Effects of bark beetle attacks on forest snowpack and avalanche formation – implications for protection forest management

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Abstract

Healthy dense forests growing in avalanche terrain reduce the likelihood of slab avalanche release by inhibiting the formation of continuous snow layers and weaknesses in the snowpack. Driven by climate change, trends towards more frequent and severe bark beetle disturbances have already resulted in the death of millions of hectares of forest in North America and central Europe affecting snowpack in mountain forests and potentially reducing their protective capacity against avalanches. We examined the spatial variability in snow stratigraphy, i.e. the characteristic layering of the snowpack, by repeatedly measuring vertical profiles of snow penetration resistance with a digital snow micro penetrometer (SMP) along 10 and 20 m long transects in a spruce beetle infested Engelmann spruce forest in Utah, USA. Three study plots were selected characterizing different stages within a spruce beetle outbreak cycle: non-infested/green, infested > 3 years ago/gray stage, and salvage-logged. A fourth plot was installed in a non-forested meadow as the control. Based on our SMP measurements and a layer matching algorithm, we quantified the spatial variability in snow stratigraphy, and tested which forest, snow and/or meteorological conditions influenced differences between our plots using linear mixed effects models. Our results showed that spatial variability in snow stratigraphy was best explained by the percentage of canopy covering a transect ($R^2 = 0.71$, $p < 0.001$), and that only 14% of the variance was explained by the stage within the outbreak cycle. That is, differences between green and gray stage stands did not depend much on the reduction in needle mass, but spatial variability in snow stratigraphy increased significantly with increasing forest canopy cover. At both study plots, a more heterogeneous snow stratigraphy developed, which translates to disrupted and discontinuous snow layers and therefore reduced avalanche formation. We attribute this to the small fine branches and twigs still present in the canopy of gray stage trees influencing snow interception and unloading, and especially increasing canopy drip. In contrast, salvage logging that reduced the canopy cover to ~25%, led to a spatially less variable and similar snow stratigraphy as observed in the meadow. At these two study plots, a homogeneous snow stratigraphy consisting of distinct vertical and continuous slope-parallel soft and hard snow layers including weak layers had formed, which is generally more prone to avalanche release. Our findings therefore emphasize advantages of leaving dead trees in place, especially in protection forests where bark beetle populations have reached epidemic phases.

Keywords: snow stratigraphy; avalanche formation; protection forest; bark beetle; snow micro penetrometer; SMP

Highlights

- Snow penetration resistance was measured repeatedly below bark beetle killed trees
- Variability in snow stratigraphy was quantified with a new layer matching algorithm
- Spatial variability in snow stratigraphy is driven by percentage of canopy cover
- Leaving dead trees in protection forests contributes to avalanche protection
- Salvage logging can result in snow stratigraphy more prone to avalanche release

1. Introduction

Mountain forests growing in avalanche terrain serve an important role in avalanche protection by reducing and disrupting the formation of continuous snow layers and weaknesses in the snowpack that contribute to slab avalanches (Bebi et al., 2009; Schweizer et al., 2003). The spatial deposition of snow and snow metamorphism determine snow stratigraphy, the characteristic layering of the snowpack with varying properties, which develops over the course of a winter (Pielmeier and Schneebeli, 2003). Forests modify snowpack properties through interception of falling snow by tree crowns, the reduction of near-surface wind speeds, changes to the energy balance beneath and around trees, and the direct support of the snowpack by stems, remnant stumps and dead wood (Schneebeli and Bebi, 2004). Collectively these processes promote a highly variable snow stratigraphy over space and time, which can inhibit avalanche formation in forests (Bebi et al., 2009; Brang et al., 2006).

Native bark beetles (Coleoptera: Curculionidae: Scolytinae) are important disturbance agents in forest ecosystems that naturally occur alongside their hosts (Jenkins et al., 2012, 2008; Raffa et al., 2008). These insects infest weakened or stressed trees under endemic population phases and, therefore, naturally alter forest ecosystems by killing live overstory trees, which creates forest openings for other tree species and age classes to establish (Raffa et al., 2008; Veblen et al., 1991). Under the right environmental and stand conditions as well as availability of suitable host material, bark beetle populations can grow from an endemic to an epidemic phase, which may overcome host resistance and initiate mass infestations that overwhelm healthy live trees (Coulson, 1979). Recent bark beetle outbreaks in North America and central Europe have reached unprecedented levels resulting in the death of millions of hectares of forest (Baier et al., 2007; Black et al., 2013). Driven by climate variability and change, this trend towards more frequent and severe disturbances is presumed to continue for the coming decades (Bentz et al., 2010). Bark beetles are also expected to further colonize previously unsuitable habitats at higher elevations and latitudes (Bentz et al., 2016; Logan et al., 2010; Seidl et al., 2009), which profoundly affects snowpack in mountain forests (Edburg et al., 2012; Pugh and Small, 2012).

