 84.9%, hanging deadwood for 3.2% and standing for 11.9%. However, there was no difference in the composition of deadwood between elevational levels, if the large standard errors are considered.

Table 1: Mean and standard deviation of the percentage of the three different deadwood types for the study area (total) and the two elevational levels.

	Lying [%]	Hanging [%]	Standing [%]
Montane	79.5 ± 16.98	9.5 ± 14.91	11.0 ± 6.86
Subalpine	84.9 ± 16.41	3.2 ± 6.59	11.9 ± 14.80
Total	**82.4 ± 16.54**	**6.1 ± 11.40**	**11.5 ± 11.61**

The three deadwood types were made up by different height classes (figure 10). Most of the lying deadwood elements belonged to the two smallest height classes (< 50 cm or 50-100cm). The only exception was one root plate in the upper subalpine transect, which had a height between 150 and 200cm. Hanging deadwood was mainly found in the second and third height classes and seemed to be more prominent in the montane level. Standing deadwood was found in all height classes. In the montane level many standing deadwood elements had heights between 50-100cm or >200cm, whereas in the subalpine level most standing deadwood belonged to the highest category, being taller than 200cm.

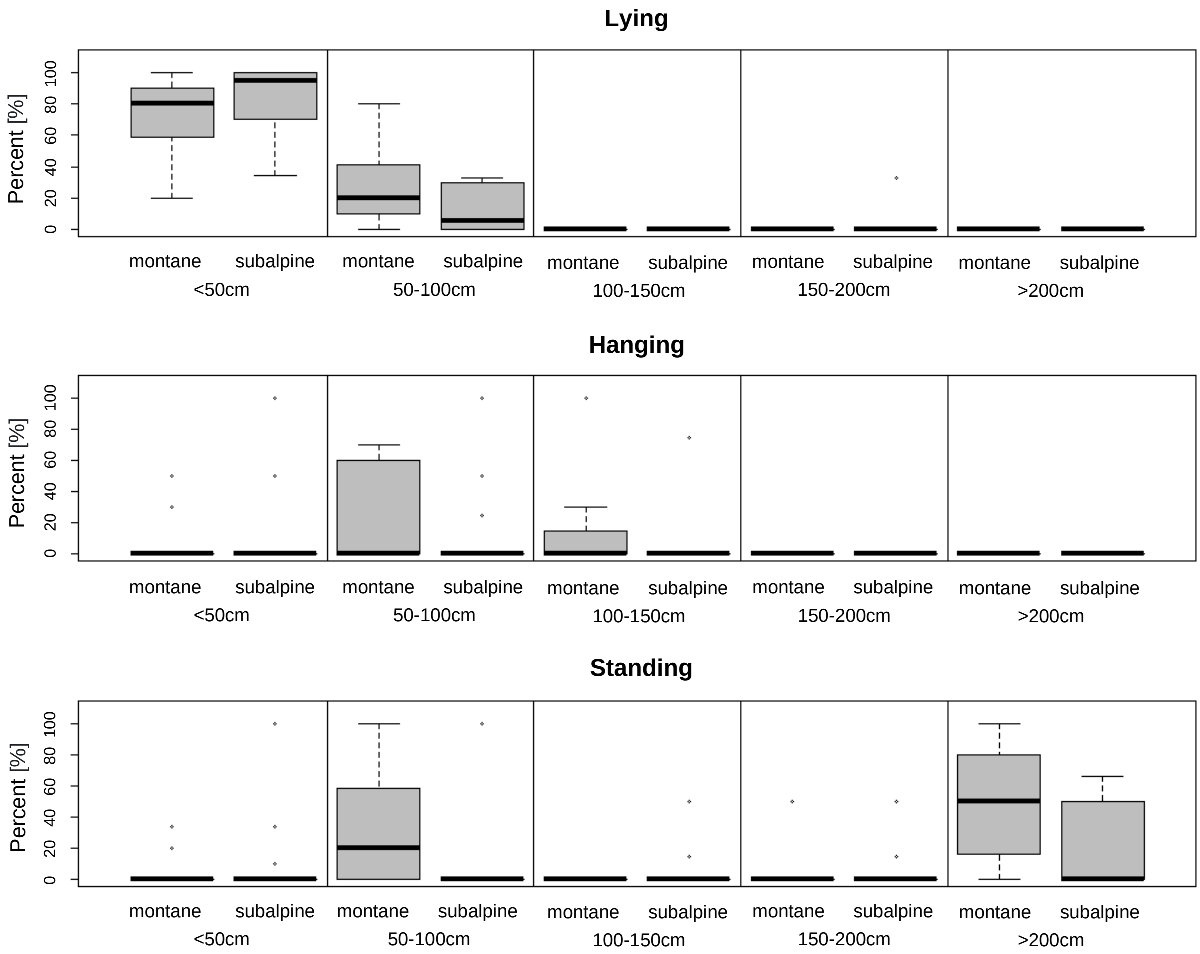

Figure 10: Estimation of the heights of all three deadwood types in the montane and subalpine level.

4.1.2 Deadwoood

The highest element per plot was most often a standing element, but also lying logs, root plates and hanging logs were found to be the highest element within some plots (table 2). In the montane level 91% percent of the highest elements were standing elements. Only 46% of the highest elements were standing elements in the subalpine level, another 23% were lying elements and 23% were root plates. Interestingly, root plates were only found in the subalpine level (n=4). The differences in the composition of the highest element were not significant between the two elevational levels (Chi-square test, $X^2 = 3.8754$, df = 3, p-value > 0.05), due to the few plots (n=24).

Table 2: Composition of the highest elements (n=24) for both elevational levels, as well as the whole study area.

	Standing [%]	Lying [%]	Hanging [%]	Root plate [%]
Montane	90.9	9.1	0.0	0.0
Subalpine	46.2	23.1	7.6	23.1
Total	**66.7**	**16.6**	**4.2**	**12.5**

Most logs were lying, with only 15.2% hanging in the montane level and 11.9% in the subalpine level (table 3). This was not a significant difference (Chi-squared test, $X^2 = 0.00032$, df = 1, p-value > 0.05).

Table 3: Percentage of the three closest logs in the category 'hanging' or 'lying' for each elevational level, as well as for the whole study area.

	Lying [%]	Hanging [%]
Montane	84.8	15.2
Subalpine	88.1	11.9
Total	**86.8**	**13.2**

The median height of the highest elements was 238cm and did not differ significantly between the two elevational levels (Wilcoxon test, p-value > 0.05). However, it is still interesting to note that the median of the height of the highest deadwood elements was 250cm in the montane level and 160cm in the subalpine level (figure 11). In the montane level values ranged from 60cm up to 11m. In the subalpine level values had a lower variability and ranged from 40cm to 8m.

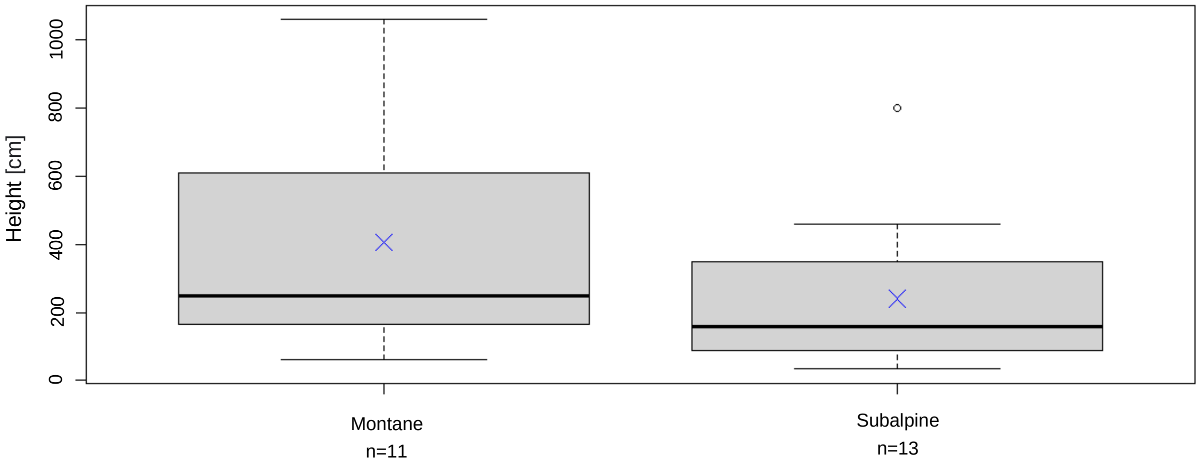

Figure 11: Heights of the highest elements in the montane (left) and subalpine (right) level.

When heights of the same deadwood type were compared between elevational levels, none of the differences were significant (Wilcoxon tests, p-value > 0.05). The median height of standing elements in the montane level was 135cm and therefore similar to the 160cm in the subalpine level. For hanging elements, the median was 44cm in the montane level and 45cm in the subalpine level. For lying elements, the median was 30cm in the montane level and 27cm in the subalpine level (figure 12).

If the deadwood types were compared the difference in height was highly significant (Kruskal-Wallis test, p-value < 0.001). The medium height of standing elements was 140cm, hanging elements were 45cm tall and lying elements 28cm. A follow-up pairwise Wilcoxon test showed a significant difference between the heights of standing and hanging deadwood (p-value < 0.01) and a highly significant difference between standing and lying deadwood (p-value < 0.001) but no difference between hanging and lying elements (p-value > 0.05).

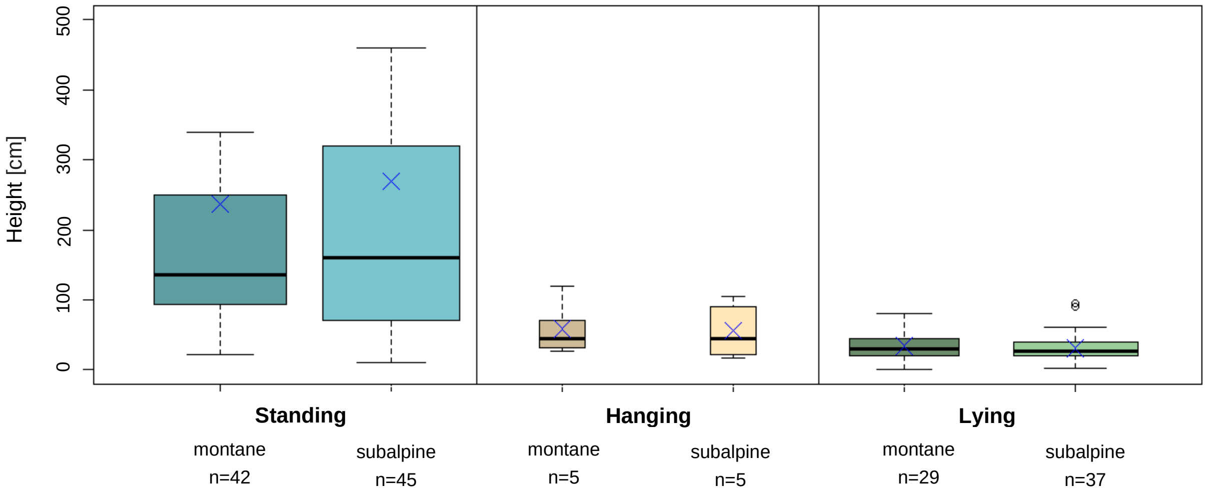

Figure 12: Heights of the different deadwood types. A total of 168 deadwood elements was surveyed, the figure only shows 163 elements, since four root plates were excluded due to their small sample size and because of one NA value for the height. Extreme values

The density of standing deadwood elements was 172 trees/ha in the subalpine level and 392 trees/ha in the montane level. The corresponding volume of standing elements was $37m^3$/ha in the subalpine level and $56m^3$/ha in the montane level.

All decay stages except for fresh deadwood (stage 1) were found on Gandberg. Sapless wood (stage 2) made up 35.4%, less solid wood (stage 3) 36.0%, soft wood (stage 4) 20.7% and very loose wood (stage 5) 7.9%. The more decayed the wood was, the smaller it's heights (Kruskal-Wallis test, p-value < 0.001). Sapless wood had a median height of 100cm, less solid wood 64cm, soft wood 43.5cm and very soft wood 20cm (figure 13). A regression analysis (table 4) showed that there was a significant difference between the height of very loose wood (stage 5) compared to sapless wood (stage 2).

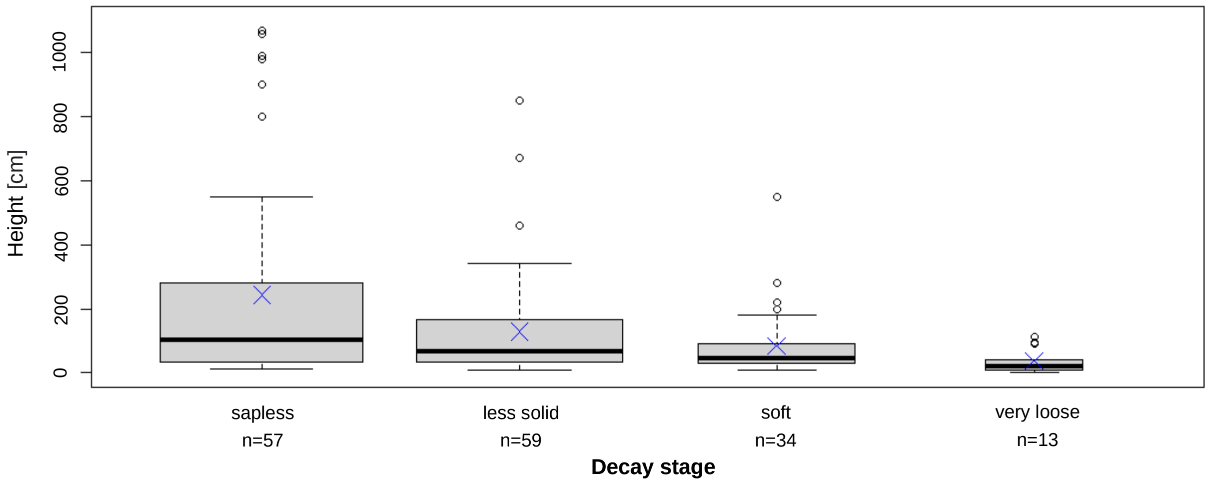

Figure 13: Heights of the deadwood elements according to their stage of decay (excluding root plates as well as one NA value in the height, resulting in n(total)=163). The first stage of decay was not found in the study area and was therefore excluded from this graph. The second stage of decay is sapless wood, followed by less solid, soft and very loose wood. The higher an element the less decayed it tended to be. The figure does not show one element of sapless wood which had a height of 1860cm.

Next to the lower heights of higher decay stages, the regression analysis also revealed smaller heights for hanging and lying elements compared to standing elements (table 4). Furthermore, the regression analysis did not indicate a difference in the deadwood heights between the elevational levels (thus dropped out of the final model in table 4).

Table 4: Regression analysis of log_{10} of the height of deadwood elements (+0.001). The reference type for type is standing and for decay it is sapless. The number of observations is 162 due to exclusion of four root plates as well as one NA value each for height and dbh.

Dependent variable:	log_{10} (height +0.001)		
	Estimate	Sd	Significance
Type: hanging	-0,453	0,125	***
Type: lying	-0,639	0,069	***
Decay: less solid	-0,059	0,071	
Decay: soft	-0,143	0,084	.
Decay: very loose	-0,325	0,124	**
dbh	0,006	0,002	*
Constant	2,019	0,092	***
Observations	162		
R2	0,527		
Adjusted R2	0,509		
Residual Std. Error	0,364 (df = 155)		
F Statistic	28,814*** (df = 6; 155)		

The dbh of deadwood correlated positively with the height of deadwood elements (table 4 and figure 14). The second and third stage of decay tended to have rather small heights, being clustered at heights below 2m (red and orange dots). The heights of less soft elements (yellow dots) went up to 8m but were mostly clustered below 3m. The height of sapless elements (green dots) went up to 10m and even 18m in one case (figure 14).

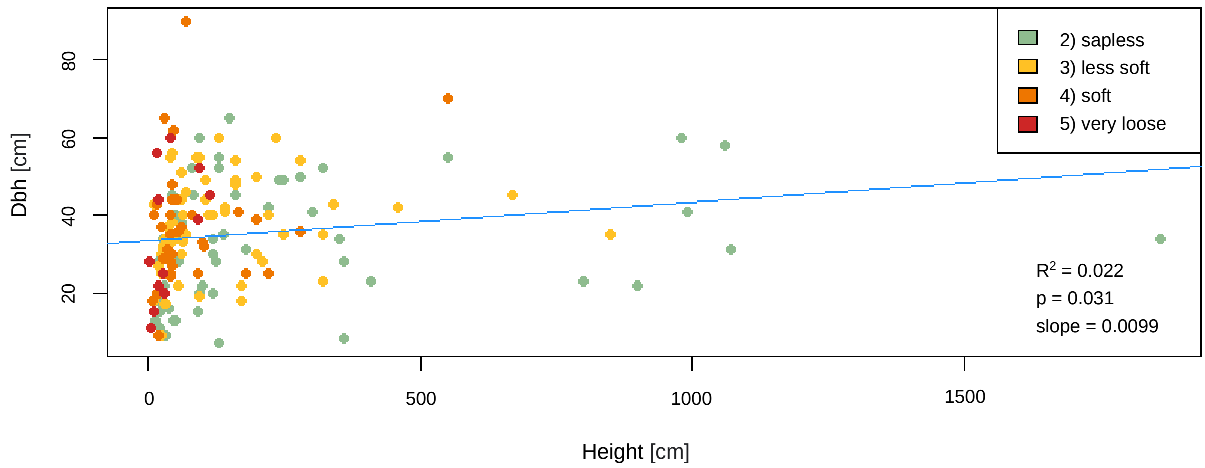

Figure 14: Correlation of dbh and height of deadwood, with colours indicating the different stages of decay.

The median of the dbh of deadwood elements was 34cm (first quartile (q1) = 24.5cm, third quartile (q3) = 44.0cm) and not different between elevational levels (Regression, p-value > 0.05). However, the dbh of the different deadwood types varied significantly (Kruskal-Wallis test, p-value < 0.001). A regression analysis showed that standing elements had a significantly higher dbh than lying and hanging elements (table 5). Standing elements had a median dbh of 40cm, followed by lying elements with 31cm and hanging elements with 20cm (figure 15). A pairwise Wilcoxon test also showed a trend towards a smaller dbh of hanging deadwood compared to standing deadwood (p-value < 0.05), a highly significant difference between the dbh of lying deadwood compared to standing deadwood (p-value < 0.001), as well as no significant difference between lying and hanging elements (p-value > 0.05).