In the mountain forests of Europe, the European spruce bark beetle (*Ips typographus* L.) is the most important biotic agent of disturbance infesting Norway spruce (*Picea abies* (L.) Karst.) (Faccoli and Bernardinelli, 2014; Jönsson et al., 2009; Seidl et al., 2009). Likewise, the spruce beetle (*Dendroctonus rufipennis* Kirby) is the most prevalent bark beetle species in high-elevation Engelmann spruce (*Picea engelmannii* Parry ex Engelm.) dominated forests in western North America (DeRose and Long, 2009; Hebertson and Jenkins, 2007; Veblen et al., 1991). Both bark beetle species (hereafter collectively referred to as spruce bark beetles) have similar impacts driving changes in community structure, composition, and function of spruce forests. Unlike wind or logging disturbances where trees are removed from the vertical forest strata, unmanaged beetle infested forests still retain stand structural integrity through standing dead tree boles (Müller et al., 2008). Following spruce bark beetle induced tree mortality, a reduction in canopy bulk density occurs (Jorgensen and Jenkins, 2011), as needles are shed from tree crowns over a one to five year period (Page et al., 2014). The loss of needles reduces canopy interception leading to enhanced subcanopy snow accumulation (Biederman et al., 2012; Pugh and Small, 2013; Winkler et al., 2014). Shifts from green-infested (current year's infestation) to phases where foliar moisture content declines and needles fade from green to yellow (previous year's infestation), to a gray phase that occurs when dead trees have dropped all their needles (approximately three to five years post-infestation), gradually alter the energy balance at the snow surface beneath canopies through increased light transmission and wind speeds (Boon, 2009; Perrot et al., 2014). This also reduces snow surface albedo through increased litter accumulation on the snow surface (Winkler et al., 2010). These changes influence subcanopy snow stratigraphy significantly by altering snow (re-)distribution and metamorphism with uncertain consequences for the avalanche hazard. That is, the reduction in canopy bulk density may promote the formation of more homogeneous and continuous snow layering and weaknesses in the snowpack that are linked to slab avalanche formation (Schweizer et al., 2003). For example, the occurrence of deciduous tree species was found to be one key forest structural parameter that influences avalanche formation in forested areas (Schneebeli and Meyer-Grass, 1993). Bebi et al. (2009) found that the presence of European larch (*Larix decidua* Mill.) is an important factor that increases the probability of avalanche release from spruce and larch dominated subalpine forests on steep slopes (slope angle >30°), in particular if they have a crown cover density between 30 and 50%. Moreover, the minimum gap widths required for avalanche formation in such subalpine forests is only 5-10 m compared to 20 m for coniferous forests with a crown cover density of 60% (Schneebeli and Bebi, 2004). Spruce bark beetle-induced tree mortality may therefore create potential avalanche release areas where the forest previously protected settlements and infrastructure against avalanches (Bebi et al., 2017; Teich et al., 2016).

Managing protection forests for stability, resilience and sustainability is a long-term investment for mitigating the avalanche hazard (Motta and Haudemand, 2000). In the European Alps, avalanche protection forests primarily consist of Norway spruce and are therefore susceptible to frequent epidemic and severe European spruce bark beetle outbreaks as predicted for the coming decades (Seidl et al., 2009). Current management strategies include salvage logging to remove infested trees through costly helicopter operations with the goal to reduce the expansion of ongoing spruce bark beetle outbreaks and the potential decline in forest’s protective effects against avalanches (Brang, 2001). However, little research has been conducted into whether or not and over what timespan infested spruce forests may still provide protection against avalanche release (Bebi et al., 2017), and only few studies have examined the stratigraphy of subcanopy snowpack in general (Fiebiger, 1978; Imbeck, 1983; Molotch et al., 2016; Perrot et al., 2014; Sturm, 1992; Zingg, 1958), despite its considerable contribution to forest avalanche formation (Teich et al., 2013). To our knowledge, no study to date has investigated the effects of spruce bark beetle infestations on the evolution of subcanopy snow stratigraphy linked to avalanche protection by forests.

Snowpack observations in forested terrain are rare, and typically describe layering and related physical and mechanical properties by point observations with snow pit profiles (Fiebiger, 1978; Imbeck, 1983; Imbeck and Ott, 1987; Zingg, 1958). Such point observations emphasize and illustrate the heterogeneous stratigraphy of subcanopy snowpack, but are not able to adequately describe spatially distributed effects of forests on the evolution of snow stratigraphy throughout the snow season. Furthermore, manual snow pit profiles disturb the snowpack such that repeat measurements are not possible, and are highly dependent on observer skills introducing uncertainty and potential bias, if the snow pit profile is mischaracterized. In contrast to time- and labor-intensive manual snow pit profiles, the SnowMicroPen (SMP) is a portable and minimally invasive digital penetrometer, which quickly measures snow penetration resistance along a vertical profile (Johnson and Schneebeli, 1999; Schneebeli and Johnson, 1998). Therefore, snow layering can be identified from SMP penetration resistance profiles enabling an unambiguous investigation of snow stratigraphy and if several adjacent SMP measurements are taken, its spatial variability. Due to that spatial variability in snow stratigraphy, continuous snow layers are not necessarily positioned at the same depth in adjacent measurements. To quantify spatial variability it is therefore necessary to track common layers between different SMP penetration resistance profiles (e.g. Kronholm et al., 2004). This tracking was generally performed manually, which limits the amount of SMP penetration resistance profiles to be processed and the number of snow layers to be compared (e.g. Kronholm et al., 2004; Sturm and Benson, 2004). By automatically tracking distinct snow layers with a recently developed matching method, vertical and slope-parallel variabilities in snow stratigraphy observed by several spatially distributed SMP measurements, can now be disentangled and quantified (Hagenmuller and Pilloix, 2016). This quantification can be used to infer, if a snow stratigraphy observed at one site might be more (homogeneous snow stratigraphy) or less (heterogeneous snow stratigraphy) prone to avalanche release. We define a homogeneous snow stratigraphy as continuous slope-parallel snow layering with a distinct vertical heterogeneity. In contrast, a heterogeneous snow stratigraphy is characterized by less distinct vertical snow layering that discontinue parallel to a slope.

We used the SMP to repeatedly examine the snowpack under tree canopies of spruce beetle infested Engelmann spruce forest stands in the Uinta Mountains in Utah, USA, over two winter seasons. We then applied the described matching algorithm to our dataset to quantify the observed spatiotemporal variability in snow stratigraphy.

We hypothesize that:

1) Associated with the decrease in live canopy, spatial variability in snow stratigraphy is gradually decreasing from a more heterogeneous snowpack to a more homogeneous snowpack (i.e., increasing distinct vertical and continuous slope-parallel snow layering) from green and green-infested to gray stage to salvage-logged spruce forest stands.

2) Forest canopy condition (i.e., green and green-infested vs. gray stage vs. salvage logged forest stands vs. no canopy), in combination with typical snow and meteorological patterns, is the main driver for changes to the spatial variability in snow stratigraphy.

3) Surface roughness in terms of the amount and height of downed woody debris is linked to a greater heterogeneity in the spatial variability of snow stratigraphy.

We test and discuss our hypotheses by linking the quantified spatiotemporal variability in snow stratigraphy to forest, snow and meteorological conditions. Guided by our small-scale but highly detailed observations, we develop a conceptual framework describing the effects of subalpine spruce forests on snow stratigraphy following spruce bark beetle outbreaks years to decades after infestation, and discuss implications for avalanche protection forest management. Developing appropriate mitigation and adaptation measures is important throughout subalpine spruce forests across Europe where infestations by European spruce bark beetle have been increasing (Faccoli, 2009; Grodzki, 2007; Jonášová and Prach, 2008; Seidl et al., 2014), and particularly in densely populated mountain regions where protection forest management is critical for safeguarding property, lives, and infrastructure (Dorren et al., 2004; Olschewski et al., 2012).

2. Methods

2.1 Study site and plot descriptions

Our study site was located in an Engelmann spruce-subalpine fir (*Abies lasiocarpa* (Hooker) Nuttall) forest at an elevation of approximately 2900 m in the Uinta Mountains in Utah, USA (40.854655N 110.9568W; Fig. 1).

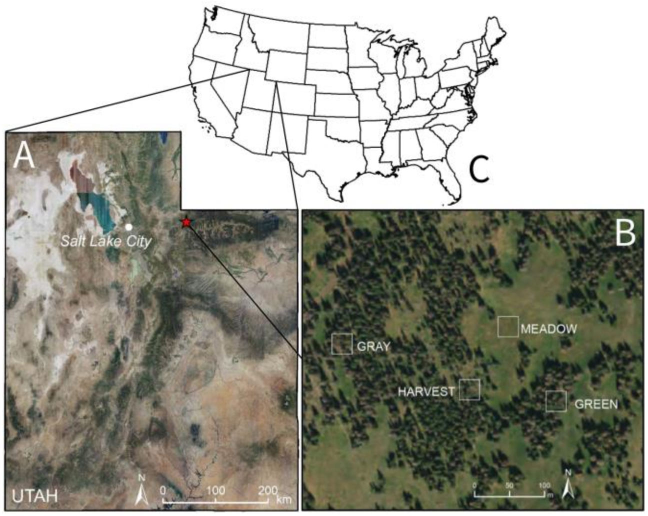

Fig. 1. Study site (A), and study plot (B) locations including one green stand (GREEN), one gray stage stand (GRAY), one salvage-logged stand (HARVEST), and one meadow area (MEADOW) in the Uinta Mountains in Utah, USA (C). Imagery from National Agricultural Imagery Program (USDA Farm Service Agency, 2014).

Four study plots were selected in October 2014 in close proximity to each other (< 350 m) to minimize meteorological and topographical differences between study plots while characterizing different stages during a spruce beetle outbreak cycle (Table 1, Figs. 1 and 2).

Table 1

Topography of four selected study plots at the study site in the Uinta Mountains in Utah, USA (Fig. 1).

Topography	**Study plot***			
	GREEN	**GRAY**	**HARVEST**	**MEADOW**
Elevation (m)	2909	2901	2909	2896
Slope (°)	5	5-10	10	10
Aspect	N-NE	N	NW	N

GREEN = green stand; GRAY = gray stage stand; HARVEST = salvage-logged stand; MEADOW = non-forested meadow area

*Each study plot was approximately 200 m^2 in size

We selected four plots that were (1) non-infested by *Dendroctonus rufipennis* (hereafter referred to as GREEN), (2) infested > 3 years prior to the study (GRAY), (3) salvage logged (HARVEST), and (4) an open meadow plot as a control (MEADOW; Fig. 2).

Fig. 2. Stand conditions of study plots in summer 2015 (A, B, C) and winter 2016 (D): A) GREEN, B) GRAY, C) HARVEST, and D) MEADOW (see Fig. 1 for locations). Photos: Michaela Teich

Salvage logging is a post-disturbance forest management strategy designed to recuperate wood product value, reduce hazardous fuels, and to enhance regeneration (Lindenmayer and Noss, 2006). The HARVEST plot was salvage logged in the fall of 2013 (USFS personal communication) where dead overstory spruce were removed and live overstory and understory trees were retained with dbh (diameter at breast height; measured at 1.37 m above ground) < 15 cm. This size class of trees is less prone to spruce bark beetle attack (Fettig et al., 2007). Logging activities increased the surface roughness over this plot through the spread of residual logging slash with effective woody debris heights found to be up to 0.95 m (Fig. 2C). A non-forested plot was installed and delineated by a roped boundary to prevent anthropogenic disturbance in an open MEADOW as the control, representing a total removal of forest canopy cover (Fig. 2D). During plot establishment, standard forest mensuration measurements of forest structure including stem density, tree height, dbh, crown diameter, canopy base height, percentage of canopy cover, and percentage of live canopy were collected in each plot.

After plot selection and beginning with winter snowpack data collection, few trees (< 5) in the GREEN plot showed signs of current year's spruce beetle infestation, i.e. reddish-brown frass had accumulated at the base of trees, and beetle entrance holes were visible, but needles were still green and had yet to fade. During the winter of 2014/2015 (hereafter referred to as winter of 2015), the infested trees were partially debarked by woodpeckers leaving layers of bark flakes on the snow surface around the boles of trees, which were subsequently buried throughout the snow season. Needles of infested trees started to turn yellowish-green and needle release began during the winter of 2015/2016 (hereafter referred to as winter of 2016) increasing the litter content on the snow surface and at snow layer boundaries. As we revisited the GREEN plot in July 2016 (after winter field campaigns were completed), almost all trees had become infested, and 5-10% of trees had begun to lose the majority of their needles indicating that they were dead.

Trees in the GRAY plot were attacked in 2011 and had already dropped needles at the time of study plot establishment leaving the upper crowns exposed with only twigs and small branches still attached (Fig. 2). Gray trees were interspersed with few green-infested trees which consistently dropped needles onto the snow surface throughout both winters.