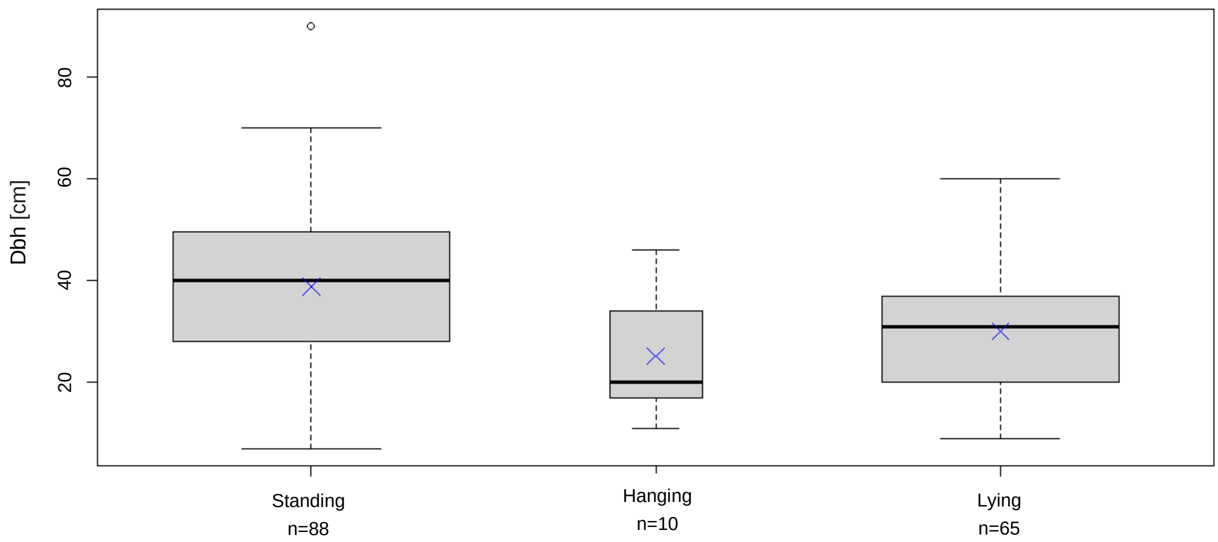

Figure 15: Dbh per deadwood type. The sample size is 163 due to exclusion of four root plates and one NA value for the dbh.

The regression analysis further showed that the dbh of less solid, soft and very loose deadwood was significantly larger than the dbh of less decayed sapless deadwood (table 5).

Table 5: Regression analysis of dbh of deadwood elements. The reference type for type is standing and for decay it is sapless. The sample size is 163 due to exclusion of four root plates and one NA value for dbh.

Dependent variable:	dbh		
	Estimate	Sd	Significance
Type: hanging	-13,301	4,355	**
Type: lying	-10,977	2,291	***
Decay: less solid	7,312	2,458	**
Decay: soft	8,085	2,976	**
Decay: very loose	9,398	4,372	*
Level: subalpine	-3,219	2,086	
Constant	36,377	2,200	***
Observations	163		
R2	0,197		
Adjusted R2	0,166		
Residual Std. Error	13,036 (df = 156)		
F Statistic	6,389*** (df = 6; 156)		

About a sixth off all deadwood elements could be moved by hand, e.g. 25 out of the 168. Neither the elevational level, nor the type of deadwood, the deadwood height, or the stage of decay had a significant influence on the movability of deadwood elements (Wilcoxon test, p-value > 0.05). The only influencing factor was the dbh of the element (Wilcoxon test, p-value < 0.05). The thicker an element, the less likely it was to be moved.

4.1.3 Regeneration on Deadwood

The dominating species growing on deadwood was spruce with 96.7% (n = 117). The only other species growing on deadwood was rowan with 3.3% (n = 4). The four rowan seedlings all grew in the subalpine level and had heights ranging from 2-50cm. The height of the tallest spruce regeneration per deadwood element ranged from 1-50cm (and there was even one element with a height of 2.4m). The median height of the tallest spruce regeneration per deadwood element was 9.5cm (q1 = 2.5cm, q3 = 13.0cm) in the montane level and 8cm (q1 = 3.0cm, q3 = 33.3cm) in the subalpine level. This difference was not significant (Wilcoxon test, p-value < 0.05).

More deadwood regeneration was observed in the subalpine level than in the montane level (table 6, regression analysis, p-value < 0.01). Out of the total 121 objects, 101 grew in the subalpine level (83.5%) and only 20 in the montane level (16.5%). However, in the subalpine level there were 13 plots and 11 in the montane level. Therefore, seedlings per plot is a more useful variable. Dividing the total number of seedlings per elevational level through the number of survey plots per elevational level, results in 7.8 (e.g. 101/13) seedlings per plot in the subalpine level and 1.8 (e.g. 20/11) seedlings per plot in the montane level. Not all deadwood elements showed regeneration. Dividing the numbers calculated above through seven, results in the average number of seedlings per deadwood element, which would be approximately one seedling per deadwood element in the subalpine level and one seedling on every fourth deadwood element in the montane level.

According to the regression analysis, less solid and soft deadwood had significantly more regeneration than less decayed sapless wood (table 6). The trend for very loose wood was not significant. Furthermore, trees that could be moved had less deadwood regeneration. There was no influence of the dbh, the type of deadwood or the height of the elements on the number of seedlings.

Table 6: Regression analysis of the number of seedlings growing on deadwood. The reference type for the decay stage is sapless. The number of observations is 164, due to the exclusion of the four root plates.

	Dependent variable:	Number of deadwood regeneration	
	Estimate	Sd	Significance
Subalpine level	0,600	0,192	**
Movement	-0,715	0,265	**
Decay: less solid	0,626	0,229	**
Decay: soft	1,262	0,252	***
Decay: very loose	0,824	0,421	.
Constant	-3,160	0,204	***
Observations	164		
R2	0,186		
Adjusted R2	0,160		
Residual Std. Error	1,209 (df = 158)		
F Statistic	7,220*** (df = 5; 158)		

In total, 19.5% of all surveyed deadwood elements had deadwood regeneration (32 out of 164). Corresponding to the higher number of seedlings in the subalpine level - as mentioned above - there was also a higher number of deadwood elements harbouring regeneration in the subalpine level. In the montane level only 13% of deadwood elements had deadwood regeneration, whereas in the subalpine level it was 25%. A Wilcoxon test confirmed this trend (p-value < 0.05).

Generally, elements that harboured deadwood regeneration had lower heights than those without regeneration (Wilcoxon test, p-value < 0.05). The median height of deadwood elements that did not have regeneration was 70cm (q1 = 34.8, q3 = 170.0cm), whereas the height of elements with regeneration was 35cm (q1 = 24.5cm, q2 = 82.5cm). Unlike in heights of deadwood elements there were no differences in the dbh of elements with and without deadwood regeneration (Wilcoxon test, p-value > 0.05). The median dbh of deadwood elements that did not have regeneration was 34cm (q1 = 22.0cm, q3 = 44.0cm), whereas the dbh of elements with regeneration was 37cm (q1 = 30.0cm, q3 = 43.3cm). The median of the stage of decay was 3 (less hard) for both deadwood elements with and without regeneration, if measured at the closest point to the plot centre (figure 16, left and middle part). However, the decay directly next to the regeneration was more advanced (median decay stage 4 = soft), as shown in the right side of figure 16 (Wilcoxon test, p-value < 0.05).

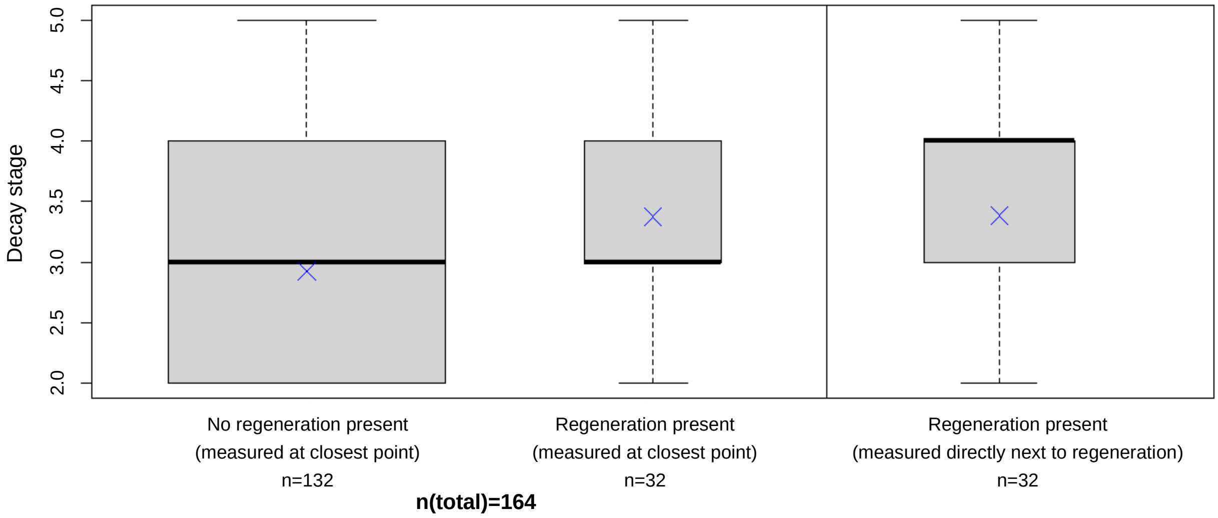

Figure 16: Stage of decay of deadwood elements without regeneration (left) and with regeneration (middle and right). A total of 32 out of 164 deadwood elements harboured regeneration (excluding the four root plates).

4.1.4 Seedlings and Saplings

Density and species

The tree density (seedlings and saplings together) was higher in the montane level (2311 trees/ha) than in the subalpine level (1830 trees/ha). The most common species was spruce, with 1352 trees/ha in the montane level and 1558 trees/ha in the subalpine level (table 7).

Table 7: Density of saplings and seedlings in both elevational levels (excluding one willow sapling).

	Montane		**Subalpine**	
	All species [ha^{-1}]	Spruce [ha^{-1}]	All species [ha^{-1}]	Spruce [ha^{-1}]
Saplings	1231	866	982	918
Seedlings	1080	486	848	640
Total	**2311**	**1352**	**1830**	**1558**

Spruce was the most common species in both elevational levels, accounting for almost 90% of trees in the subalpine level and almost 60% in the montane level (table 8). There was a significantly larger percentage of broadleaved species in the montane level compared to the subalpine level (Chi-square test, $X^2 = 69.37$, df = 4, p-value < 0.001).

Table 8: Percentage of the different tree species, of both seedlings and saplings, in the montane and subalpine level, as well as for the whole study area.

	Subalpine [%]	Montane [%]	**Total [%]**
Spruce	87.7	57.7	**72.6**
Birch	1.5	31.6	**16.7**
Sycamore maple	3.1	5.6	**4.3**
Rowan	7.7	4.6	**6.1**
Willow	0.0	0.5	**0.3**

In the subalpine level (transects US and LS) saplings were mainly composed of spruce, with only a few rowan and birch trees. Seedlings showed a larger amount of sycamore maple and rowan trees, compared to saplings in the subalpine level. In the montane level (transects UM and LM) saplings were still mainly composed of spruce but also showed around 20% birch trees. Seedlings of the montane level showed the highest percentage of broadleaved species, e.g. more than 50% (figure 17). The one willow sapling in the upper montane transect was excluded from further analysis.

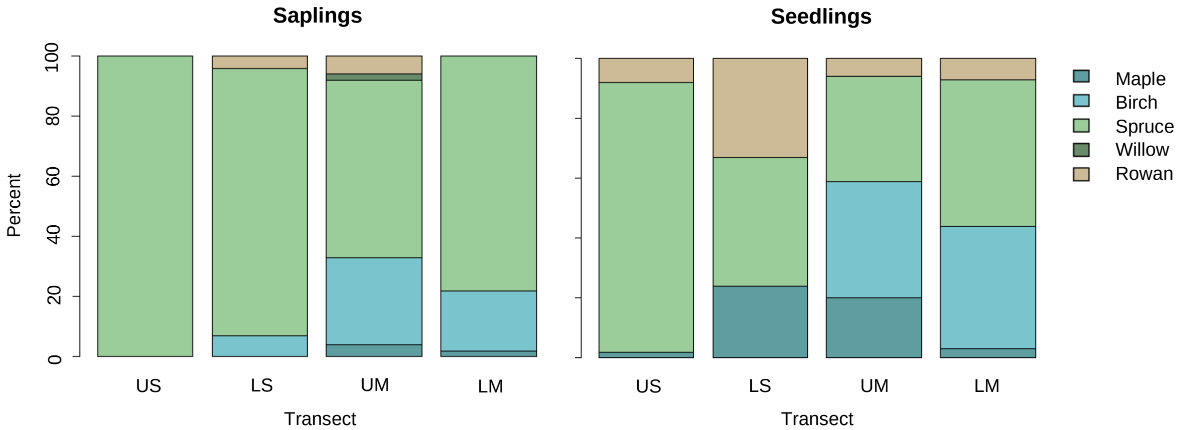

Figure 17: Relative percentage of all tree species of saplings (left) and seedlings (right) in the four transects (subalpine level: US and LS, montane level: UM and LM). The subalpine transects showed a higher percentage of spruce than montane transects. Saplings showed lower percentages of broadleaved species compared to seedlings.

Tree height

For the analysis of height and dbh, three large spruce trees with heights > 10m were excluded, since they were likely remainders from before Vivian. For large trees of the species birch, rowan and sycamore maple it was not possible to tell if they had survived the storm or grew afterwards. They were not excluded from this analysis, to make sure no trees of the secondary regeneration were disregarded. A total of 202 saplings and 184 seedlings were counted. Smaller tree heights were more common than larger ones in both elevational levels, but in general there were more tall trees in the montane level (figure 18).

The height distribution of spruce seedlings was different in the montane and subalpine level. In the montane level there were many seedlings in the smallest height class but a uniform, low amount in the rest of the height classes. In the subalpine level most seedlings were in the lowest height classes and their number decreased mostly gradually afterwards (see graphs in appendix C.2).

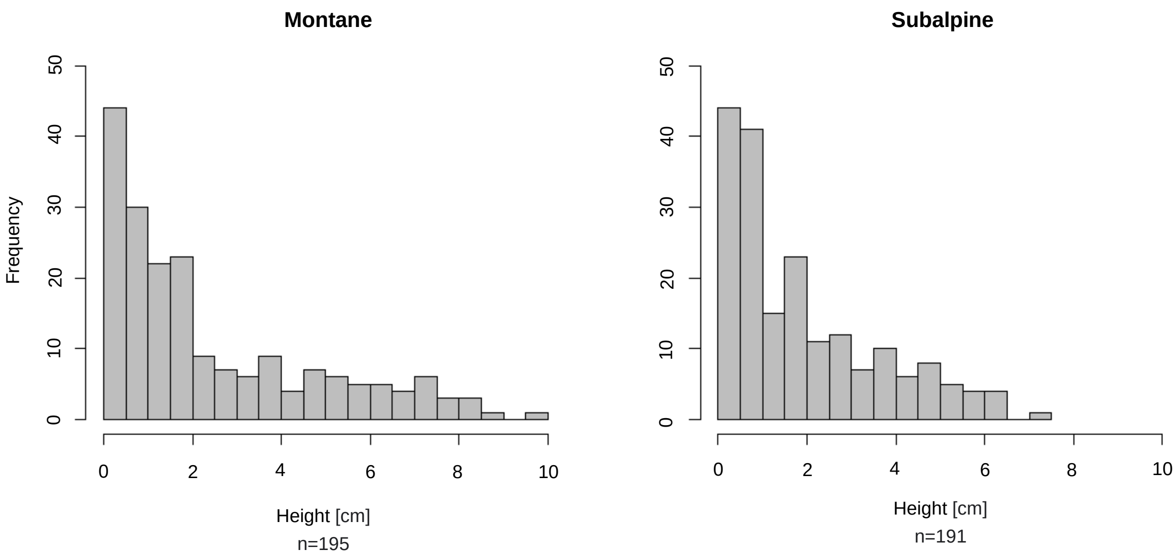

Figure 18: Height distribution of trees (seedlings and saplings) in the montane level (left) and the subalpine level (right).

Saplings of the montane level tended to be taller than those in the subalpine level, but there was no difference between the heights of seedlings (table 9). Saplings had a median height of 3.7m in the montane level and 2.9m in the subalpine level (Wilcoxon test, p-value < 0.05). The difference between levels became significant when only spruce trees were analysed (Wilcoxon test, p-value < 0.01). Seedlings of the montane and subalpine level did not show significant differences in height (Wilcoxon test, p-value > 0.05).

Table 9: Heights of all seedlings (> 0.2m & <1.3m) and saplings (>1.3m), as well as heights for spruce trees separately. The bold values indicate the median, the first quartile (q1) and third quartile (q3) are also given. The p-value was calculated with a Wilcoxon test and compares the montane and subalpine level.

	Montane				**Subalpine**				
	q1 [m]	**median**	q3 [m]	n	q1 [m]	**median**	q3 [m]	n	p-value
Saplings (all)	1.96	**3.70**	5.70	105	1.99	**2.90**	4.20	97	< 0.05*
Saplings (Spruce)	2.10	**3.90**	5.90	73	1.97	**2.90**	4.12	92	< 0.01**
Seedlings (all)	0.37	**0.55**	0.94	90	0.37	**0.54**	0.85	94	> 0.05
Seedlings (Spruce)	0.31	**0.60**	1.02	40	0.4	**0.56**	0.92	75	> 0.05

Sycamore maple saplings showed the largest median height with 5.7m, followed by rowan with 3.7m, spruce with 3.3m and birch with 1.7m (figure 19, left). The tallest spruce saplings were almost 10m tall. The tallest seedlings were birch with a median of 0.59m, closely followed by spruce with 0.56m (figure 19, right). Sycamore maple and rowan seedlings had smaller heights of 0.44m and 0.38m, respectively. For saplings there was no significant difference between the height of the different tree species (Kruskal-Wallis test, p-value > 0.05), due to the very low number of maple and rowan. However, for seedlings there was a significant difference between species (Kruskal-Wallis test, p-value < 0.01). A pairwise Wilcoxon test found a trend towards lower heights of rowan compared to birch seedlings (p-value > 0.05).

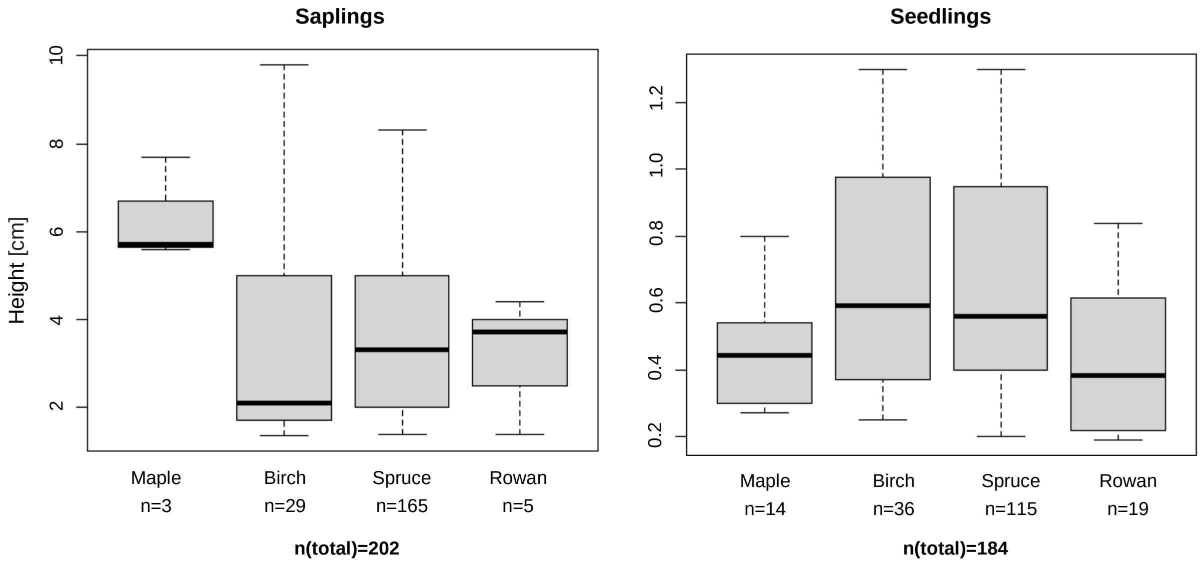

Figure 19: Heights of the different tree species for saplings (left) and seedlings (right). Note: the scale is different on the left and right figure.