2.2 Field measurements

The SnowMicroPen (SMP) is a digital snow penetrometer that records penetration resistance with a constant penetration speed of 20 mm s^{-1} every 4 µm to a depth of 1.2 m (Schneebeli and Johnson, 1998). The SMP measures the penetration resistance in a range from 0.01 N for soft low density snow up to 41 N (which was manually set as overload limit to prevent sensor damage) for dense hard snow. The obtained depth-resistance signals (further referred to as SMP profiles) can therefore be interpreted as snow hardness measurements, which are used in practice and research as indicators for snow mechanical properties (Fierz et al., 2009; Marshall and Johnson, 2009), and thus snowpack stability (Reuter et al., 2015).

We used the SMP to examine the snow stratigraphy and to monitor the evolution of the snowpack in our four study plots from mid-January to mid-April of 2015 and 2016 for a total of 15 winter field campaigns (Table A1). During the first campaign of each sampling season, we defined and marked start and endpoints of the initial transect (Transect 1) in each of the four plots, which served as reference for all following field campaigns (Fig. 3; Table A1).

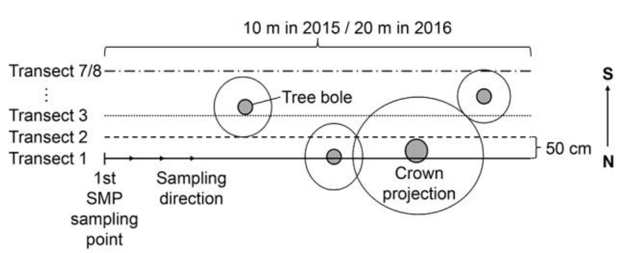

Fig. 3. Schematic of sampling design. SnowMicroPen (SMP) measurements were taken in an east to west direction at 0.3 m intervals in winter of 2015 and increased to every 0.5 m in winter of 2016.

In 2015 transects were 10 m in length and adapted to 20 m in length in 2016, and in both years oriented in an east-west direction. We recorded SMP measurements along the entire length of each transect at 0.3 m intervals in 2015 and in 0.5 m increments in 2016 resulting in a maximum of 34 (2015) and 41 (2016) sampling points per study plot and sampling date. We omitted sampling points, if their location coincided with a tree bole, and moved on to the next sampling point along a transect. In addition to SMP recordings, we measured snow depth with a 300 cm graduated avalanche probe and canopy cover by using a GRS Densitometer (Geographic Resource Solutions; Forestry Suppliers, Jackson, MS) at each SMP sampling point. The densitometer was used by two independent observers to determine whether the reading was open sky (recorded as 0) or if canopy was present (recorded as 1). The percentage of canopy cover was calculated for each transect from the number of canopy readings (record 1) divided by the total number of readings per transect. The mean height of the snowpack (HS) was calculated from our snow depth measurements for each transect and sampling date.

Each week during 2015, and every other week during 2016, transect start and endpoints were moved 0.5 m south from the previous point and measurements were repeated along each transect. This 0.5 m offset was sufficient to avoid any potential disturbances of snow layers along the current sampling transect that may have resulted from previous SMP measurements and/or footprints. In total, we sampled eight times throughout winter 2015 spanning a period of nine weeks and seven times in 2016 over a 14-week period.

During each field campaign, a snow pit profile was excavated in the MEADOW plot. Each pit boundary was marked by bamboo poles so previous pit locations could be avoided during subsequent site visits. The International Classification for Seasonal Snow on the Ground (Fierz et al., 2009) was used to manually assess and classify layering, grain shape, grain size, and hand hardness.

Surface roughness in terms of downed woody material present at GREEN, GRAY, and HARVEST plots was measured in August 2015 and June 2016. Ten and 20 m long transects matching the exact location of the snowpack measurement transects were established. Along each transect the height and width of underlying down woody debris pieces were measured using a standard meter tape and counted along every other transect for each fuel diameter size class (1 hour fuels ≤ 0.6 cm, 0.6 cm < 10 hour fuels ≤ 2.5 cm, 2.5 cm < 100 hour fuels ≤ 7.6 cm, 1000 hour fuels > 7.6 cm) following the method described in Brown (1974). We used these measurements to calculate mean and maximum heights of debris > 7.6 cm in diameter (coarse woody debris, CWD), and the volume per ha of downed woody material for each fuel diameter class (see Brown, 1974), to retrieve a standardized measure describing the surface roughness found in our three forested study plots.

2.3 Climate conditions and meteorological data

The climate in the study area is typical of a continental subalpine site in the western USA, having a dry summer/wet winter pattern (Shaw and Long, 2007), with the majority of precipitation falling as snow during the winter months November through April (Gillies et al., 2012; Munroe, 2003). Meteorological data of the study area are measured by Natural Resources Conservation Service (NRCS) SNOwpack TELemetry (SNOTEL) stations. The closest SNOTEL site is Chalk Creek #1 (ID392) and is located approximately 150 m lower at an elevation of 2741 m and 8.2 km west of the study site. Daily data for snow depth and average air temperature were obtained for both winters (starting November 1) from the SNOTEL network via the NRCS website (www.wcc.nrcs.usda.gov/snow/; [accessed on 2 August 2017]) describing winter conditions over the study period (Fig. 4). During both winters, a permanent snow stake was installed at the MEADOW plot and readings were recorded when approaching the plot during each winter field campaign (Fig. 4).

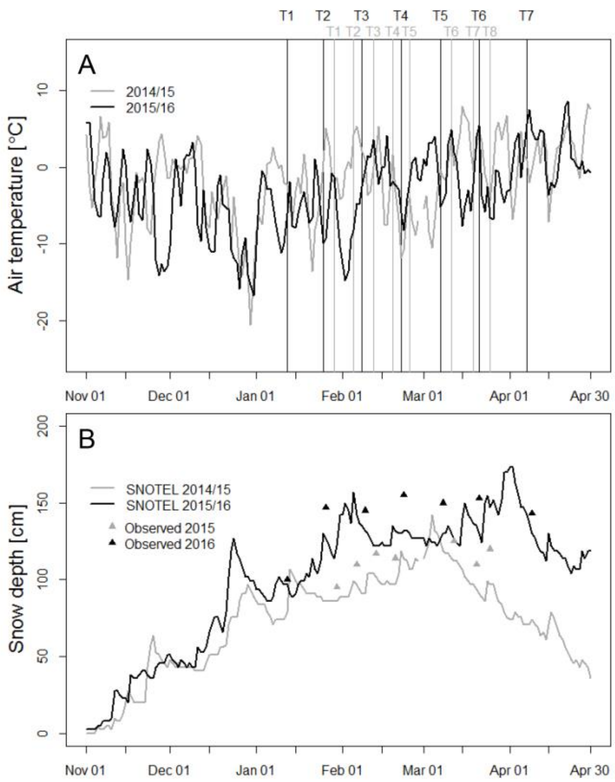

Fig. 4. Daily average air temperature (A), and total snow depth measured at SNOTEL site Chalk Creek #1 (ID392), and snow depths observed with a snow stake permanently installed at the MEADOW plot (B) in winters of 2015 and 2016. Vertical lines indicate first day of sampling transects (T) 1-8 in 2015 and T1-7 in 2016; the majority of measurements were taken on two consecutive days (Table A1).

To characterize the general weather pattern prior to each sampling date, which, in combination with the forest cover, may have influenced the snow stratigraphy observed at our four plots, we used daily values for average temperatures and accumulated precipitation from the SNOTEL site Chalk Creek #1 and calculated a set of variables known to be associated with avalanche release from forests (Teich et al., 2012, 2013; Table 2). Precipitation as well as temperature variables were calculated for one to three day periods prior to our sampling dates since, if driven by temperature gradient metamorphism, complete turnover of snow crystals appears within a rather short time where little if any of the original grain remains after two to three days (Pinzer et al., 2012).

Table 2

Variables on meteorological conditions present prior to each winter field campaign calculated based on daily values for average air temperature and accumulated precipitation obtained from SNOTEL site Chalk Creek #1 (ID392). All data was screened manually for outliers and obvious instrument errors.

Variable	**Symbol**
Average air temperature 1 day prior to measurements (°C)	T_a1
Average air temperature within a 3-day period prior to measurements (°C)	T_a3
Average air temperature difference between 1 and 3 days prior to measurements (°C)	ΔT_a3
Accumulated precipitation 1 day prior to measurements (mm)	N1
Accumulated precipitation 1 to 3 days prior to measurements (mm)	N3

2.4 SMP profile processing and similarity metrics calculations

Prior to processing, all SMP recordings were checked for signal errors and quality according to the classification scheme of Pielmeier and Marshall (2009). Only profiles which were classified as "C1" (no error), and "C2" signals (trend or offset in absolute SMP penetration resistance) with a negligible linear drift in the air signal were retained. Air/snow and snow/ground interfaces were determined manually and cut-off automatically through profile processing from the initial SMP profile leaving only the signal recorded within each snowpack.

Profiles were automatically adjusted for offsets. Hereafter, we interpret the snow penetration resistance measured by the SMP as a measure for snow hardness.

We further processed SMP profiles collected along each transect at each sampling date using the matching algorithm developed by Hagenmuller and Pilloix (2016). Due to variations in internal layer thicknesses observed in a set of measurements, layers at the same depth are not necessarily at the same position in the stratigraphic sequence, which creates an apparent spatial variability in stratigraphic features. To account for these stratigraphic mismatches, Hagenmuller and Pilloix (2016) developed a method to automatically adjust layer thicknesses to minimize the difference between adjacent SMP profiles. This provides us qualitative and quantitative measures to compare differences in snow stratigraphy observed throughout the two winters at our four study plots and to test, which forest, snow and/or meteorological conditions influence the spatial and temporal variability in the layering of subcanopy snowpack.

The algorithm consists of three steps:

1. SMP profile transformation and re-sampling on a regular grid:

Each SMP profile is first re-sampled onto a one-dimensional regular depth grid h spanning 0 to 120 cm (maximum SMP measurement depth) with a constant 0.1 cm vertical step Δh defining the resolution of the re-sampled profile (σ, h) by preserving thin snowpack features after re-sampling. The transformation procedure T modifies the depth h by stretching or thinning the thickness l of the recorded layers j by a constant factor α_j, i.e., the new thickness of layer j is $\alpha_j \times \Delta l$. We restricted the transformation to stretch or thin the layer thickness by less than a factor of two, i.e., α_j, in [0.5, 2]. The transformed depth points h_T of the hardness measurements σ are then derived from the new layer thicknesses, but h_T do not necessarily lie onto the regular grid points

h. The transformed profile (σ, h_T) is thus linearly interpolated on the regular depth grid to obtain the final profile (σ_T, h).

2. Similarity metrics:

To quantify how similar individual SMP profiles are, we define two metrics: a) a distance D between one profile and a reference profile, and b) the intra-set variability V of a set of multiple profiles.

a) The distance D between two profiles (σ, h) and (σ_{ref}, h), which are re-sampled on the same depth grid h is defined as the mean square difference of the hardness in a log-scale ensuring that hardness differences of crusts are as important as differences of soft (including weak) layers.

b) The intra-set variability V is defined as the standard deviation of the hardness logarithm for a given height between different profiles, which is then averaged over the depth of the whole profile. V therefore quantifies how different several profiles are from each other without appointing one of them as the reference.

3. Optimization and quantification of spatial variability:

To quantify the similarity between two SMP profiles accounting for potential depth shifts, we computed the transformation T that minimizes the distance D between profile (σ_T, h), that is, the profile (σ, h) transformed by T, and profile (σ_{ref}, h). The resulting minimal distance D_{min} is a measure of the similarity between the two profiles (i.e., if $D_{min} = 0$, then the two profiles are considered the same; if $D_{min} = +\infty$, then the two profiles are completely different) neglecting impacts of layer thickness variations in the range [-50%, +100%]. Hereafter, we denote D_{min} by D.

We computed a pairwise distance matrix for our data set by matching and comparing each SMP profile collected along a transect with every other SMP profile recorded along that transect. The intra-set median distance was then calculated as the median D of all SMP profile pairs.