Diameter at breast height

Thinner saplings were more frequent, than thicker ones. The dbh ranged from 1-15cm. The median dbh was 5cm (q1 = 2cm, q3 = 9cm) in the montane level and 4cm (q1 = 3cm, q3 = 7cm) in the subalpine level, which was not a significant difference (Wilcoxon test, p-value > 0.05). However, if only spruce trees were analysed, the dbh was 6cm (q1 = 3cm, q3 = 9cm) at the montane level and 4cm (q1 = 3cm, q3 = 6cm) at the subalpine level (Wilcoxon test, p-value < 0.05).

Sycamore maple had the highest dbh of the different tree species with a median of 12cm, followed by spruce with 5cm, rowan with 4cm and birch with 1cm (figure 20). These differences in dbh between species was significant (Kruskal-Wallis test, p-value < 0.01). A pairwise Wilcoxon test found trends towards a smaller dbh of spruce and birch compared to sycamore maple (p-value < 0.05), but no differences between the other species.

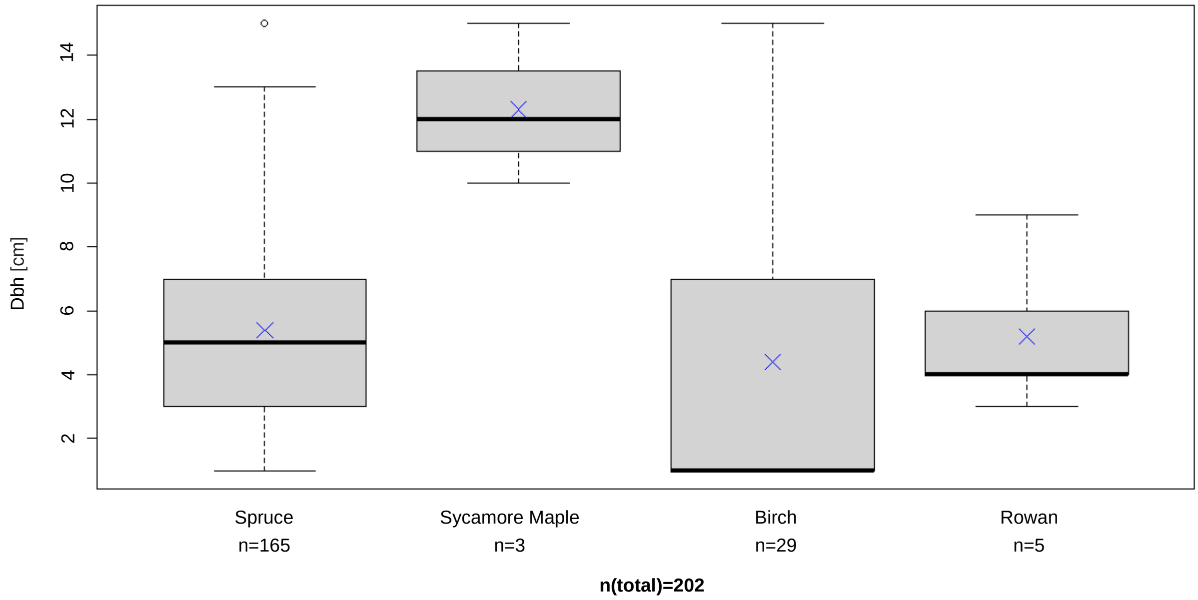

Figure 20: Dbh of the different tree species. Note: sycamore maple and rowan had very small sample sizes.

Browsing on seedlings

The browsing intensity of spruce was 25.0% (sd = 32.8%) in the montane level and 13.3% (sd = 20.2%) in the subalpine level (Wilcoxon test, p-value > 0.05). The other species were not compared between levels due to the small sample size. Different species had different browsing intensities. Sycamore maple had the highest browsing intensity with 85.7%, rowan had the second highest browsing intensity with 63.2%, followed by birch with 30.6% and spruce with 17.4% (sd = 27.6%). Out of the 115 spruce seedlings only 20 were browsed (figure 21). The differences in browsing intensity between the four species were highly significant (Chi-square test, X^2 = 39. 433, df = 3, p-value < 0.001, n = 184).

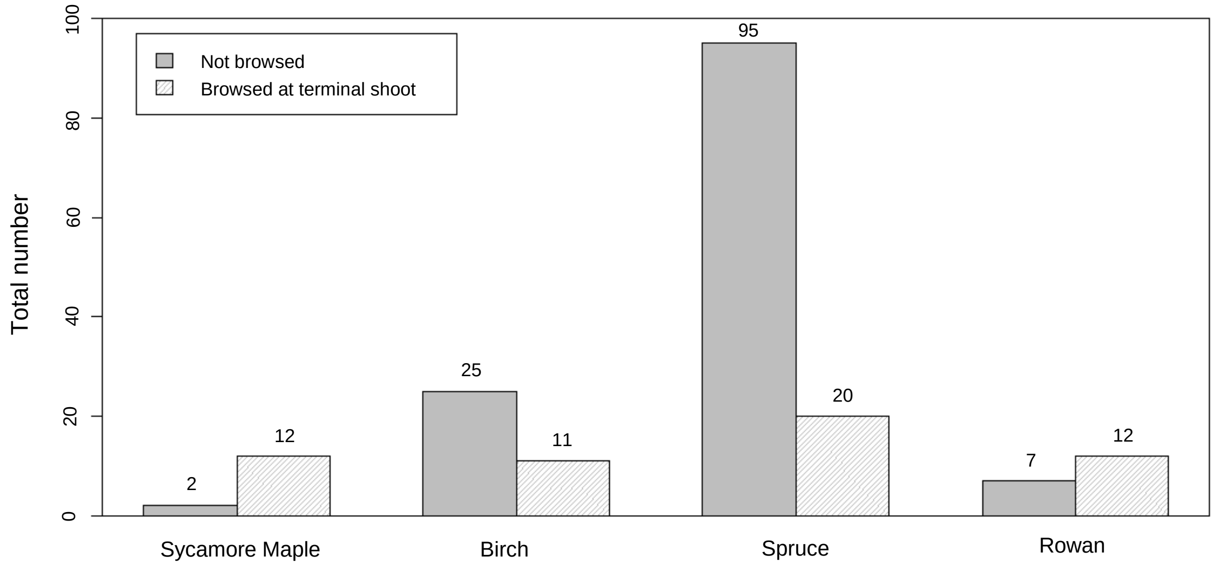

Figure 21: Total number of browsed trees compared to number of un-browsed trees for all tree species.

Damages

The most frequent type of damage observed in the field was galls (see picture in appendix C.1). Damages such as breakage, bent stems and snow fungi were observed occasionally. The percentage of seedlings which had other damages than browsing was lower (43%) than the percentage of damaged saplings (78%). The percentage of saplings, with damages, did not differ between levels, but was slightly higher in the subalpine level (Chi-square test, $X^2 = 0.8044$, df = 1, p-value > 0.05, n = 202). For seedlings the difference between levels was significant, with 28.9% damaged seedlings at the montane and 56.4% at the subalpine level (Chi-square test, $X^2 = 13.086$, df = 1, p-value < 0.001, n = 184).

Furthermore, the severity of all damages (including browsing) was estimated for both seedlings and saplings. Seedlings had a higher share of severely damaged and dead individuals than saplings (table 10). For saplings there was no difference in the severity of damages between elevational levels (Chi-square test, $X^2 = 1.7811$, df = 4, p-value > 0.05). However, the severity of damages on seedlings did differ between levels (Chi-square test, $X^2 = 17.93$, df = 4, p-value < 0.001), with more severe damages and more dead seedlings in the subalpine level than in the montane level (table 10).

Table 10: Severity of damages on seedlings and saplings.

	No Damages [%]	Slight [%]	Medium [%]	Severe [%]	Dead [%]
Saplings montane	15.2	56.2	22.9	5.7	0.0
Saplings subalpine	11.4	57.7	24.7	5.2	1.0
Saplings total	**13.4**	**56.9**	**23.8**	**5.4**	**0.5**
Seedlings montane	31.1	13.4	43.3	12.2	0.0
Seedlings subalpine	17.0	12.8	35.1	24.5	10.6
Seedlings total	**23.9**	**13.0**	**39.1**	**18.6**	**5.4**

Seedlings and saplings on deadwood

The most common seedling species growing on deadwood was spruce. A total of 66.1% of all spruce seedlings grew on deadwood but only 8.3% of birch and 7.1% of maple and 0% of rowan (Chi-square test, $X^2 = 64.151$, df = 3, p-value < 0.001, n = 184). For saplings there were 40.6% of spruce, 13.8% of birch, 0% of maple and 20% of rowan growing on deadwood (Chi-square test, $X^2 = 10.002$, df = 3, p-value < 0.05, n = 202).

There was a highly significant difference in the number of spruce seedlings growing on deadwood between the two elevational levels (Chi-square test, $X^2 = 43.43$, df = 1, p-value < 0.001). In the montane level only 25% of the spruce seedlings grew on deadwood, whereas it was 88% in the subalpine level (table 11). There were also more saplings growing on deadwood in the subalpine level with 58.7%, compared to the montane level with 17.8% (Chi-square test, $X^2 = 26.545$, df = 1, p-value < 0.001)

Table 11: Percentage of spruce seedlings and saplings growing on deadwood per elevational level.

	Deadwood [%]	Other substrate [%]
Montane spruce seedlings	25.0	75.0
Subalpine spruce seedlings	88.0	12.0
Total seedlings	**66.1**	**33.9**
Montane spruce saplings	17.8	82.2
Subalpine spruce saplings	58.7	41.3
Total saplings	**40.6**	**59.4**

4.2 Remote Sensing and Avalanche Hazard

4.2.1 Avalanche Protection Forest

Tree densities of living trees and the heights of standing deadwood decreased after the disturbances and therefore the protective function of the forest decreased as well (figure 22). In the year 1985, before the disturbances, the forest was very dense, and many trees had heights of more than 20m. This is visible both in the orthophoto (figure 22a) and the VHM (figure 22b) of that time. The protective forest layer (figure 22c) shows that in 1985 most of the forest on Gandberg offered sufficient protection even against extreme avalanches with return periods of 300 years, as indicated by the red colour.

In the year 1997, after Vivian and the subsequent bark beetle infestations, some first gaps appeared and are visible both on the orthophoto (figure 22d) and the VHM (figure 22e). Gaps which were visible in 1997 were mostly caused by windthrows (see map in appendix A.1). Examples for such windthrow areas are indicated with black circles on the protection forest layer (figure 22f). Whereas before the disturbances most of the forest offered protection against large avalanches, in 1997 some areas only offered protection against small avalanches with return periods of 30 years (blue colour) or no protection at all (no colour).

In 2016, large gaps are visible in both the orthophoto (figure 22g) and the VHM (figure 22h). This is also reflected in the protection forest layer (figure 22i). The stands which were infested by bark beetles showed a decreased protective function in 2016. However, most stands did not lose their protective function entirely and were still effective against smaller frequent avalanches with return periods of 30 years (blue colour). Interesting to mention is, that some parts of the windthrow areas already recovered their protective function by the year 2016 (white circles).

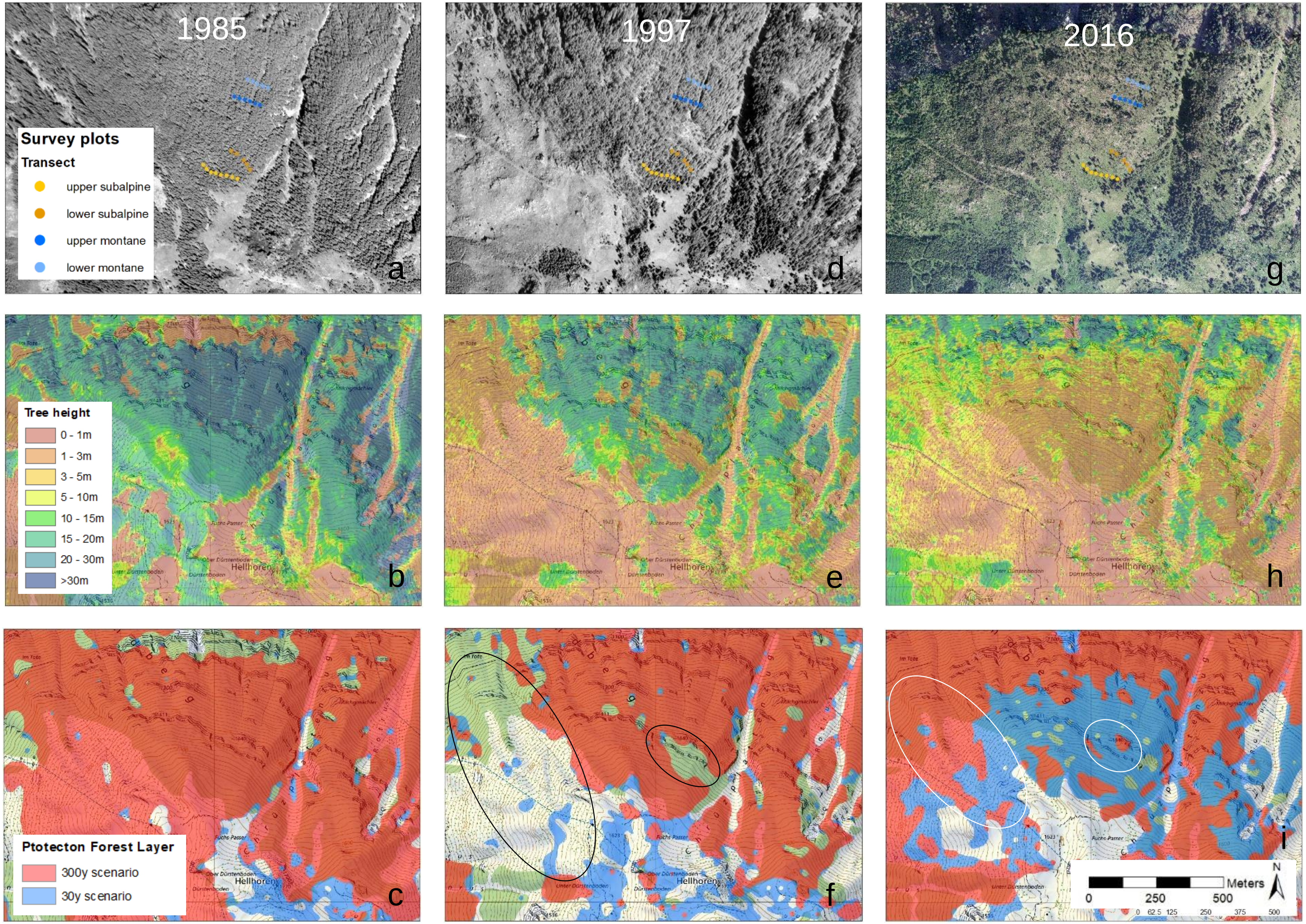

Figure 22: Development of the protective function of the Gandberg forest for the years 1985, 1997 and 2016. The top row shows orthophotographs by © swisstopo, with the dots indicating the survey plots. The middle row shows the vegetation height models (VHMs) by Ginzler et al. (2020). The bottom row shows the protective forest layer developed at SLF Davos (Bebi et al., 2020). The black circles indicate areas killed by Vivian and the withe circles indicate areas which had already recovered by 2016.

4.2.2 Potential Avalanche Release Areas

All potential avalanche release areas

The potential avalanche release areas (PRAs) that were drawn with the help of a slope map and the VHM, had different sizes for the two return periods addressed in this study (figure 23). For the frequent scenarios (return period of 30 years) the PRAs were drawn smaller and only in steeper areas, whereas for the extreme infrequent scenario (return period of 300 years) the areas were drawn bigger and also incorporated some flatter areas.

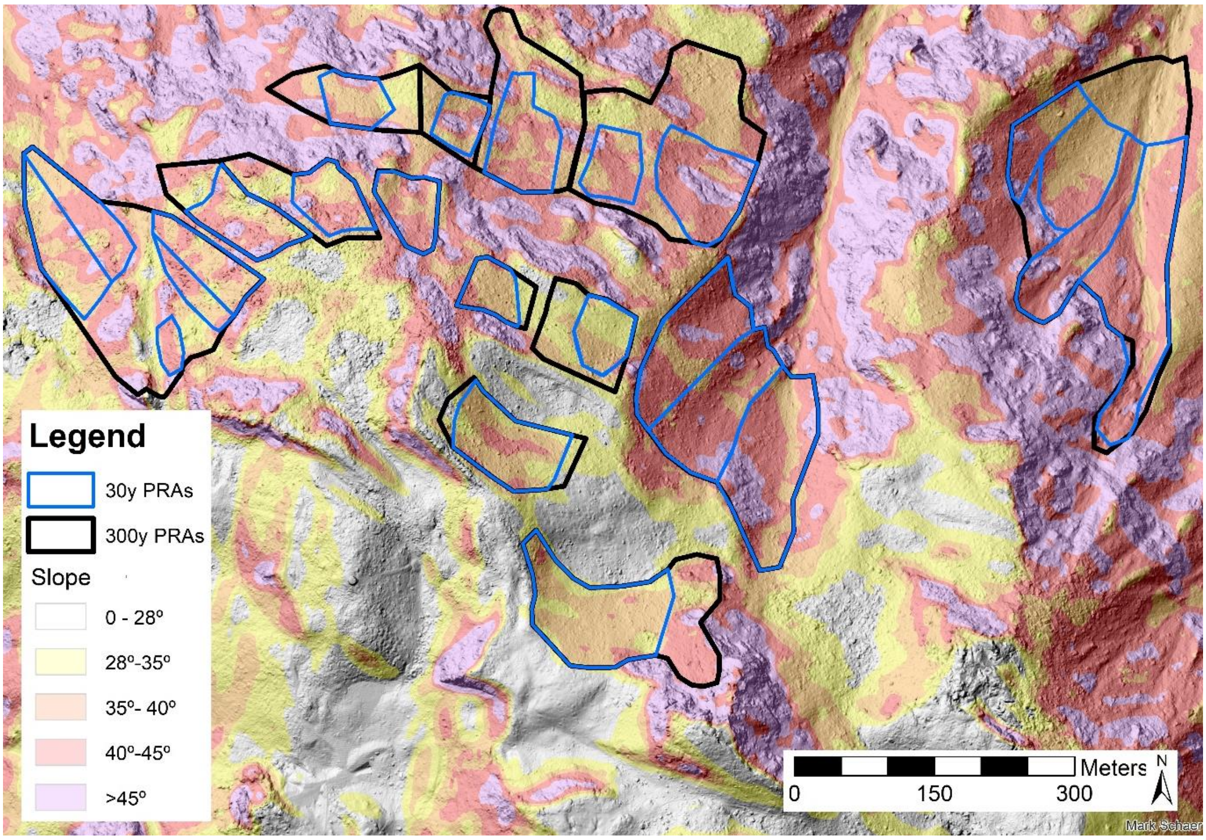

Figure 23: Potential avalanche release areas, drawn based on the slope angle, for an extreme scenario with a return period of 300 years (black) and an infrequent scenario with a return period of 30 years (blue). The background map is a DEM by © swisstopo, 2016.