To quantify the similarity between more than two SMP profiles accounting for potential depth shifts, we computed the set of transformations $\{T\}$ that minimized the intra-set variability V between all profiles transformed by $\{T\}$. This complex optimization problem was heuristically solved by iteratively matching each profile to the mean profile of the set (evolving with iterations) as proposed by Petitjean et al. (2011). The resulting minimal intra-set variability V_{min} provides a quantitative measure of the variability of SMP profiles collected at a given site and time (i.e., if $V_{min} = 0$, then all profiles are considered the same; if $V_{min} = +\infty$, then the profiles are completely different) neglecting impacts of layer thickness variations in the range [-50%, +100%]. The mean profile of the transformed profiles also provides one representative profile for the SMP profile set. Hereafter, we denote V_{min} by V. For further details about the matching and optimization procedure see Hagenmuller and Pilloix (2016).

2.5 Data analysis

First, repeated measures ANOVA ($\alpha = 0.05$) and paired-samples t-tests were conducted to compare V (intra-set variability), which we calculated for each sampled transect and year as a measure to quantify the combined vertical and slope-parallel variability in snow stratigraphy (see section 2.4), between our four study plots GREEN, GRAY, HARVEST and MEADOW.

We then used linear mixed effects models (LMMs; Zuur et al., 2009) to characterize the relationships between forest, snow and meteorological variables as potential drivers for variability in snow stratigraphy, and the response variable V. LMMs extend traditional linear models by including a combination of fixed and random effects as predictor variables explicitly allowing to model non-independent observations and are therefore suitable for running repeated measures analyses (Zuur et al., 2009). Modeling random effects that typically represent some grouping variable supports correct inference about fixed effects and allows the estimation of variance in the response variable within and among these groups (Harrison et al., 2018). We used LMMs since we took repeated SMP measurements grouped by our four study plots every week (in winter of 2015) and every other week (in winter of 2016) in a snowpack that developed over the season and measurements are therefore not independent. Using LMMs allowed us to estimate the effects of explanatory variables (fixed effects) on V while also estimating and controlling for effects on V of the selected study plots (PLOT) and differences in winter conditions between 2015 and 2016 (YEAR; random effects) that were not accounted for with fixed effect terms.

Tested drivers for variability in snow stratigraphy were percentage of canopy cover, CWD mean and maximum heights (forest variables), a set of five meteorological variables (see Table 2), and mean height of the snowpack (snow variable). All these drivers were treated as fixed effects and “PLOT” and “YEAR” (for models that included both winters’ data) as random effects during model development and selection, which was guided by our global model:

$$V = f\,\{\, \mathrm{CANOPY} + \mathrm{DEBRIS_{mean}} + \mathrm{DEBRIS_{max}} + \mathrm{T_a1} + \mathrm{T_a3} + \Delta\mathrm{T_a3} + \mathrm{N1} + \mathrm{N3} + \mathrm{HS} + (1|\mathrm{PLOT}) + (1|\mathrm{YEAR}) \,\}$$

where V = intra-set variability; CANOPY = percentage of canopy cover per transect; $\mathrm{DEBRIS_{mean}}$ = CWD mean height per transect; $\mathrm{DEBRIS_{max}}$ = CWD maximum height per transect; see Table 2 for descriptions of $\mathrm{T_a1}$, $\mathrm{T_a3}$, $\Delta\mathrm{T_a3}$, N1, N3; HS = mean height of the snowpack per transect; PLOT = four study plot categories GREEN, GRAY, HARVEST and MEADOW; YEAR = winter the transect was sampled, 2015 or 2016; the parentheses indicate the term is a random effect (*re*), all other terms are fixed effects; (1 | *re*) indicates that the intercept was allowed to vary randomly.

To analyze and test for differences between winters 2015 and 2016, we fit a model for each year separately and one for both years combined. To derive the "best-fit" models, we followed a four-step procedure: 1) We determined the optimal random effects structure for the model including data of both years and selected amongst three LMMs (fit with restricted maximum likelihood) with possible combinations of random effects "PLOT" and "YEAR", but with no fixed effect term. 2) We used the function "dredge" implemented in the R package MuMIn (Barton, 2018) to automatically fit and rank LMMs with all possible combinations of fixed effect terms (all forest, snow and meteorological variables) and the random effect structure selected in step one (fit with maximum likelihood). 3) Based on the results of steps one and two, and our hypotheses, we selected the variables and their two-way interactions to be included in the models to be further tested (fitted with maximum likelihood). 4) We fit the models selected for each year and the one combining both winters with restricted maximum likelihood and considered these models to be our final ‘‘best-fit’’ models (Zuur et al., 2009).

Akaike's information criteria (Akaike, 1973) with small sample bias adjustment (AICc; Hurvich and Tsai, 1989) was used to determine the most parsimonious combination of fixed effect terms to select amongst models. For our best-fit models, we assessed the significance of the fixed-effects model coefficients using *F*-tests, and calculated marginal R^2 as the proportion of variance in the response variable explained by the fixed effect explanatory variables, and conditional R^2, which can be interpreted as the variance explained by both fixed and random effects terms, i.e. by the entire model (Nakagawa and Schielzeth, 2013; Xu, 2003). All models were fit in R version 3.5.0 using the lme4 package (Bates et al., 2015; R Core Team, 2018). The

R package MuMIn was used to support model selection, and test statistics were calculated with functions implemented in MuMIn or the R package car (Barton, 2018; Fox and Weisberg, 2011). We verified that the model residuals were normally distributed to validate using linear mixed effects models rather than generalized linear mixed effects models.

3. Results

3.1 Forest characteristics

Forest stand structure is similar between GREEN and GRAY study plots in terms of mean dbh, tree height, and crown diameter (Table 3). The GREEN plot was found to have a higher mean stem density and mean basal area compared to GRAY and HARVEST plots. Overall percentage of canopy cover was much higher in GREEN (85%) and GRAY (80%) plots compared to the HARVEST plot (27%). The percentage of live canopy decreased over the course of the entire study in GREEN and GRAY plots. In the GREEN plot initial infestation occurred in 2014, yet trees still retained the majority of live canopy during 2015 and 2016 winter campaigns. Spruce beetle infestation reached its highest level in summer 2016 where a reduction to 47% live canopy was estimated in June after winter field campaigns were completed. However, percentage of live canopy was always higher in the GREEN plot compared to the GRAY plot. The initial percent of live canopy cover found in the GRAY plot were attributed to interspersed subalpine firs and residual spruce saplings that were not infested by spruce beetles, and decreased only slightly over the course of the study to 34%.