PRAs for the year 1985 (before Vivian)

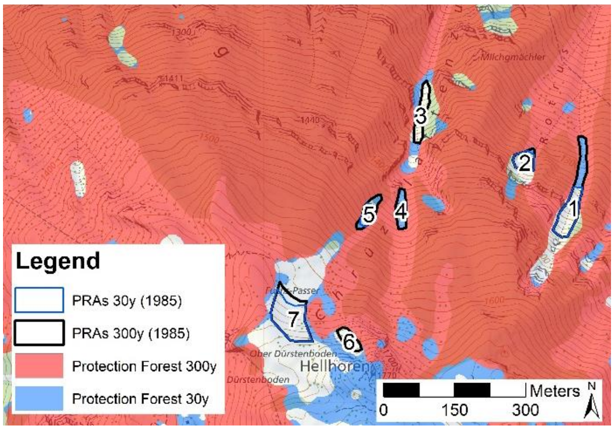

Figure 24: PRAs for the years 1985, e.g. before Vivian (Map: © swisstopo, protection forest layer by Bebi et al. (2020))

Before Vivian most of Gandberg forest offered protection against the release of frequent and extreme avalanches (figure 24). The PRAs were limited to a few relatively small areas, mostly located within two main channels. There were four PRAs for the frequent scenario and seven for the extreme scenario. The PRAs of the frequent scenario had a total area of 11`131m² and the ones of the extreme scenario 19`707m².

PRAs for the year 1997 (after the disturbances)

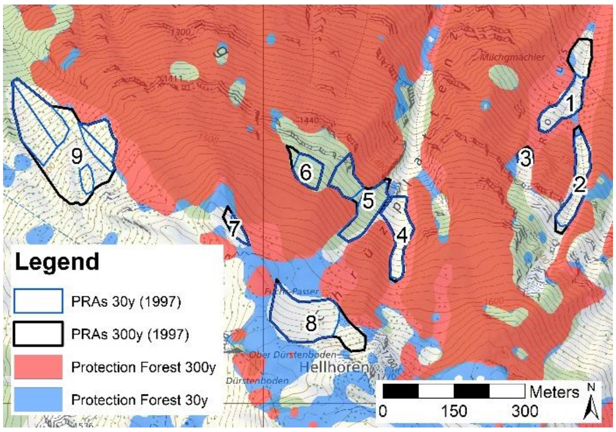

Figure 25: PRAs for the years 1997, e.g. after Vivian and the bark beetle infestations (Map: © swisstopo, protection forest layer by Bebi et al. (2020))

After Vivian, the protective function of the areas which were affected by windthrows decreased rapidly. Compared to 1985 there were more and larger PRAs in 1997. In the two larger gaps caused by windthrows, the protective function of the forest had decreased, causing additional potential release areas, e.g. 5, 6 and 9 (figure 25). In total there were 14 PRAs for the frequent scenario (with a total area of 60`162m²) and nine PRAs for the extreme scenario (with a total area of 82`811m²).

PRAs for the year 2016 (recent situation)

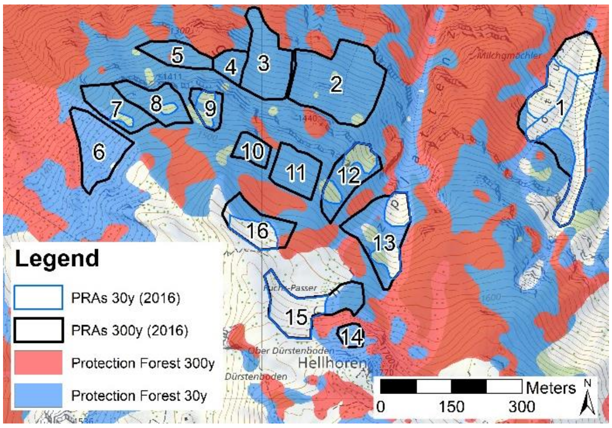

Figure 26: PRAs for the year 2016, e.g. current situation (Map: © swisstopo, protection forest layer by Bebi et al. (2020))

In 2016 the effects of the bark beetle caused die-back were clearly visible (figure 26). There were many additional PRAs for extreme avalanches, compared to the other two scenarios. In total there were 16 PRAs for the extreme scenario (181`262m²) and 12 PRAs for the frequent scenario (50`642m²). Interesting to mention is, that the lower part of the larger windthrow area had recovered and was already offering protection against extreme avalanches again (PRA 6 in figure 26 is smaller than PRA 9 in figure 25).

4.2.3 **Snow Height Analysis**

The snow heights calculated with the method of Burkard & Salm (1992) resulted in a cumulative 3-day snow height of 65cm for the 30y scenario and 90cm for the 300y scenario in the montane level. At the subalpine level the snow height was 75cm for the 30y scenario and 100cm for the 300y scenario (see calculations in appendix C.3).

4.2.4 **RAMMS Simulations**

Total volume, velocity, height and pressure of the simulated avalanches

There were clear differences in the dimensions of the avalanches in the six different scenarios (table 12). The largest avalanches were simulated for the 300y scenarios of the years 1997 and 2016. Both of those avalanches belonged to the volume category large, however the total volume of the PRAs of 2016 was with about 230\`000m$^3$ twice as big as the one of 1997 with about 105\`000m^3. Maximal pressures and flow heights were also similar for those two scenarios, with flow heights above 10m and pressures bigger than 370kPa, in both. The second highest volume was simulated for the 30y scenario of 1997 with roughly 56\`000m$^3$, closely followed by the 30y scenario of 2016 with roughly 47\`000m^3. The maximal flow heights for those two scenarios were around 7m and pressures were around 230kPa for 2016 and 270kPa for 1997. The smallest volumes, flow heights and pressures were simulated for the 30y and 300y scenarios of 1985. For the 30y scenario the total volume was roughly 25\`000m$^3$, with a flow height of 4.7m and maximal pressure of 145kPa. For the 300y scenario the total volume was roughly 10\`000m^3, with a flow height of 6.7m and maximal pressure of 190kPa. Overall, the most severe avalanches were simulated in the scenario of 2016 with a return period of 300 years. The total volume of the 300y scenario in 2016 was almost 10 times larger than the one in 1985 and pressures increased by a factor of two.

Table 12: Cumulative volume, maximal velocity, maximal flow height and maximal pressure for each scenario and return period.

Year	Return period	Total volume [m3]	Volume range [m3]	Volume category	Maximal velocity [m/s]	Maximal flow height [m]	Maximal pressure [kPa]
1985	30y	10\`386	886 - 5102	small	21.98	4.70	144.95
1985	300y	24\`720	1841 - 7970	small	25.14	6.69	189.56
1997	30y	56\`498	793 - 11\`128	medium	30.08	7.07	271.44
1997	300y	105\`106	1234 - 40\`007	large	35.44	10.27	376.74
2016	30y	46\`823	623 - 10\`051	medium	27.42	7.16	225.57
2016	300y	229\`140	2988 - 41\`088	large	35.14	11.41	370.41

Visualization of avalanche simulations

The RAMMS simulations show the effect of the decreasing forest cover after the windthrow and subsequent bark beetle infestations on Gandberg (figure 27). In line with the reduced protective function of the bark beetle stands described in chapter 4.2.1 and with the larger PRAs described in chapter 4.2.2 and 4.2.3, the visualization of the RAMMS simulations show that many more avalanches should have been possible after the disturbances.

In the year 1985 (before the disturbances), there were only two active avalanche channels in the simulation (figure 27, maps a and b). The avalanches in the bigger channel resulted in an avalanche run out distance of around 1500m and the smaller channel in 1200m. The main difference between the frequent and extreme scenarios were larger maximal snow heights for the extreme scenario. In the frequent scenario the height of the deposited snow in the valley was around 1m, whereas it reached up to 4m in the extreme scenario.

In 1997 (after the disturbances), several additional avalanches were simulated, compared to 1985. Those avalanches were released from PRAs located in the two windthrow areas. The avalanches which were released from the smaller windthrow area (middle of the map) did not reach the valley and had run out distances of 200-800m (figure 27, maps c and d). The avalanches released from the bigger windthrow area (on the left side of the map) flowed through a channel into the river below and had run out distance of 1200m. This indicates that some of the lower parts of Gandberg forest were capable of stopping at least the smaller avalanches which were released from the windthrow areas. For the frequent scenario, deposition heights reached up to 6m and in the extreme scenario up to 8m and more.

It is interesting to see, that the avalanches, which were released from the large windthrow area on the left side of the map, had smaller sizes in the year 2016 (recent situation) compared to the year 1997. This indicates that some parts of the windthrow areas had already recovered by then. However, in 2016 the effect of the bark beetle infestations finally became visible (figure 27, map e and f). Again, in the 30y scenario some of the smaller avalanches were stopped by the forest (run out distances of 600-1200m). In the extreme scenario all simulated avalanches reached the valley, with run out distances larger than 1000m for all avalanches. In this scenario, the destruction of large parts of the forest is likely. Deposition heights were up to 5m for the frequent scenario and often larger than 8m for the extreme scenario. The maximal snow pressures were also simulated (see map in appendix C.4). In all six scenarios, avalanches still had pressures up to 30kPa when they reached the valley.

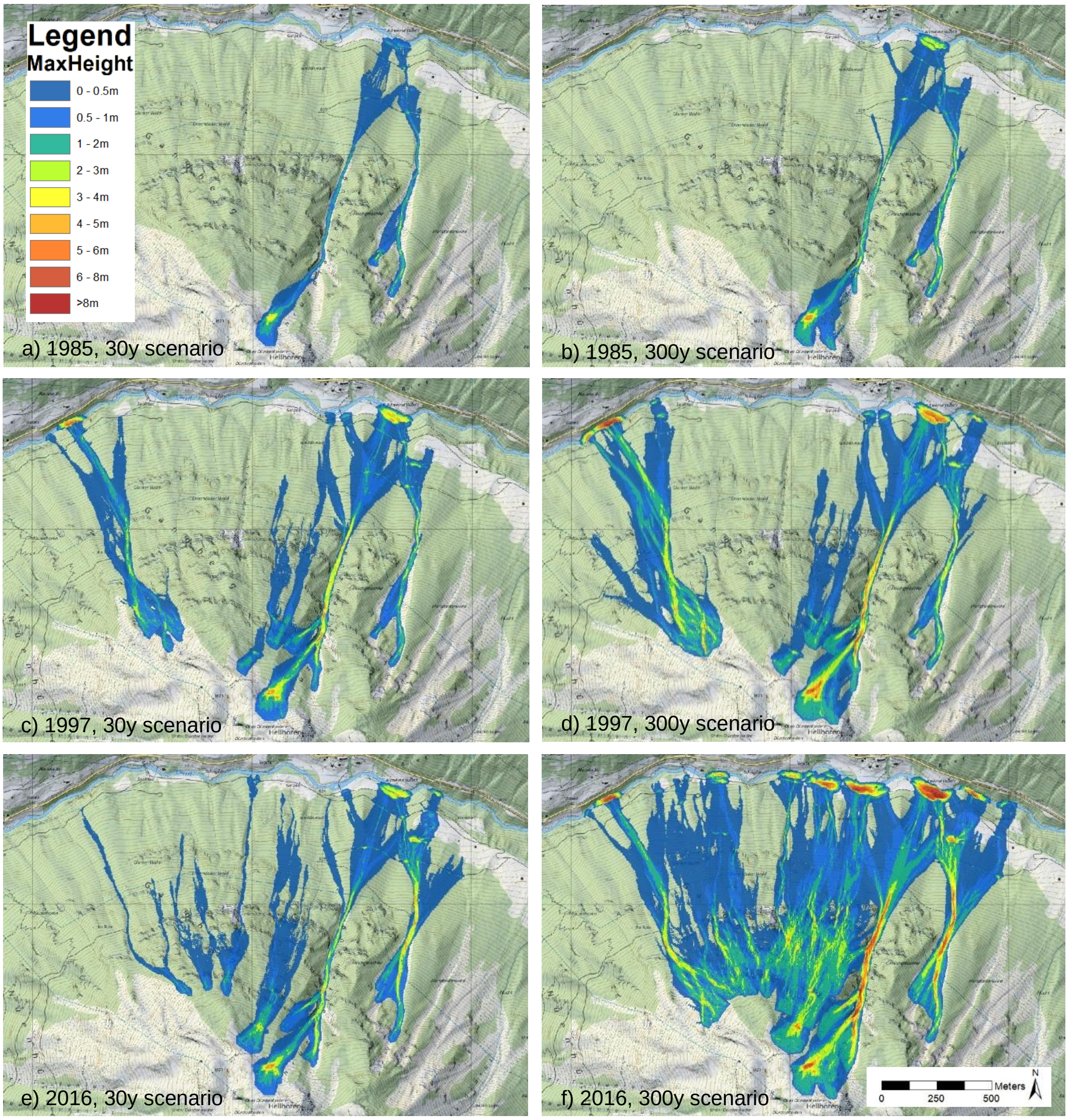

Figure 27: RAMMS simulations for the six scenarios showing the run out pathways and the maximal snow heights for the potential avalanches on Gandberg (Map: © swisstopo) .

5 Discussion

5.1 Field Survey: Current Stand Structure and Implications for Avalanche Protection

5.1.1 Surface Cover

Most of the forest floor was covered by ground vegetation, rather large percentages of the surface were covered by deadwood and the crown cover was still rather low 23-28 years after the bark beetle infestations. All surveyed plots were covered by a lot of ground vegetation (115%). This is more than in other Vivian stands, which had averages of 91% (Brang et al., 2015). The high percentage of ground vegetation and especially grass, could impede the development of tree regeneration and facilitate snow gliding (Frehner et al., 2005; Winter et al., 2015; Wohlgemuth & Kramer, 2015).

Deadwood covered 25% of the surface area of all plots. The amount of deadwood cover was comparable to other studies which evaluated disturbed forests (Tsvetanov et al., 2018) but higher than in typical managed forests in Switzerland, where deadwood cover is around 3% (Brändli et al., 2020). Deadwood elements play a crucial role in enhancing the surface roughness (Bebi et al., 2009). This high amount of deadwood might therefore play an important role in the remaining protective function of the bark beetle stands on Gandberg.

The percentage of crown cover was the only type of surface cover, which differed between elevational levels. It was significantly lower in the subalpine level (10%) compared to the montane level (30%). This is not surprising as growing conditions in the subalpine level tend to be harsher and vegetation periods shorter in the subalpine level (Frehner et al., 2005; Winter et al., 2015). In general, these values are rather low and might not yet be sufficient to create the beneficial effects against avalanche formation, which are known from mature forests. Several studies suggest that crown coverages over 30-50% and gaps smaller than 15-40m are necessary to reduce the likelihood of avalanches (Bebi et al., 2009; Frehner et al., 2005; Margreth, 2004; Teich et al., 2016). Half of the survey plots were intersected by a gap (one gap every 40m). Gaps had lengths of 20-100m and most of them were located in the subalpine level. Such rather large gaps, could be problematic as avalanches, which travel more than 50-150m, have the potential to destroy the forests below (Bebi et al., 2009).

The surface cover is only one of several aspects which are important to assess the protective function of a forest. Still, an evaluation of the vegetation, deadwood and crown cover allows a first rough estimation on whether Gandberg forest offers sufficient protection against avalanche formation. The high percentage of grass, the low crown cover and the frequent gaps are first indicators that the protective function of the bark beetle stands on Gandberg might not be sufficient to reduce the likelihood of avalanches in neither elevation, and that the situation is worse in the subalpine level. Other important factors, such as height and decay stage of deadwood elements (chapter 5.1.2), suitability of deadwood elements as seedbeds (chapter 5.1.3), tree height and densities (chapter 5.1.4), as well as spatially explicit models (chapter 5.3), will be discussed below.

5.1.2 Deadwood

There are still some tall standing deadwood elements left on Gandberg 23-28 years after the disturbances. The highest deadwood element per survey plot was most often a standing element, with 90% of the highest elements being standing elements in the montane level and 50% in the subalpine level. In the subalpine level root plates and lying elements made up a fourth of the highest elements each. The medium height of the highest element per plot was higher in the montane level (2.5m) than in the subalpine level (1.6m). However, likely due to the small sample size of n = 24, this difference was not significant. Similar to the crown cover and occurrence of gaps, this finding also implies that the subalpine level offers a lower protective function than the montane level. Even though a few of the highest elements per plot still had heights up to 8-11m, most deadwood elements on Gandberg were not tall enough to break through the maximal snow height of a scenario with a return period of 30 years, which is 2.5m in the montane level and 3.2m in the subalpine level (Kupferschmid Albisetti, 2003).

Not only the height of the highest elements but also the density and spatial distribution of the other deadwood elements might be important factors influencing the likelihood of avalanche formation in forests. Looking at the median height of all seven deadwood elements allows a comparison of the heights of different types of deadwood. Standing elements were the tallest deadwood type, with heights of 140cm. Hanging elements had heights of 45cm and lying elements 28cm. Therefore all types of deadwood are likely to be fully covered by snow for scenarios with return periods of 30 years or more, allowing a smoothing of the terrain and the development of weak snow layers (Brožová, Baggio, et al., 2020). This could indicate that, even though there is a high percentage of deadwood cover, the elements do not offer sufficient protection against avalanches anymore, because tall elements are spaced to far apart, to prevent the homogenization of snow layers.

The stage of decay had an influence on the height of the deadwood elements. The more decayed an element was, the lower was its height. Most deadwood elements were still in early to medium decay stages and should be able to offer some protection against natural hazards. As decay progresses their heights, strengths and therefore their protective effect are expected to decrease further.

The dbh was the only variable which correlated with the movability of a deadwood element. In total 17.5% of all elements could be moved by hand, with thicker elements being less likely to be moved. This makes sense as thinner elements are also lighter and therefore easier to move. However, in the field it was observed that sometimes even large standing deadwood elements could be moved, indicating that the strength required to break those deadwood elements is rather low.