Surface roughness associated with down woody debris is expected to influence snow stratigraphy. We found loading of fine woody debris (FWD) with diameters < 7.6 cm (1, 10 and 100 hour fuels) was highest in the HARVEST plot associated with residual slash following harvesting (Table 3). The HARVEST plot also had a higher mean CWD load (1000 hour fuels) compared to GREEN and GRAY plots, and was found to have the highest maximum CWD fuel heights whereas the greatest overall mean CWD height was found in the GRAY plot.

Table 3

Stand characteristics (measured during plot establishments in October 2014) and fuel load characteristics (collected in August 2015 and June 2016) for forested study plots GREEN, GRAY, and HARVEST in the Uinta Mountains in Utah, USA.

	GREEN		**GRAY**		**HARVEST**	
	M	*SD*	*M*	*SD*	*M*	*SD*
dbh (cm)	28	13	30	10	18	3
Height (m)	17.5	5.9	17.6	5.0	14.4	3.7
Canopy base height (m)	6.1	4.1	4.6	2.6	5.5	2.4
Crown diameter (cm)	370	166	381	190	267	56
CWD mean height (cm)	18	20	21	12	17	14
Density (stems ha^{-1})	1127	-	676	-	526	-
Basal area (m^2 ha^{-1})	57.3	-	36.0	-	9.3	-
Canopy cover (%)*	85	-	80	-	27	-
Live canopy (%)**	89	-	37	-	100	-
CWD maximum height (cm)	30	-	49	-	60	-
Fuel load (kg ha^{-1})						-
1 hr	19	-	95	-	151	-
10 hr	192	-	150	-	1589	-
100 hr	322	-	403	-	6038	-
1000 hr (sound)	4296	-	0	-	25477	-
1000 hr (rotten)	0	-	0	-	1268	-

M = mean; *SD* = standard deviation; dbh = diameter at breast height; CWD = coarse woody debris (diameter > 7.6 cm); hr = hour

Fuel load size classes: 1 hr ≤ 0.6 cm, 0.6 cm < 10 hr ≤ 2.5 cm, 2.5 cm < 100 hr ≤ 7.6 cm, 1000 hr > 7.6 cm, volumes were calculated based on Brown (1974).

[*]Canopy cover (%) refers to the total percent canopy cover for a plot.

[**]Live canopy (%) refers to the percentage of canopy within a plot that is live (green).

3.2 Snowpack characteristics and evolution

3.2.1 Snow height

On average, snowpack was higher in winter of 2016 compared to 2015 (Fig. 4). Spatially distributed snow depth measurements that were taken at every SMP sampling point during each field campaign showed that HS for winter 2015 was highest in the MEADOW, followed by the HARVEST, GRAY and GREEN plots (Fig. 5A). This pattern was found to be similar in winter of 2016 (Fig. 5B), although differences in HS between GREEN ($M = 87$, $SD = 12$) and GRAY ($M = 89$, $SD = 14$) as well as between HARVEST ($M = 129$, $SD = 19$) and MEADOW ($M = 132$, $SD = 17$) plots were smaller compared to HS differences observed in the winter of 2015 (GREEN: $M = 52$, $SD = 7$; GRAY: $M = 61$, $SD = 7$; HARVEST: $M = 102$, $SD = 10$; MEADOW: $M = 107$, $SD = 8$).

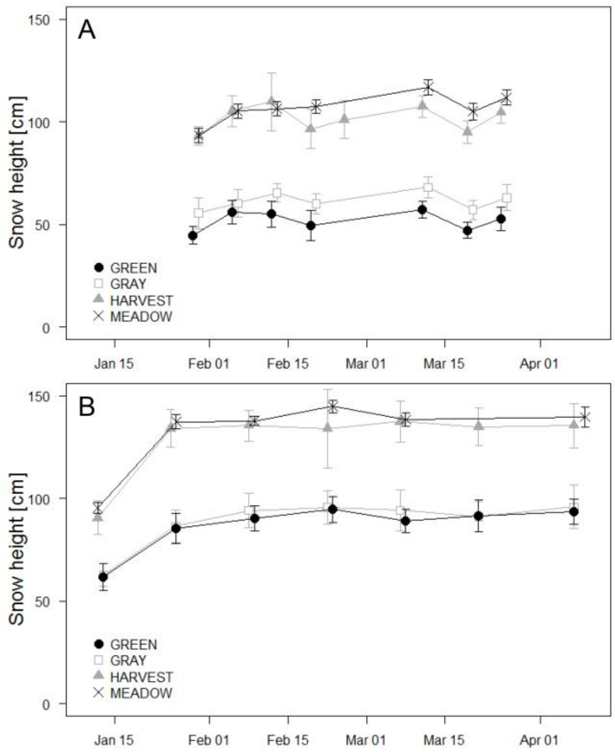

Fig. 5. Evolution over time of the mean height of the snowpack (HS) measured along transects at GREEN, GRAY, HARVEST, and MEADOW study plots in A) 2015, N~34 per transect and date (Transects 1 to 8), and B) 2016, N~41 per transect and date (Transects 1 to 7, Table A1). Error bars represent standard deviations.

3.2.2 Qualitative snowpack observations

In general, larger differences in hardness that were measured by the SMP were also manually observed as layers of different hardness in the snow pit profiles excavated at the MEADOW plot. Figure 6 shows an example of a snow stratigraphy observed in the MEADOW plot on January 25, 2016. For example, a hard snow layer was detected at 42 cm snow height by measurements from both the SMP and hand hardness tests in the snow pit. This continuous hard layer was correctly tracked by the matching algorithm and is visible in the snow hardness profile assembled from plotting SMP profiles side-by-side in the order they were taken along the transect. Moreover, snow layers that were missed or misclassified by the snow pit observer can be easily identified from the SMP derived snow hardness profile.