In addition to the surface cover, the evaluation of the height and decay stage of deadwood elements allows to draw a more conclusive picture about the protective function of the bark beetle stands on Gandberg. Even though the percentage of deadwood cover is rather large, the heights of most deadwood elements on Gandberg are likely to be insufficient to offer protection against avalanche formation for snow heights with return periods of 30 years or more. Nonetheless, they offer a greater structural heterogeneity than a flat surface and might therefore still be beneficial against avalanche formation (Schönenberger et al., 2005).

5.1.3 **Regeneration on Deadwood**

The deadwood elements on Gandberg have reached a sufficient decay stage to offer a seedbed for tree regeneration. Especially spruce seedlings in the subalpine level often depend on this substrate, as other suitable microsites are sparse (Bače et al., 2012). This was visible on Gandberg, as the most common species on deadwood was spruce with 97% accompanied by 3% rowan. The height of the tallest spruce seedling per deadwood element was between 8.5-9cm. Studies in mountain forests in Europe found the highest abundance of spruce on logs 30-60 years after tree death, on medium to late decay stages (Tsvetanov et al., 2018; Zielonka, 2006). However, they also found that much earlier colonization was possible, with the first seedlings germinating during the second decade after tree death. This suggests that the deadwood on Gandberg has just become a favourable seedbed and that the importance of this substrate will grow in the future.

The number of seedlings growing on deadwood was influenced by the elevational level and the decay stage, but neither height nor dbh of deadwood elements. The subalpine level showed a higher number of seedlings growing on deadwood elements than the montane level. In the subalpine there was an average of one seedling per deadwood element, whereas in the montane level there was only one seedling on every fourth element. At first glance it seemed surprising that there would be more seedlings on deadwood in the subalpine level. However, past studies have also found that deadwood is more important for spruce in the subalpine level (Kupferschmid & Bugmann, 2005a). The dbh of the deadwood elements did not have an influence of the number of seedlings. This was also somewhat unexpected as other studies have suggested that there is less interspecific competition from herbs on stems with a larger diameter and that broader stems also offer better growing conditions because their smaller surface to volume ratio allows for more stable moisture conditions (Bače et al., 2012; Renvall, 1995). A reason for this could be that not only logs, but also standing deadwood elements, where seedlings often grew on the roots, were surveyed. Therefore, the effect of the diameter might have been underestimated in this study. There was a higher number of seedlings on deadwood with the decay stages 3 and 4 compared to stage 2. The difference between stage 2 and 5 was not significant. Other studies also found that seedling densities peaked on logs with a medium decay stage and decreased thereafter (Bače et al., 2012; Zielonka, 2006). Bače et al. (2012) explained the decline of seedling densities on the most advanced decay stages with the growing intraspecific competition between spruce seedlings, as well as the fact that logs with a higher decay stage often have lower heights, which in turn leads to higher interspecific competition with herbs and dwarf shrubs.

About a fifth of all deadwood elements nursed regeneration. Smaller elements tended to be more likely to nurse regeneration than taller elements. The median height of deadwood elements not harbouring regeneration was 70cm, whereas the height of elements with regeneration was 35cm. Bače et al. (2012) found that a higher degree of ground contact positively influenced the density of seedlings. Since higher logs also tend to have less ground contact, this could explain why they were less likely to harbour deadwood regeneration.

Overall, it is likely that deadwood elements on Gandberg will become a more important seedbed, as the decay continues and moisture conditions improve. In the future, when those seedlings become mature trees, the deadwood regeneration is likely to contribute to the protective function of Gandberg and also cause more heterogenous forest stands.

5.1.4 Seedlings and Saplings

Besides deadwood elements, trees can also increase surface roughness and therewith reduce the likelihood of avalanches (Schönenberger et al., 2005). The density of seedlings (0.2m-1.3m) and saplings (>1.3m) together was around 2311 trees/ha in the montane and 1830 trees/ha in the subalpine level. This is a bit more compared to another study in Vivian sites which found 1433 trees/ha (Wohlgemuth & Kramer, 2015). However, that study also reported an extremely high variability of 700-78`000 trees/ha. The differences in densities between the two elevational levels, which were found in this study, can be attributed to harsher growing conditions, larger distance to seed trees as well as fewer seed years in the subalpine level (Kupferschmid et al., 2006; Kupferschmid & Bugmann, 2005b). Similar findings have also been reported by several other authors (Červenka et al., 2020; Winter et al., 2015; Wohlgemuth & Kramer, 2015).

Bühler et al. (2005) have suggested that 2000 seedlings/ha are required for a sustainable regeneration of subalpine spruce forests, which is about twice as much as was found on Gandberg. However, their study also included seedlings between 10-20cm (Bühler, 2005), explaining at least some of the larger density. Another study by Brang & Nikolova (2020) has suggested densities between 2250-3000 trees/ha as indicator values for sustainable regeneration in forests which were affected by large-scale disturbances. They count trees with sizes between 10-39cm half, trees between 40-129cm once and trees taller than 130cm thrice (Brang & Nikolova, 2020). On Gandberg the number of saplings alone was 1231 per ha in the montane and 982 per ha in the subalpine level. If those values are multiplied by three, as proposed by Brang & Nikolova (2020), values of more than 2250-3000 trees/ha are already reached, even without accounting for the seedlings. Therefore, the regeneration on Gandberg seem to be sufficient for forest recovery.

Spruce saplings of the montane level had heights of 3.9m and were significantly taller than in the subalpine level with 2.9m. The tree height for both elevations were rather large, compared to the height age ratios proposed by Brang & Duc (2002), which predicted tree heights between 0-2m for 25-year-old spruce trees. The taller heights on Gandberg were most likely caused by the higher light availability in disturbed areas, compared to mature forests, which were used for the model. Wohlgemuth et al. (2017) found average heights of 2.2m in unsalvaged windthrow areas 20 years after the storm event, which is more in line with our findings. Furthermore, Brang et al. (2015) found the average height growth rate of spruce trees on Vivian sites to be around 10cm per year (e.g. around 2.3-2.8m in 23-28 years).

Even though heights are similar or even larger than in other Vivian sites, trees on Gandberg are still not tall enough to offer sufficient protection against avalanche formation for neither frequent nor extreme avalanches. According to Frehner et al. (2005) trees should be at least twice the height of the snowpack, to prevent avalanche formation within forests (Frehner et al., 2005). This would mean, that trees needed to be 5m in the montane level and 6.5m in the subalpine level to be able to prevent avalanches with return periods of 30 years from starting, which is currently not yet the case. Therefore, their effect against larger avalanches would be even worse. Especially in the subalpine level trees are still much too small. However, smaller trees might still reduce the run out distances of small and medium sized avalanches and therefore be beneficial for avalanche protection (Teich et al., 2012).

Another factor which could influence the speed of recovery is the browsing intensity (Kupferschmid et al., 2015). The different browsing intensities of the four species found on Gandberg were 86% for sycamore maple, 63% for rowan, 31% for birch and 17% for spruce. Due to the high browsing intensities it is unlikely that silver fir or broadleaved species will establish in high densities, which was already suggested by past studies (Kupferschmid et al., 2006). This is disadvantageous as higher heterogeneity and diversity would also improve the resistance of the forest against future bark beetle disturbances (Bauhus et al., 2017). The browsing intensity on spruce was, with 17%, still in the range of the acceptable browsing intensity of 12% (Eiberle & Nigg, 1987), if the large standard deviation of 28% is considered. A browsing intensity of 17% is estimated to cause 30% game induced mortality in spruce trees (Rüegg & Schwitter, 2002). However, a study by Wohlgemuth & Kramer (2015) found no direct correlation between browsing intensity and tree density in Vivian areas. Still, frequent browsing is known to reduce the height growth of trees, which could prolong gaps in the protective function of post disturbance forests (Kupferschmid et al., 2015).

In summary, it can be said that, even though tree densities seemed to be sufficient for a sustainable reforestation of Gandberg, other tree parameters were not. According to the rule that trees need to be twice the height of the snowpack, tree heights on Gandberg were neither large enough to prevent avalanches with a return period of 30 years nor for avalanches with return periods of 300 years. Furthermore, browsing might be reducing the speed of tree growth and the recovery of the bark beetle stands on Gandberg.

Together, the types and percentages of surface cover, the deadwood heights and decay stages, as well as tree heights and densities should allow a comprehensive assessment on how effective the bark beetle stands on Gandberg are in preventing avalanche formation. The results of the field survey indicate that trees often grow in dense clusters, interspersed with tree-free gaps, as is common for subalpine and to some degree also for montane forests. Within these clusters, trees are not yet tall enough to prevent avalanche formation. Especially in the subalpine level, there are some factors favouring the release of avalanches: 1) high amount of grass cover, 2) gaps between trees and other roughness elements, and 3) small percentage of crown cover and 4) rather small tree heights. Only the high percentage of deadwood cover might compensate for some of that, even though most elements were lower than the maximal snow height.

In the future the tree heights and percentages of crown cover are likely to increase as trees continue to grow and new trees are recruited on suitable microsites. More such microsites are likely to become available in the future as deadwood decay continues and deadwood becomes a more suitable seedbed. Furthermore, the shading by trees will increase, reducing the light availability for ground vegetation, in turn favouring shade-tolerant tree species such as spruce (Frehner et al., 2005). Therefore, some of the gaps will be closed. Even though the height of deadwood elements will further decrease, and tree growth in mountain forests is a slow process, the new trees are likely to take over the protective function eventually, resulting in a higher protective function of the bark beetle stands in the future compared to today.

5.2 Field Survey: Comparison to Past Studies

5.2.1 Surface Cover

Whereas 20 years ago the view on Gandberg was dominated by dead but still standing trees, only some smaller standing deadwood elements and many lying logs remained in 2020 (figure 28, also see additional pictures in appendix D.1).

Figure 28: The pictures show the bark-beetle stands a few years after the disturbance compared to recent pictures from 2020. Pictures a & b: Both pictures were taken from a large outcropping overlooking the montane level. The left picture was taken in October 2000, the right one in October 2020. Pictures c & d: The pictures show part of the upper subalpine transect in 1999 and 2020.

In 2020, the percentage of deadwood cover was slightly higher than in past surveys. In 2000 it was 19% in the montane level and 12% in the subalpine level (Kupferschmid & Bugmann, 2005b). In 2020 the values were 25% and 20%, respectively. This is not surprising since in 2000 many dead trees were not yet broken (Kupferschmid Albisetti et al., 2003), whereas all were broken in 2020. Besides changes in the cover of deadwood there was also a shift in vegetation cover. Before Vivian the vegetation cover was mainly composed of *Oxalis acetosella* and mosses (Kägi, 1992). After the bark beetle infestations, the dominant species in the montane level was the light demanding *Rubus idaeus* and in the subalpine level mosses dominated (Kupferschmid & Bugmann, 2005b). Kupferschmid & Bugmann (2005b) predicted a slow succession, with *Rubus* being replaced by spruce in the montane level and with ferns dominating for a long time in the subalpine level. However, this study shows that currently the dominant type of vegetation is ferns in the montane level and grasses in the subalpine level. The unexpected reduction of *Rubus* could have been caused by a decrease in light availability, with increasing crown cover, thus partly by upgrowing spruce.

5.2.2 Deadwood and Deadwood Regeneration

In 2020, the height of the remaining standing deadwood elements was considerably lower compared to past surveys. In 2000, 25% of standing deadwood elements were not broken yet and 25% were broken above 10m (Kupferschmid Albisetti et al., 2003). In 2020, only 3.5% were still taller than 10m. Further, in the montane level the volume of standing deadwood elements decreased from 545m^3/ha to 56m^3/ha and in the subalpine level from 346m^3/ha to 37m^3/ha, which is almost a factor of ten in 20 years. This can be explained by the proceeding wood decay (Kupferschmid Albisetti et al., 2003). Those findings underline the fact that bark beetle stands continuously provide newly fallen logs for several decades.

Logs also had lower heights in 2020, than 20 years ago. Whereas around 20 years ago the height of logs was 92cm in the montane and 78cm in the subalpine level (Kupferschmid Albisetti et al., 2003), the heights in 2020 were 32cm and 26cm, respectively. This indicates that the importance of deadwood as a roughness element has considerably decreased over the years. Similar findings have been reported from windthrow areas in Switzerland, where initial heights were 2.1m and decreased to 0.8m after 20 years (Wohlgemuth et al., 2017).

As a result of the decreasing height, the percentage of logs with ground contact has increased. In past surveys only between 25-32% of logs were lying on the ground (Kupferschmid Albisetti et al., 2003), whereas in 2020 the values were between 85-88%, depending on the elevational level. More ground contact is expected to speed up the decay, as more moisture from the ground is available (Kupferschmid Albisetti et al., 2003). In 2020, most deadwood elements were in the second and third stage of decay (out of five). Therefore, they now offer a better growing substrate for spruce seedlings (Bače et al., 2012). While in 2000 there was no regeneration on the deadwood elements that were caused by Vivian and the subsequent bark beetle infestations (Kupferschmid Albisetti et al., 2003), in 2020 13% of deadwood elements in the montane level and 25% in the subalpine level harboured seedlings.

5.2.3 Seedlings and Saplings

The large growing stock from before Vivian - 816m^3/ha in the montane level and 593m^3/ha in the subalpine level (Kupferschmid Albisetti et al., 2003) - has not nearly re-established today. The new trees are still below the calipering threshold, which was used in previous studies (16cm), therefore it does not make sense to compare growing stocks or basal areas. However, it is interesting to compare the current densities to past studies. In the year 1990, tree densities (>16cm bhd) were 560 per ha in the montane and 513 per ha in the subalpine level (Kupferschmid Albisetti et al., 2003). In 2001, the densities of spruce seedlings were 1961 per ha in the montane and 3047 per ha in the subalpine level (there were no saplings yet) (Kupferschmid et al., 2006). In 2020, there were 1352 spruce seedlings and saplings per ha in the montane and 1558 per ha in the subalpine level. This reduction in spruce was expected since saplings need more growing space than seedlings. If only the number of spruce seedlings is compared to past studies, the decrease is even more pronounced, as in 2020 there were only 486 spruce seedlings/ha in the montane level and 640 spruce seedlings/ha in the subalpine level. It is important to note that the previous study included all seedlings older than one year, whereas this study only evaluated seedlings taller than 20cm, which at least partially explains the decrease in density. The decrease in seedling density might also hint at a decrease in available seedbeds. Tsvetanov et al. (2018) found that, after windstorms, two peaks in post disturbance regeneration occur. The first peak happens right after the disturbance, when sufficient light is available and suitable microsites are not yet occupied by competing ground vegetation. The authors have also argued that, after the first peak, regeneration densities decrease again due to the increase in ground vegetation and limited seedling survival, which is possibly what we see now on Gandberg. After 30-50 years, when the trees of the first peak are tall enough to offer some shelter and when logs become suitable seedbeds, regeneration densities are likely to increase again (Tsvetanov et al., 2018). This would indicate that the seedling establishment on Gandberg is likely to continue in the future when deadwood becomes a suitable seedbed. However, if logs had been removed, this could not happen and gaps could persist longer (Brang et al., 2015).

A shift in species composition was observed on Gandberg. Before Vivian, spruce dominated and only a small share of white fir (1%) and sycamore maple (3%) trees occurred (Kupferschmid et al., 2002). In 2020, spruce was still the most common species with 72.6%, but there was a larger percentage of early successional broadleaved species: 16.7% birch, 6.1% rowan, 4.3% sycamore maple and 0.3% willow. Even though the percentage of broadleaved species increased in both elevational levels, the shift was more pronounced in the montane level, which could be explained by the fact that the harsher growing conditions in the subalpine level are less favourable for pioneer species (Tsvetanov et al., 2018). Early successional species, such as birch and rowan, are known to co-dominate a few years after disturbances and decline afterwards due to their limited live span (Tsvetanov et al., 2018). However, their percentage on Gandberg was smaller than could have been expected after a large-scale disturbance. This might be explained by the fact that bark beetle caused die-backs do not create as many suitable microsites for early successional species as windthrows, which cause more exposed mineral soil (Fischer et al., 2015). Many other studies also found that bark beetle induced disturbances often created suitable conditions for the re-establishment of the dominant species, e.g. spruce (Červenka et al., 2020; Winter et al., 2015; Zeppenfeld et al., 2015).

Browsing intensities in 2020 were lower than in past studies. In 2000, the browsing intensities on spruce were on average 34.5% in the montane and 23.5% in the subalpine level (calculated from values given in table 3 of Kupferschmid et al. (2005a)). In 2020 they were lower with 25.0% and 13.3%, respectively. The large standard errors do not allow a conclusive estimation on whether browsing intensities truly decreased. However, a reduction in browsing intensity was also observed by forest practitioners and was likely a result of a highly infectious disease that blinds chamois and severely reduced their numbers on Gandberg in the past years (Luchsinger, 2021). A second explanation for the decrease in browsing intensities could be that other food sources became available with successional vegetation changes. This is unlikely as chamois on Gandberg mainly browse trees in winter when other vegetation is dry and covered by snow anyway. The decrease in browsing intensities since 2000 is even more surprising if it is considered that in 2020 there were more trees in mid height classes (see graph in appendix C.2), which are known to be browsed the most (Kupferschmid et al., 2020). Therefore, the "chamois blindness" is most likely the main cause for the reduction in browsing intensities. As browsing does not seem to have affected the densities of the first wave of regeneration, I would also not expect it to negatively influence future regeneration densities, given browsing intensities do not increase again. In summary, the main differences of this study compared to past studies were: 1) higher cover but lower heights of deadwood, 2) higher stage of decay and more deadwood regeneration, 3) taller tree regeneration with a higher percentage of broadleaved species and 4) lower browsing intensities on seedlings.

5.2.4 Past Predictions About the Development of the Protective Function

The previously mentioned decrease in the protective function of the deadwood and the increase of the protective function of living trees is in line with the predictions of past studies (figure 29). Kupferschmid Albisetti (2003) predicted a higher protective function in the subalpine level (straight blue line) compared to the montane level (dashed blue line). However, I found the opposite, with a higher protective function of the montane level compared to the subalpine level 23-28 years after the bark beetle infestations (orange quadrangle).

Kupferschmid Albisetti (2003) argued that the higher seed inflow from surviving trees and the lower browsing intensity in the subalpine level would lead to higher seedling establishment and growth. They simulated the development of seedlings from two seed-years, which occurred after Vivian, and predicted 330 saplings/ha in the montane level and 930 saplings/ha in the subalpine level for the year 2023 (Kupferschmid et al., 2006; Kupferschmid Albisetti, 2003). In 2020, the effective densities of spruce saplings were 866 per ha in the montane level and 918 in the subalpine level, indicating that regeneration in the montane level grew better than expected. Possible explanations for this discrepancy, between the predictions and the current state, could be that browsing intensities decreased or that a considerable seed inflow occurred after the two modelled seed years in the montane level. Evaluating the protective effect of deadwood is harder since the knowledge about it is limited. The field data indicate that deadwood (brown line) might already be at or below the threshold of effective protection (red line), since most elements are likely to be covered completely by snow in winter, as discussed in chapter 5.1.2.

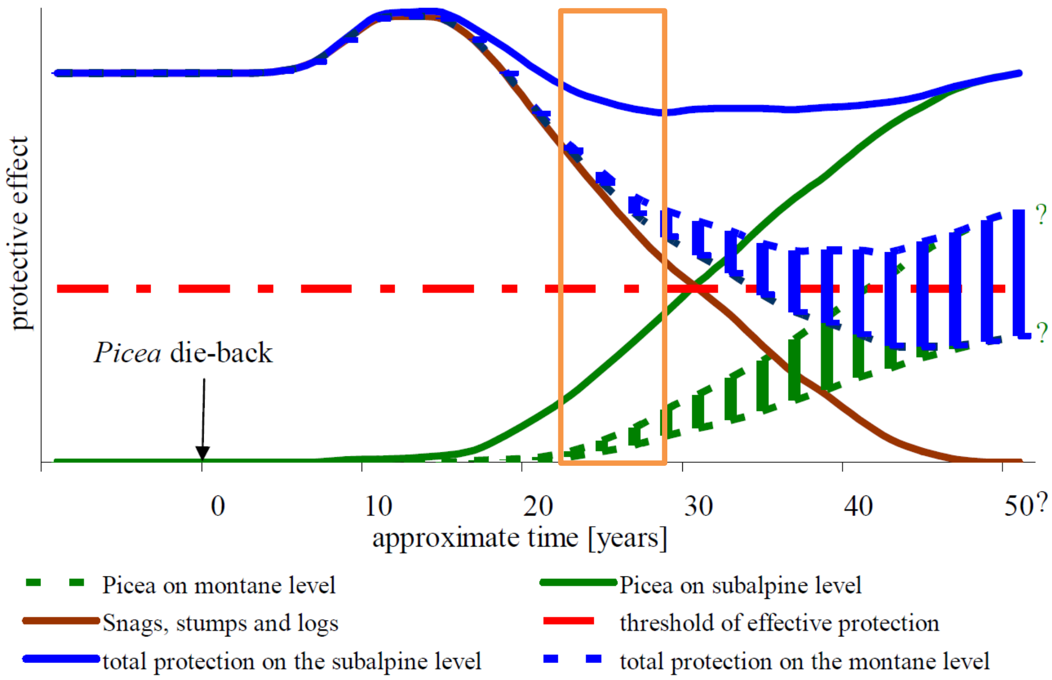

Figure 29: Predicted development of the protective function of the bark beetle stands on Gandberg, for both elevational levels (Kupferschmid Albisetti, 2003). The blue lines show the cumulative protective effect of deadwood (brown line) and tree regeneration (green line). Dashed lines indicate the area between an optimistic and a pessimistic scenario. The orange quadrangle was added to the original figure to indicate the current situation, e.g. 23-28 years after the bark beetle induced dieback.

5.3 Remote Sensing and Avalanche Hazard

5.3.1 Before the Disturbances (1985)

Forests can reduce the likelihood of avalanche formation in potential starting zones (Bebi et al., 2009), decelerate small to medium sized avalanches and reduce their run out distances (Brožová, Fischer, et al., 2020; Teich et al., 2012). Before the disturbances, most parts of the Gandberg forest offered protection even against extreme avalanches with return periods of 300 years (figure 22c) and only few PRAs could be identified (figure 24). This underlines the fact that dense mature forests offer good protection against avalanches (Margreth, 2004). All avalanches which could potentially have been released in 1985 were not modelled in the bark beetle stands, but in two channels next to it. The modelled avalanches located in those channels reached the valley below in every scenario (figure 27), independently of the changing forest structure. As the release areas of the larger of those channels is located above the tree line, this is not a surprising result. Many authors have argued that avalanches starting above the tree line build up enough energy to destroy the forest below and therefore behave independently of the forest structure (Feistl et al., 2014; Margreth, 2004; Teich et al., 2012). However, medium and small avalanches that are released within a forest have stronger dependencies on the forest structure and might be stopped by forests (Teich et al., 2012).

5.3.2 After the Disturbances (1997)

In 1990, Vivian caused scattered windthrows, which resulted in visible gaps in 1997, where the forest could not offer protection against neither extreme, nor small avalanches (figure 22f) and several additional PRAs occurred (figure 25). In comparison to the area affected by windthrows, most bark beetle stands still offered sufficient protection against avalanches, as the dead trees were still standing. Other studies also found that the gradual decay of bark beetle infested trees can delay the occurrence of protection gaps compared to windthrow areas (Bebi et al., 2015; Kupferschmid & Bugmann, 2005b). A study which evaluated the effects of bark beetle infestations on the snowpack in North America found that there were no differences in snow density layers between still green stands and stands which had been killed three years ago, even though needle loss was thought to decrease interception and increase light transmission and wind speeds, which could potentially negatively alter the snow stratigraphy towards a more heterogenous layering (Teich et al., 2016). However, those trees likely still had some of their smaller branches which would also have intercepted some of the snow. Furthermore, the study found that if trees were harvested, the canopies of the remaining smaller trees and woody debris had no significant impact on snow stratigraphy (Teich et al., 2016). This underlines the findings of this study that bark beetle stands offer protection against avalanches in the first years after the disturbances, if left unharvested.

Not all the avalanches which could potentially have released from the windthrow areas in 1997 reached the valley in our simulations. Some were stopped by the forest below (figure 27c and 27d). The run out distances of the avalanches which stopped within the forest were between 200-800m. This is in line with findings of from Teich et al. (2012) who found run out distances between 50-700m for avalanches released within forests and of 360-1800m for avalanches which were released into forest from above the tree line. Feistl et al. (2014) explained the capability of forest to stop small to medium sized avalanches by increasing friction and by directly extracting mass.

5.3.3 **Recent Situation (2016)**

The two gaps caused by windthrows recovered their protective function, at least partially, by 2016 (figure 22i). However, only the smaller gap which was located within the bark beetle stands did so by itself, the larger windthrow area, on the right side of the bark beetle stands, recovered its protective function faster due to several factors: 1) interventions by the forest management (clearing), 2) different aspect and more light availability and 3) more advance regeneration (Tschudi, 2021). Even though the two windthrow areas recovered by 2016, the protective function of the bark beetle stands decreased substantially, and the upper subalpine part of the forest lost its protective function completely. Many additional PRAs occurred in the bark beetle stands in 2016 (figure 26) compared to previous scenarios. Even though there were more PRAs for the 300y scenario, also some additional PRAs in the 30y scenario occurred, meaning that in 2016 even smaller snow heights could cause avalanches. This reduction in the protective function of the bark beetle stands was a consequence of the progressing wood decay of the standing deadwood elements and subsequent stem breakages after storms. Lothar for example broke many remaining standing deadwood elements in the year 1999 (Kupferschmid Albisetti et al., 2003).

Interesting was that the small avalanches which were released from the bark beetle stands in the simulation of the frequent scenario did not reach the valley (figure 27e). This is in line with findings from Teich et al. (2012) who found that the occurrence of small trees with diameter from 1-15cm in the starting zone and in the first 200m of the avalanche path had a significant effect on the run out distances of medium and small avalanches. They attributed this effect to the higher biomass in the zone where avalanches accelerate and to smaller bending stresses and the complete deflection of such trees, which consumes avalanche energy. Bebi et al. (2015) have also argued that small trees can decrease the mass and the energy of avalanches, and therefore enhance the likelihood that avalanches are stopped by the forest below.

The large avalanches simulated for the extreme scenario were not hindered by the forest (figure 27f), because they reached sufficient volumes and intensities to break trees. Margreth et al. (2004) have argued, that avalanches bigger than 10`000m^3 are not slowed down by forests. Critical snow pressures for stem breakage are > 50kN/m^2 for flowing avalanches and > 3-5 kN/m^2 for powder avalanches, which have a larger area of contact (Margreth et al., 2008). Both those thresholds were exceeded by many avalanches of the extreme scenario and also by some avalanches of the frequent scenario, explaining why they were not stopped by the forest.

The largest total avalanche volume occurred in the simulation of the extreme scenario of 2016, with a volume of 230`000m^3, maximal flow heights of around 10m and maximal pressures of around 370kPa. The total volume of the extreme avalanches in 2016 was more than twice as big as in 1997 and almost 10 times larger than in 1985. This intensification of possible avalanches indicates that the regeneration in the bark beetle stands did not grow fast enough to compensate for the reduction in the height of deadwood elements.

Furthermore, it is important to note that, in all six scenarios, avalanches still had pressures up to 30kPa when they reached the valley (see map in appendix C.4). Avalanches with pressures smaller than 3kPa are classified as low intensity, avalanches with pressures between 3-30kPa are classified as medium intensity and avalanches above 30kPa as strong intensity (Bründl & Romang, 2009). This shows that the modelled avalanches which reached the valley still had medium intensities and therefore some damage potential.

5.3.4 **Simulations vs Reality**

Only potential avalanches were simulated in this study and it is important to distinguish between avalanches that *could* happen and avalanches which *actually* happen. Even though the RAMMS simulations showed that avalanches could have been possible after the disturbances, no avalanches occurred between 1990 and 2021, not even in the snow rich “avalanche winters” of 1999, 2018, 2019 and 2021. Several reasons could explain the lack of avalanches: 1) too small snow heights, 2) an underestimation of the protective function of deadwood, or 3) an underestimation of the protective function of small trees.

To evaluate the return periods of the snow heights in the above mentioned years, data from the meteorological station in Braunwald was used, assuming that if the snow height in Braunwald was equal to a scenario with a return period of 30 years, so would the snow height on Gandberg have been. The data from the Braunwald shows that snow heights with return periods of 300 years were not reached in any of the years, explaining the lack of large avalanches. However, in 1999 and 2021, the maximal snow height for a 30y scenario was reached (see graphs in appendix D.2). This would indicate that at least in 1999 and 2021 snow heights were sufficient to cause small avalanches and that the lack of avalanches was caused by another factor than snow height.

In the snow rich winter of 1999, the deadwood in both the windthrow area and the bark beetle stands might still have played an important role in preventing avalanche formation on Gandberg. Similarly, other studies observed only few avalanches on windthrow sites between 1990-2012 (Bebi et al., 2015; Wohlgemuth et al., 2017). The importance of deadwood as a roughness element has not yet been sufficiently surveyed by scientists and is hard to adequately implement into RAMMS simulations. Therefore, it is possible that the surface roughness of deadwood elements played an even more important role in the first years after the disturbances, than what was assumed for the simulations of the year 1997.

There were also no avalanches in the bark beetle stands between 2000 and 2021. A study by Bühler et al. (2019), which mapped avalanches with the help of satellite images, reported only one avalanche in 2018, in our study area (see map in appendix D.3). This avalanche was in the right most channel, which was active in all our simulations. The lack of avalanches on Gandberg in 2021, was somewhat surprising. Some studies in windthrow areas have predicted that deadwood loses its strength in the first decades after breaking and that tree regeneration might not reach sufficient heights to prevent a gap in the protective function of a forest 20-50 years after a disturbance (Bebi et al., 2015; Frey & Thee, 2002), e.g. around now on Gandberg. However, it is possible that bark beetle sites behave differently than windthrow stands, as relatively well conserved deadwood is continuously supplied from the standing dead trees, which could reduce the duration of or even prevent the gap in the protective function. The deadwood on Gandberg might therefore offer protection for a longer period than expected. Furthermore, the establishment of tree regeneration might not be delayed considerably compared to windthrow areas, because trees lose their needles shortly after the die-back and sufficient light for spruce is available from an early stage. This would lead to an overall shorter duration of the protection gap in bark beetle stands. Also, small trees, not only mature ones, could offer some protection against avalanches (Teich et al., 2012). Our simulations might therefore have been too pessimistic, or the recommendations for protection forests to strict, explaining why no avalanches occurred in the past few years.

5.4 Limitations

5.4.1 Field Survey

Field surveys are always prone to certain measurement errors and uncertainties. The most important obstacle for obtaining significant results was the small sample size. With only eleven plots in the montane level and 13 in the subalpine level, the validity of some results was limited. This is especially true for variables which were measured only once per plot like the highest deadwood element (e.g. n = 24). Even though statistical tests allowed for a reliable analysis of significant results, some results were not significant due to the relatively high variance compared with the low number.

The small sample size also limits the applicability of our results to other areas. Many findings and concepts mentioned in this study might also be valid in similar biological regions. However, due to the large fine-scale-heterogeneity of mountain areas (Bueno de Mesquita et al., 2018; Frehner et al., 2005), the extrapolation of our findings should be done carefully. For more reliable predictions, a larger sample size would have been necessary. Furthermore, this study only addressed one single study area. Future studies should try to assess several study areas, to allow for a better evaluation of the forest recovery under different environmental conditions. This would be a time-intensive undertaking though, as work in steep mountain slopes is often difficult.

One goal of this study was to compare our data to past surveys undertaken on Gandberg. It was not always possible to be sure that the survey plots were located at the exact same location as was used for past studies, since no reliable GPS coordinates were available. Every time a pole was found, which was installed by Kupferschmid Albisetti (2003), the distance to it was measured. This allowed a rough estimation of the error that occurred by following the azimuth given by Landolt (2001). An accuracy of about 5m can be presumed. For most results this slight deviation should not have had a large effect, as the measured variables should not vary extremely within that distance. In addition, the differences in methods between squares of 5 x 5 m (Kupferschmid Albisetti, 2003; Landolt, 2001) and the circular plots (5m radius) chosen in this study can lead to clear differences in the results, even when taken in the same year. This is particularly true for the subalpine level, were trees often grow in groups.

The variables measured in this study allowed to draw some useful conclusions about the forest recovery of bark beetle stands. In retrospect it would have been useful to record a few additional variables: 1) density of the regeneration on deadwood, 2) length of lying logs, 3) stage of decay at several locations, 4) presence of wood decaying fungi. The method used in this study did not allow to make an estimation on how many seedlings occurred on deadwood, as only their total number per element was counted, making the comparison to other studies which did evaluate densities impossible (Bače et al., 2012; Zielonka, 2006). Furthermore, the length of lying logs was not recorded, only their dbh, which did not allow to make an estimation on the deadwood volume. This would have been valuable to know in order to compare the values to past studies (Kupferschmid Albisetti et al., 2003) and Swiss averages (Brändli et al., 2020). The decay stages of deadwood were greatly variable within single elements on Gandberg. Many logs showed the full range of decay stages and taking one single measurement might not have been sufficient to accurately reflect this fact. A possible improvement could therefore be to take three measurements of the decay stage in certain distances. However, this could also lead to an unwanted homogenisation of results. Further, it would have been interesting to re-evaluate the presence of deadwood fungi to see if *Fomitopsis pinicola* was still dominant in 2020, as it was 15-20 years ago (Hamdan et al., 2005). This would allow an assessment of the suitability of deadwood as a seedbed, since elements which are inhabited by this species might be a poor growing substrate (Bače et al., 2012).

Most of the measurement methods used in this study are state of the art or have been long established and are used by many practitioners (Brändli et al., 2020; Lachat et al., 2019). However, especially the estimation of surface cover is a very subjective variable and might therefore greatly differ between studies. An option to circumvent this would have been to make cover estimations based on satellite imagery. However, if this would have led to more accurate results is disputable, as especially vegetation cover would have been hard to detect.

5.4.2 **Remote Sensing**

Analysing remote sensing data was a valuable addition to the field samples, as it allowed a spatially explicit assessment of the avalanche hazard. Remote sensing data made an in-depth analysis of potential avalanche release areas and run out pathways possible. However, several uncertainties did flow into the simulations presented in this study: 1) extrapolation of snow heights, 2) differences in the protection forest layer due to the non-existent forest layers for the years 1997 and 1985 and inaccuracies of VHMs, 3) subjective estimation of PRAs, 4) inherent model uncertainties of RAMMS and lack of knowledge on how to implement roughness into RAMMS simulations.

The snow height for Gandberg was extrapolated using the snow height from the meteorological station in Braunwald. If other stations would have been used for the extrapolation, slightly smaller snow heights for Gandberg would have been the result (see calculations in appendix C.3). Therefore, the snow heights used in this study were on the pessimistic side, in terms of avalanche size and destructiveness. For future studies it would make sense to do a sensitivity analysis and run the simulation with different snow heights.

The protection forest layer is typically calculated with the help of a forest layer to save time. This layer was only available for the year 2016, leading to slight discrepancies in the calculations for 2016 compared with the two pervious scenarios. Furthermore, the protection forest layer is based on VHMs which are not always accurate. Since they are based on photogrammetry methods, they are sometimes prone to errors due to the steepness of slopes or due to shading effects on north-facing mountain slopes (Ginzler & Hobi, 2015), as is the case on Gandberg. Therefore, the protection forest layer hast to be regarded with certain reservations. The use of Lidar data might have enhanced the accuracy of the simulations (Brožová, Fischer, et al., 2020), but they were not available since Gandberg is a game reserve and aerial surveys are not allowed.

Inaccuracies in the protection forest layer might in turn have led to errors in the size of the PRAs. The PRAs were drawn in GIS based on the standard procedure used at SLF and expert opinions have been consulted in order to draw reliable PRAs. Nonetheless, the shape and size of the PRAs are somewhat subjective. I recommend using cadastre data to verify PRAs as well as run out pathways, which was not possible in the case of Gandberg since no cadastre data was available.

RAMMS is a very useful tool to simulate avalanches, but as it is a model, it is only a simplification of reality and results should therefore always be questioned and doing a sensitivity analysis is recommended (Bartelt et al., 2017), this would however have exceeded the scope of this master thesis. One of the main uncertainties in the RAMMS simulations was how to include the roughness of the deadwood elements. As an approximation MuXi values in-between forest and flat surfaces were chosen. For future assessments I would recommend to do a more in-depth analysis on how to choose appropriate values for the roughness of deadwood elements, as they can play an important role in enhancing the surface roughness and in reducing the likelihood of avalanche formation.

5.5 Implications for Natural Hazard Management

As shown by the field data and the RAMMS simulations, the bark beetle stands should currently be unable to prevent the release of avalanches on Gandberg. Our field data indicated that especially the bark beetle stands of the subalpine level should have been prone to avalanche releases due their high percentage of grass, small percentage of crown cover, many gaps and low tree heights. This assumption was underlined by the fact that for both frequent and infrequent avalanche scenarios the RAMMS simulations of the year 2016 showed potential avalanche releases from the bark beetle stands.

The assumption that there currently is a lack in the protective function of Gandberg forest is disputed by the fact that there were no avalanches in the snow rich winters of 2018, 2019 and 2021, indicating that the young trees or the deadwood played a more important role than expected, at least against the release of smaller avalanches in 2021. Since no avalanches occurred in the past and because Gandberg has no direct protective function, the decision, not to clear the area, was a valid one. The only thing that could potentially have suffered damages, is the forest below. Measures such as plantings and temporary or permanent avalanche barriers would not have been cost-effective, as there is no large damage potential in the area.

Even though the measures taken after the disturbance were suitable, some measures could have helped to prevent the disturbances or their severity in the first place. The montane stands of Gandberg forest were a result of a clear-cut (Forstverwaltung Kt. Glarus, 1949, as cited in Kupferschmid Albisetti et al., 2003), which lead to dense homogenous stands with little advance regeneration (Kupferschmid et al., 2002) . In the future such homogenous stands should be prevented wherever possible, as more heterogenous and species rich forests are known to be more resistant and resilient against many types of disturbances (Bauhus et al., 2017; Thompson et al., 2009). Further, making sure that a forest has enough advance regeneration, through adequate forest practices, could reduce the risks and consequential costs after a disturbance (Rüegg & Schwitter, 2002). Since advance regeneration is able to react quickly to openings in the canopy, trees which germinated prior to a wind throw are often taller than those which germinated afterwards (Rüegg & Schwitter, 2002; Wohlgemuth et al., 2017), giving the new stand a "head-start".

Even though every situation is unique and strongly depends on local characteristics, the developments on Gandberg allow to make some recommendations on how to handle other bark beetle stands, where damage potential does exist. As we have seen, uncleared bark beetle stands can offer protection against avalanches at least for the first decade after a disturbance, maybe even longer, whereas the protective function of windthrow areas might decline more quickly, as all trees are thrown at once. Therefore, measures in bark beetle stands do not necessarily have to be taken immediately and forest managers can still decide at a later point in time if additional measures are necessary. However, the speed of recovery should be monitored closely. If reforestation is hampered by adverse growing conditions, such as high browsing pressures, poor soil, or short vegetation periods, additional measures might need to be considered.

In general, there are different combinations of management options which can be undertaken in the first years after a disturbance event: "clearing" or "non-clearing", "planting" or "natural regeneration" and "installing technical solutions" or "no technical solutions" (Schwitter et al., 2015). Several combinations of those measures are discussed in the "Entscheidungshilfe für

Sturmschäden im Wald“ (FOEN, 2008). Schwitter et al. (2015) found that especially areas, which had been salvaged, replanted and where avalanche barriers were installed, fulfilled the requirements for a protection forest. This is how windthrow areas have traditionally been managed. However, as bark beetle stands might offer longer protection against avalanches because relatively well conserved deadwood is continuously supplied from the standing dead trees (Bebi et al., 2015), less cost-intensive measures might be sufficient there. One possibility would be to take a patchwork approach and combine patches of “no intervention” with patches of “clearing and planting” or with patches of “group plantings in uncleared areas” in different proportions (Schwitter, 2011; Schwitter et al., 2015).This would allow to make use of the benefits each option offers.

“No intervention” retains all benefits offered by the deadwood elements: 1) deadwood is a valuable substrate for many saproxylic species (Brändli et al., 2020), 2) it can act as an effective avalanche barrier in the first years after a disturbance (Bebi et al., 2015; Frey & Thee, 2002) and 3) it can become a valuable seedbed (Frehner et al., 2005). However, Bače et al. (2012) found that bark beetle wood might not be as suitable for seedlings as other kinds of deadwood because of the presence of *Fomitopsis pinicola*. In bark beetle stands, which have also been affected by windthrows, it is therefore advisable to retain large diameter trees, root plates and deadwood elements caused by windthrows as they offer good growing conditions for seedlings (Bače et al., 2012). Another benefit of uncleared stands could be a reduced browsing intensity (Wohlgemuth & Kramer, 2015). However, a study on the Gandberg found that this was not true for chamois, which were not hindered by the lying stems but instead favoured as there was less snow and earlier snowmelt around the logs (Kupferschmid & Bugmann, 2005a).

“Clearing and planting” facilitates the planting efforts but also “plantings in uncleared areas” might be a possibility if natural gaps occur, where planting is possible. Both approaches allow to use the benefits offered by plantings. Studies in Vivian sites found that clearing and planting can lead to increased tree heights of 1.0-2.4m and prevent tree free gaps (Brang et al., 2015). Schöneberger et al. (2002) suggested that plantings can give trees a 10-year lead over naturally established trees and therefore considerably accelerate reforestation. To be effective plantings should be done right after the disturbance and in high enough densities (Schwitter et al., 2015). Furthermore, plantings should be done on suitable microsites and in groups to reduce maintenance efforts (Bebi et al., 2015). Group plantings could also result in a more heterogenous and therefore resilient forest when planting not only spruce but different tree species (Bauhus et al., 2017; Schönenberger, 2001). If clearings are considered, surviving trees should be retained, as they can act as seed sources and speed up forest recovery (Kupferschmid et al., 2002).

In areas where large damage potentials overlap with large risk potentials, as for example in steep slopes with large snow heights above a densely populated area, additional measures might be necessary after a large-scale bark beetle infestation, to guarantee a continued protection. If a street was located within the area, temporary street closures might be sufficient to reduce the damage potential. If other valuable infrastructures, like human settlements, are at risk, the situation looks different, as forest managers might want to reduce the risk as much as possible. Depending on the protection objective different measures can be implemented.

If Gandberg was a protection forest of high importance this would mean that measures would have to be taken against all frequent avalanches from the simulations of 2016 and maybe against some avalanches which were simulated in the 300y scenario as well. The RAMMS simulations would be very useful in this case to identify hotspots where damage potential and hazard potential overlap. The avalanche maps would allow practitioners to visit those hotspots and evaluate the forest structure at those specific locations in more detail. If it is clear that the forest will recover its protective function completely in a few years no interventions are necessary. This would for example be the case in the montane level of our field survey where tree heights and crown cover already were rather large and are likely to increase in the future. However, if the regeneration in such hotspots is visibly hampered, as was the case in the subalpine survey plots, measures such as temporary or even permanent avalanche barriers should be considered.

Since scenarios with return periods of 300 years are very rare, they are not usually used as a reference for the construction of avalanche barriers. As shown by the simulations for the 300y scenario most of Gandberg would be affected by avalanches. However, it would not be cost effective to build avalanche barriers everywhere. In all cases a cost benefit analysis should be done carefully, considering the potential of the forest to recover as well as the consequences of potential avalanches if recovery does not happen in time.

6 Conclusion

The main goal of this study was to contribute to the current knowledge about the speed of deadwood decay and forest renewal in uncleared bark beetle stands, as well as to give forest practitioners an example of how the protective function of such stands can develop over time. I showed that, compared to past studies, the height of deadwood elements decreased considerably, while trees took over the protective function only slowly, causing an overall decrease in the protective function of Gandberg forest.

That no avalanches occurred in the snow rich winter of 1999, can be attributed to the fact that the deadwood elements in the bark beetle stands remained standing for several years, which contributed substantially to the surface roughness. The decision not to clear the bark beetle stands did therefore not impede the protective function of the bark beetle stands in the first years after the disturbances. A second snow rich winter occurred in 2021. The comparison of the field data to reference values for protection forests suggests that both tree heights and crown cover should not have been large enough to offer sufficient protection against avalanche formation. In line with those findings was that the RAMMS simulations of the year 2016 showed a higher predisposition for avalanche releases in the bark beetle stands. Nonetheless, no avalanches actually occurred. An explanation for the lack of avalanches could be that requirements for protection forest are usually based on mature stands and might underestimate the capability of young trees and deadwood elements to prevent avalanche formation. Furthermore, it is important to consider that both the snow rich winters of 1999 and 2021 only reached snow heights of a scenario with a return period of 30 years. If larger snow heights occur, avalanches are still possible. I therefore conclude that Gandberg forest currently offers protection against small avalanches with frequent return periods, but not against bigger more infrequent avalanches.

In similar situations with low damage potentials, “no intervention” might be a suitable and cost-effective management option. However, local conditions in mountain regions can be highly variable. In general, forest practitioners should consider if a hazard potential overlaps with a damage potential. If so, “no intervention” might not be a valid option. Especially if forests are located in areas with frequent large snow heights, steep slopes, harsh growing conditions or above valuable human infrastructure, additional measures should be considered after a large-scale bark beetle infestation.

This study has taken a first step towards evaluating long-term effects of bark beetle disturbances on the protective function of a mountain forest. It would be interesting to survey the forest structure again in 10-20 years. Such a repetitive study would allow for an even more comprehensive and complete picture on the long-term development of bark beetle stands. The applicability of this study to other areas is restricted, because it was a case study with a limited sample size. Nonetheless, it is a valuable contribution to the scientific knowledge about the post-disturbance development of bark beetle stands and the associated changes in their protective function, as such studies have been rare in the past.

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Appendix A Supplementary Documents: Introduction

A.1 Year of Stand Death Caused by Vivian and Bark Beetles

Different stands of Gandberg died in different years (figure 30, modified from Kupferschmid Albisetti (2003)). In 1990, Vivian caused a large windthrow on the left side as well as scattered windthrows on the rest of Gandberg (dark green). These windthrows were followed by bark beetle infestations, which took place between 1992-1997 (green - red).

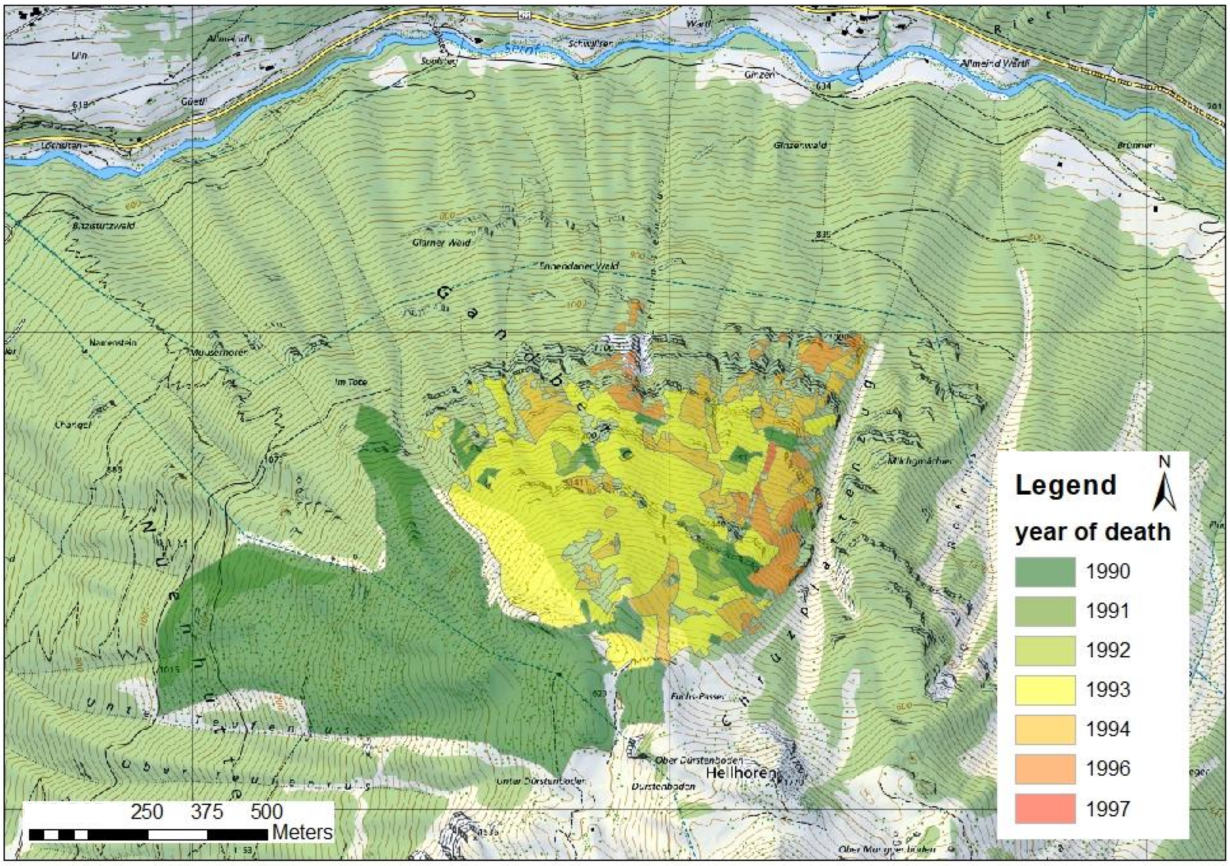


Figure 30: Map showing in which year which parts of the forests were killed (map modified from Kupferschmid Albisetti (2003)).

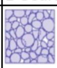
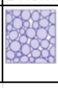
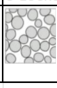
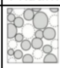
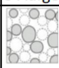
Appendix B Supplementary Documents: Methods

B.1 Field Protocol

The field protocol that was used in this study had three parts: part A for the surface cover, part ET for the deadwood and part EV for the seedlings and saplings.

A	X			Y			Höhe	
Ort		Plot Nr.		Datum		Uhrzeit		
Lücke (0/1)		Länge (m)		Breite (m)		Bemerkung		
Bodenvegetation		Typ 1	Anteil %	Typ 2	Anteil %	Typ3	Anteil %	
Deckungsgrad								

	Deckungsgrad		Wirkungshöhe				
Totholz	Total		<50cm (%)	50-100cm (%)	100-150cm (%)	150-200cm (%)	> 200cm (%)
	liegend						
	stehend						
	hängend						

	%	1 Gedrängt	2 Normal	3 Locker	4 Räumig	5 Aufgelöst	6 Gruppen
Kronendekungsgrad							
Bemerkungen							

	Art	Anzahl
Sträucher	Hasel	
	Holunder	
	Geissblatt	
	Grünerle	
	Heckenrose	
	Andere	

ET	An nächster Stelle									An dickster Stelle	Moderholzverjüngung									
Totholz	Azimut (°)	Distanz (m)	Höhe (cm)°	Durchmesser beim Moderholz (cm)	Durchmesser WT (cm)	BHD WT (cm)	Hängend oder liegend (H/L)	Vermod.grad (1-5)	Bewegung 0/1	Durchmesser (cm)	vorhanden 0/1	Baumart	Anzahl	Höhe (cm)	Vermoderungsgrad bei Verjüngung (1-5)	Baumart	Anzahl	Höhe (cm)	Vermoderungsgrad bei Verjüngung (1-5)
h El.																				
Stamm1																				
Stamm2																				
Stamm3																				
Stehend tot 1																				
Stehend tot 2																				
Stehend tot 3																				

°Bei Stämmen: Höhe des Stammes über Boden, an Stamm Oberseite, bergseitig. Bei stehend tot: Höhe des Stirzels

Skizze

EV

Plot Nr.

	Nr.	Baumart	Azimut (°)	Distanz (m)	BHD (cm)	Höhenklasse (1-4)*	Höhe (höchster) (cm)	Verbiss (0/1 und E, S oder ES)	Schadengrad 1-3 (4-tot)	andere Schäden (0/1)	Moderholz (0/1)	Anzahl	Bemerkung
Grosse Bäume	**1**												
	2												
	3												
	4												
	5												
	6												
	7												
	8												
	9												
	10												
	11												
	12												
	13												
	14												
	15												
	16												
	17												
	18												
Verjüngung	**1**												
	2												
	3												
	4												
	5												
	6												
	7												
	8												
	9												
	10												
	11												
	12												
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	24												
	25												
	26												
	27												
	28												
	29												
	30												
	31												
	32												
	33												

*analog LFI2: 9.11 Jungwaldklasse (Code):

1 = Klasse 1 10 cm bis 39 cm Höhe (bei uns nur ab 20cm)

2 = Klasse 2 40 cm bis 69 cm Höhe

3 = Klasse 3 70 cm bis 99 cm Höhe

4 = Klasse 4 100 cm bis 129 cm Höhe

B.2 Gumble Diagrams

The Gumble diagrams show the extreme value statistic, calculated with the online tool EVA+, for the meteorological station Braunwald, which was used to calculate the 3-day cumulative now height for Gandberg (figure 31). The 3-day cumulative snow height for Braunwald for a return period of 30 years is 122.3cm (dark green arrows) and for a return period of 300 years is 163.8cm (light green arrows).

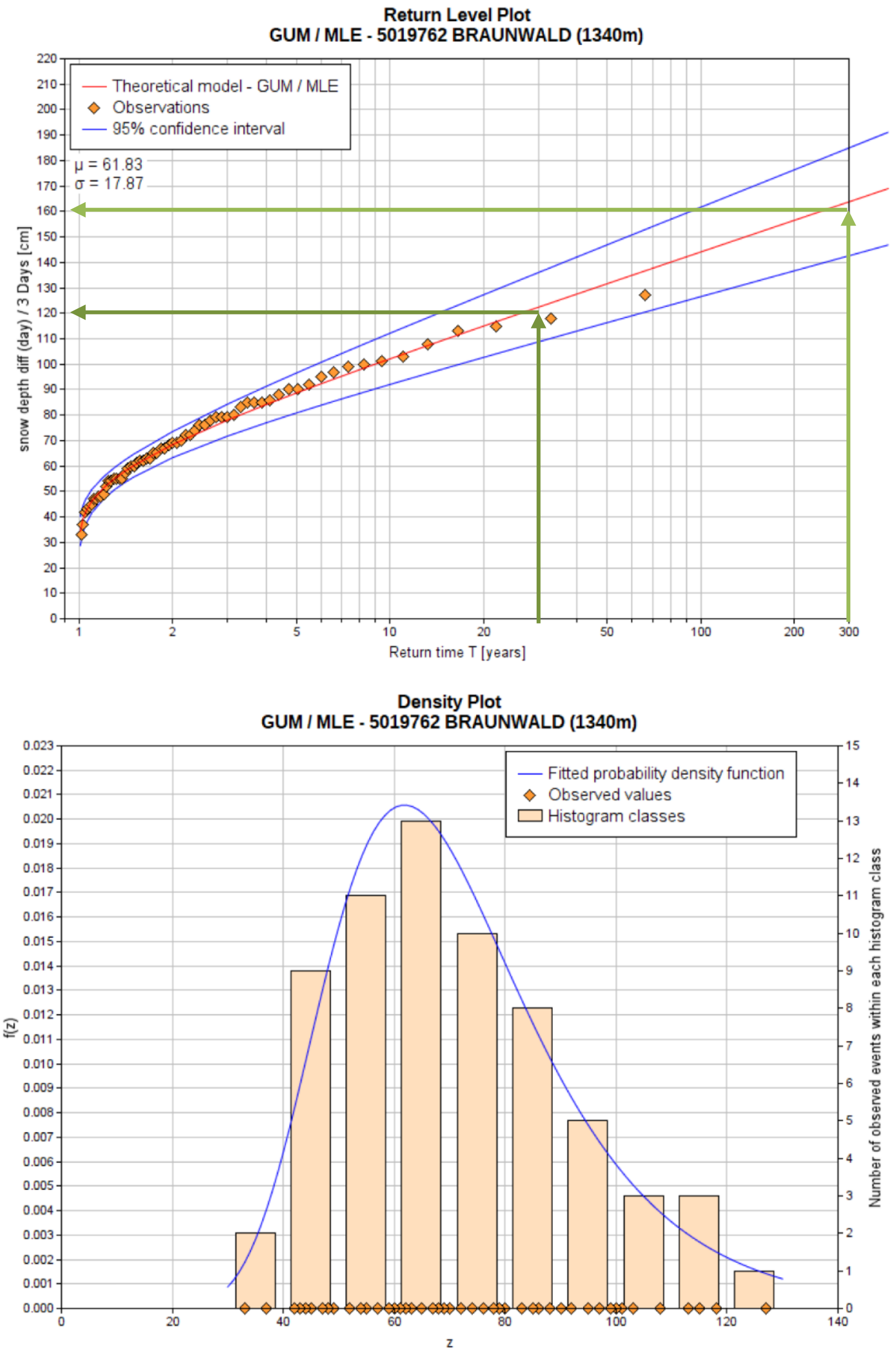

Figure 31: Fitted Gumble distribution and the corresponding density plot for the snow values of the meteorological station in Braunwald.

Appendix C Supplementary Documents: Results

C.1 Pictures of Some Interesting Aspects of Gandberg Forest

The following pictures show interesting aspects of the bark beetle stands on Gandberg (figure 32).

Figure 32: Pictures of interesting aspects of Gandberg forest. From top left to bottom right: A) a forest gap in the subalpine level, B) typical ground cover types: fern, moss, grass and deadwood (with a spruce seedling), C) standing, hanging and lying deadwood in different stages of decay, D) seedling growing in an indentation with high stage of decay, whereas next to it the wood is still quite hard, showing the heterogeneity of decay stages within a single deadwood element, E) galls on spruce causing crooked branches, F) recently killed spruce tree with a living bark beetle.

C.2 Height Distribution of Spruce Seedlings

In the montane level there were many seedlings in the lowest height class, whereas afterwards the distribution was rather uniform (figure 33, left). In the subalpine level the distribution looks more like expected with most individuals in the lowest height class and a decrease afterwards (figure 33, right).

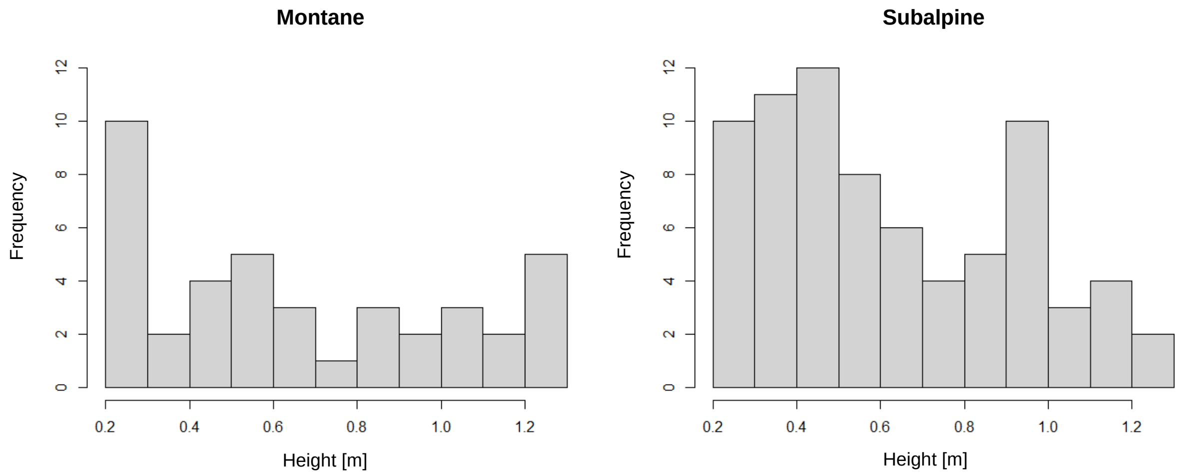

Figure 33: Height distribution of spruce seedlings for both elevational levels.

C.3 Snow Height Calculation

The snow height for Gandberg was calculated using the Braunwald station. However, if other stations had been used the snow heights would have been slightly smaller (table 13).

Table 13. calculation of the cumulative 3-day snow heigh for the meteorological stations in Braunwald, Flumserberg and Elm (s=subalpine, m=montane). Braunwald has a distance of roughly 11km to Gandberg, Flumserberg 18km and Elm 6km. The number of observations was 66 for Braunwald, 67 for Flumserberg and 30 for Elm.

	station 3-day snow accum-ulation [cm]	altitude weather station [m]	height cor-rection per 100m [cm]	median height PRAs [m]	Height diff. of station and PRAs [m]	addition for height differenc e [cm]	PRAs 3-day snow accum-ulation [cm]	PRAs d0* [cm]	drift-snow addit -ion	avera ge slope angle PRAs [°]	slope correct -ion factor	**snow height d0 in PRAs [cm]**
Braunwald												
m 30y	122.3	1340	5	1355	15	0.75	123.05	108.6	0	39	0.62	**65.0**
m 300y	163.8	1340	5	1355	15	0.75	164.55	145.3	0	39	0.62	**90.0**
s 30y	122.3	1340	5	1565	225	11.25	133.55	117.9	10	41	0.58	**75.0**
s 300y	163.8	1340	5	1565	225	11.25	175.05	154.6	20	41	0.58	**100.0**
Flumserberg												
m 30y	84.7	1310	5	1355	45	2.25	86.95	76.8	0	39	0.62	**50.0**
m 300y	110.3	1310	5	1355	45	2.25	112.55	99.4	0	39	0.62	**60.0**
s 30y	84.7	1310	5	1565	255	12.75	97.45	86	10	41	0.58	**55.0**
s 300y	110.3	1310	5	1565	255	12.75	123.05	108.6	20	41	0.58	**75.0**
Elm												
m 30y	130.4	1690	5	1355	-335	-16.75	113.65	100.3	0	39	0.62	**60.0**
m 300y	173.6	1690	5	1355	-335	-16.75	156.85	138.5	0	39	0.62	**85.0**
s 30y	130.4	1690	5	1565	-125	-6.25	124.15	109.6	10	41	0.58	**70.0**
s 300y	173.6	1690	5	1565	-125	-6.25	167.35	147.8	20	41	0.58	**95.0**

C.4 Map of the Maximal Snow Pressures

As not only the snow height is relevant to the destructiveness of avalanches but also the pressure, maps showing the pressure of the different scenarios are shown below (figure 34). The highest pressures occurred in the 300y scenario of 2016.

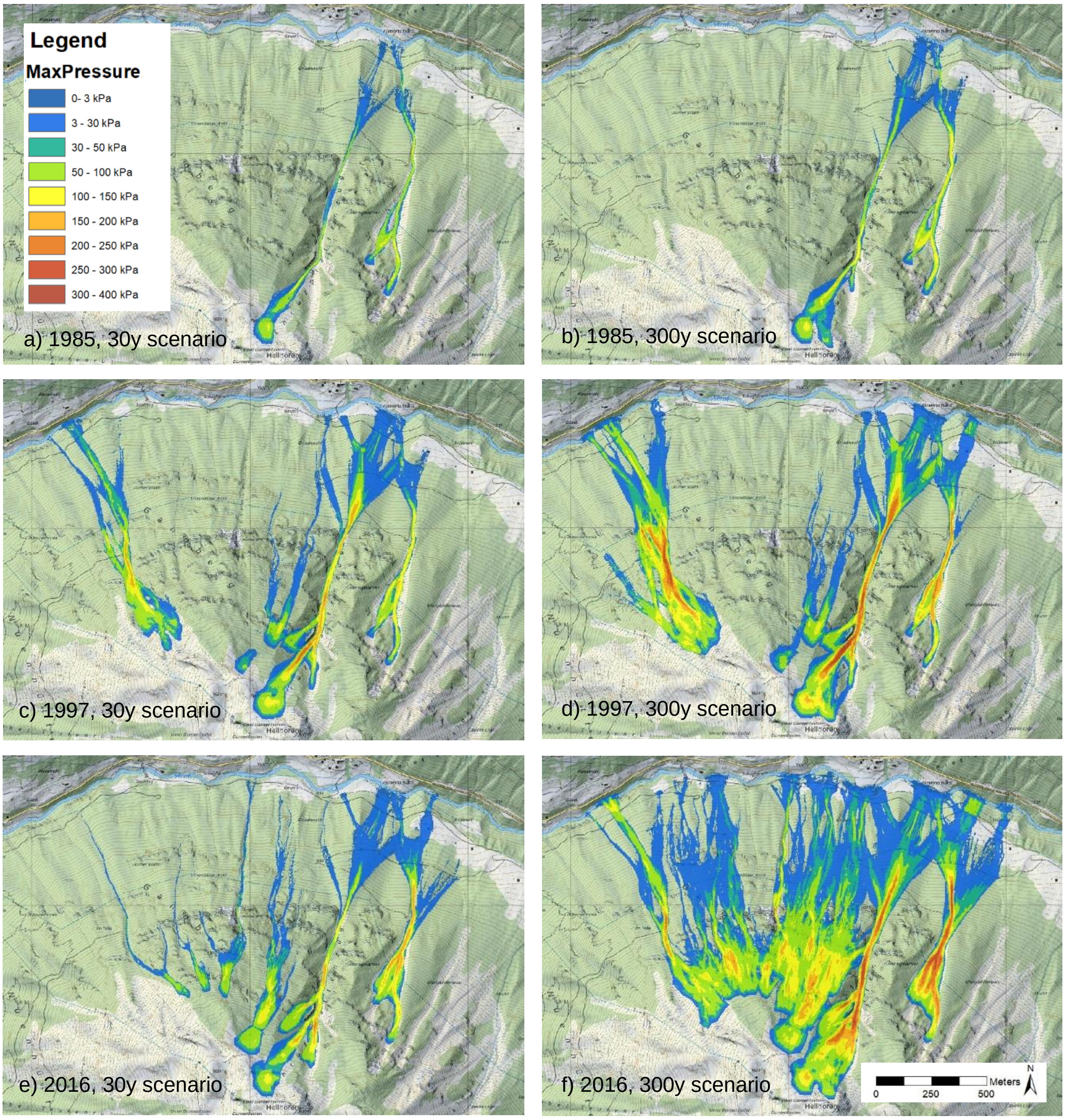

Figure 34: RAMMS simulations of the snow pressures of the potential avalanches of all six scenarios (Map: © swisstopo).

Appendix D Supplementary Documents: Discussion

D.1 Pictures Comparing the Years 2000 and 2020

Compared to 20 years ago there were less tall deadwood elements and more tree regeneration in 2020 (figure 35). The two pictures on the top show the montane level in 2003 and 2020 and the two on the bottom show the Gandberg from the opposite side of the valley in 1996 and 2020.

Figure 35: Pictures 1 & 2: The pictures were taken in the montane level, standing on the path facing the outcropping. The left picture is from March 2003, by Andrea D. Kupferschmid and the right one was taken in October 2020. Pictures 3 & 4: View of the study site from the opposite side of the valley. The picture on the right side was taken during the bark beetle infestation in 1996 by Ulrich Wasem and the picture on the left in the year 2020.

D.2 Snow Heights at Braunwald Station in the Years 1999, 2018, 2019 and 2021

The 3-day cumulative snow height for Braunwald for a return period of 30 years is 122.3cm and for a return period of 300y 163.8cm (see Gumble diagram in appendix B.2). Only in the years 1999 and 2021 did the 3-day cumulative snow height reach values with return periods of around 30 years (e.g. 118cm between February 5-8th of 1999 and 116cm between January 12-15th of 2021, figure 36 black arrows). In 2018 and 2019 the 3-day cumulative snow height was below a scenario with a return period of 30 years. Snow height with return periods of 300 years were reached in none of those years.

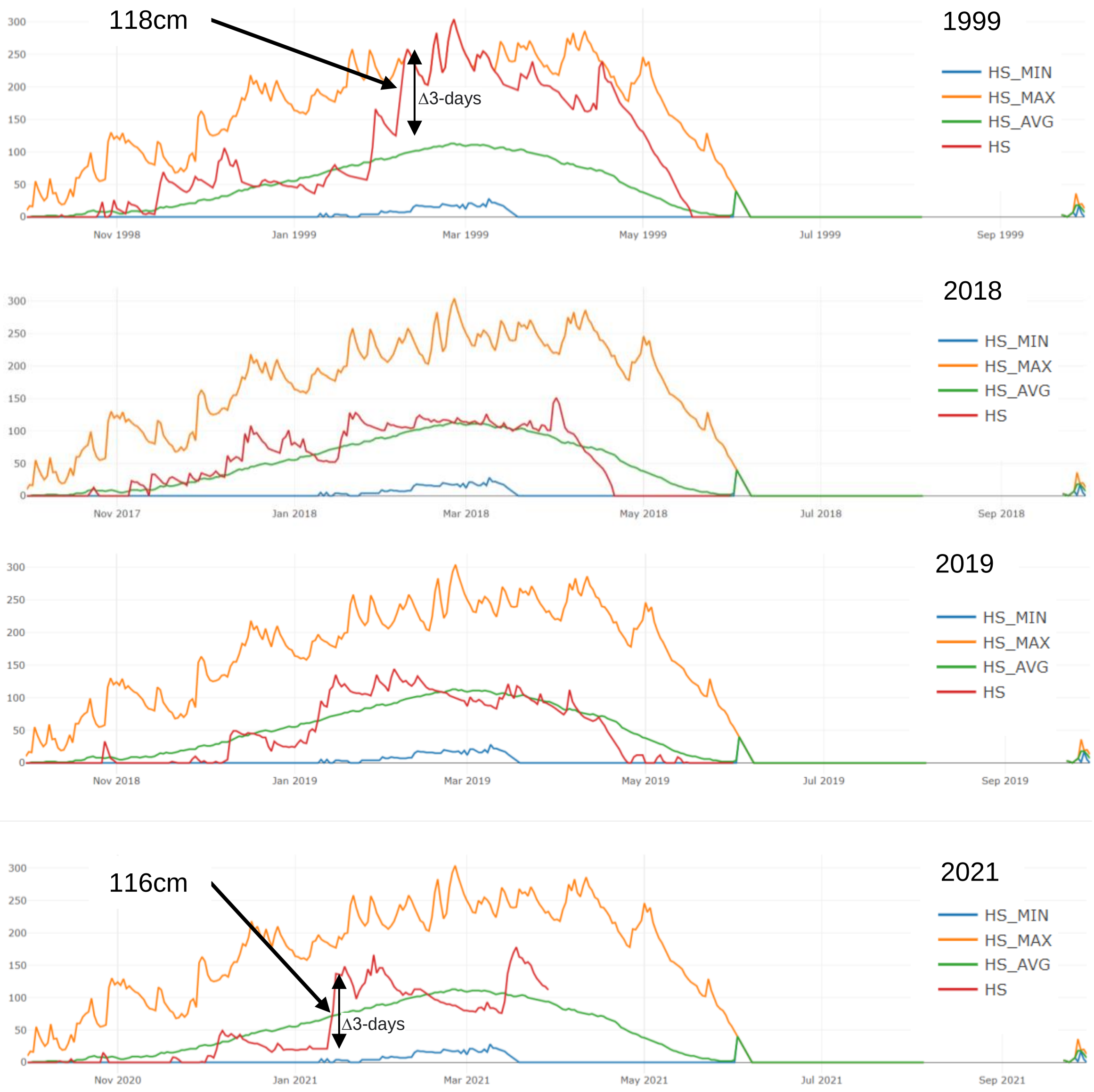

Figure 36: Snow heights at Braunwald station for the years 1999, 2018, 2019 and 2021. The orange line (HS_MAX) shows the maximal snow height that was ever measured, the blue line (HS_MIN) shows the minimal snow height which was ever measured, the green line is the average snow height (HS_AVG) and the red line (HS) shows the effective snow height of the corresponding year. The arrows indicate the dates with the highest 3-day cumulative snow height of 1999 and 2021 (Δ3-days), which were snow heights with a return period of roughly 30 years.

D.3 Avalanches in the Canton of Glarus in the Year 2018

The map below shows avalanches which actually occurred on Gandberg in 2018 (figure 37). None of the avalanches are located in the bark beetle stands.

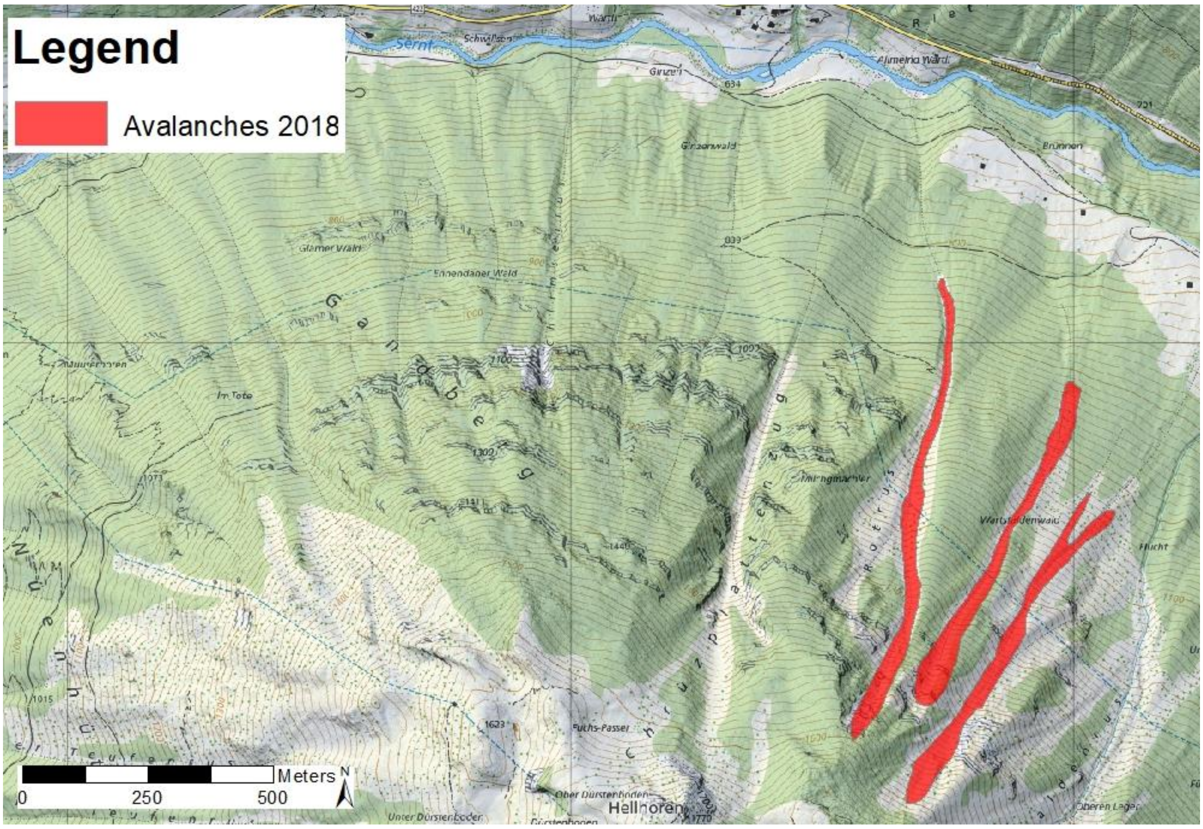

Figure 37: Avalanches which occurred on Gandberg in January 2018 (map with raw data from Bühler et al. (2019)). Avalanches were mapped with the help of satellite images (Bühler et al., 2019). Only the left most avalanche was also simulated in our study, the other two were not simulated since they lay outside of the area of interest. No avalanches occurred within the bark beetle stands in 2018 (Map: © swisstopo, 2020).