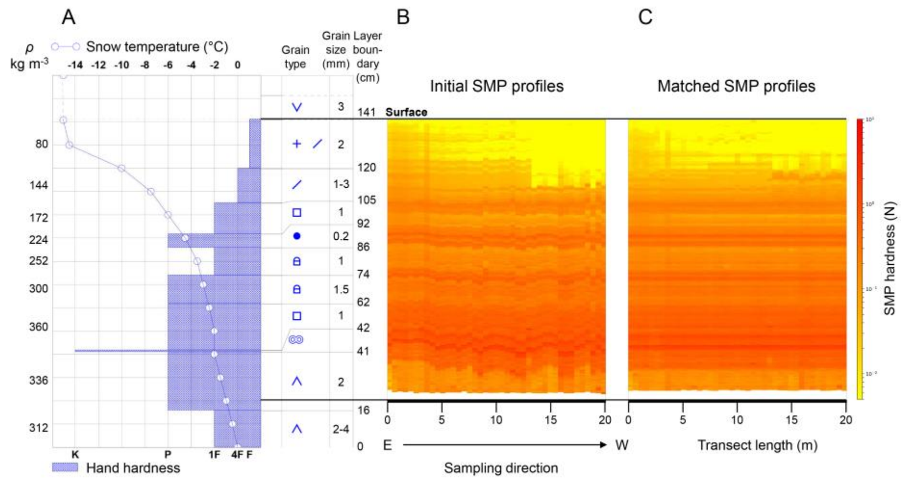

Fig. 6. Stratigraphy of the snowpack observed at the MEADOW plot on January 25, 2016: (A) in the excavated snow pit profile, and, aligned to the corresponding height in the snow pit profile, (B and C) along the sampled SMP transect (Transect 2, 2016). Initial (B) and matched (C) SMP profiles are plotted side-by-side in the same order as measurements were taken in 0.5 m intervals. Visualization of snow pit profile adapted from Snowpro Plus+ (snowprofile.ca). Symbols according to the International Classification for Seasonal Snow (Fierz et al., 2009).

Throughout the winter of 2015, snow hardness profiles constructed from individual but matched SMP profiles show that continuous persistent hard layers such as melt-freeze snow, and wind or sun crusts were present in the MEADOW and HARVEST plots visible as dark red bands in Figure 7. Distinct vertical and continuous slope-parallel hard and soft snow layers indicate that snow stratigraphy is more homogeneous at these plots. In the GREEN and GRAY plots, discontinuous hard and soft layers were observed at different snow heights within the snow stratigraphy. These observations demonstrate a more heterogeneous snow stratigraphy throughout the winter.

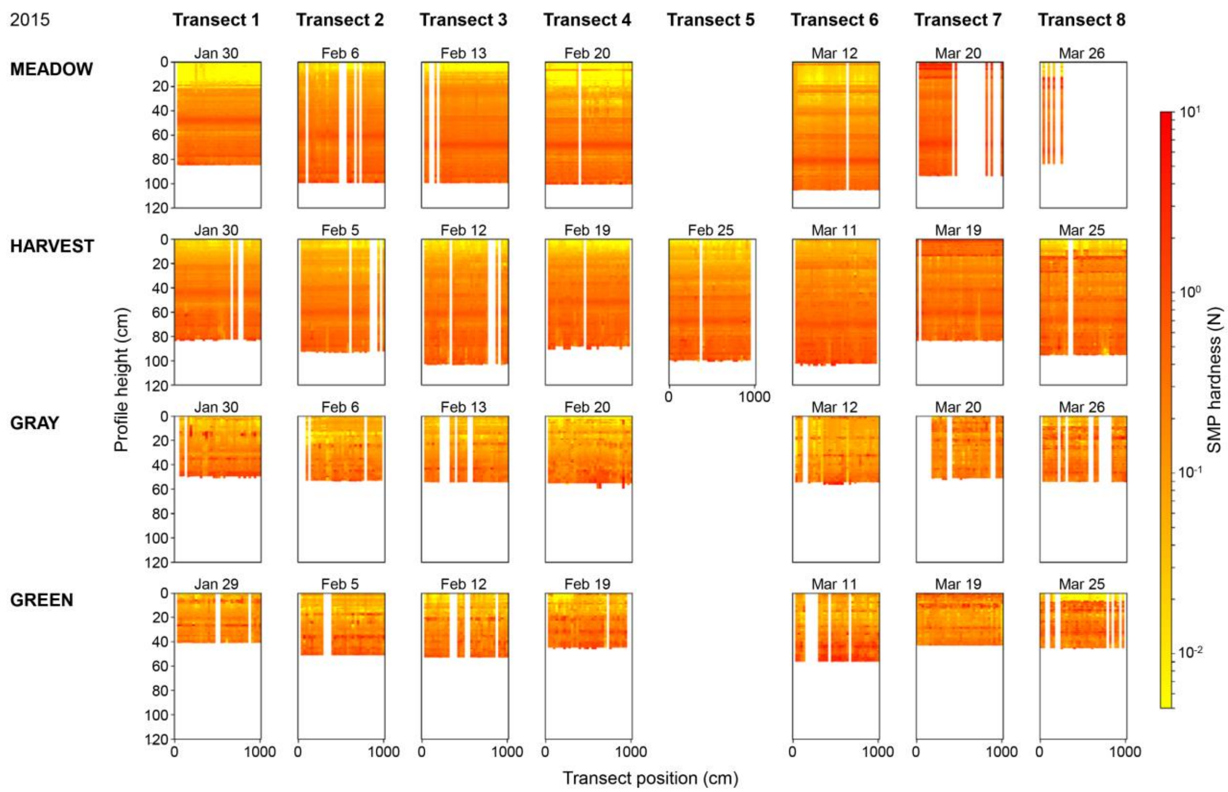

Fig. 7. Matched SMP profiles plotted side-by-side in the order taken in winter 2015 in the study plots MEADOW, HARVEST, GRAY and GREEN every 0.3 m along 10 m long transects. Snow hardness profile height corresponds to the actual snow height. Missing SMP profiles (white columns) are either sampling points that were coinciding with a tree bole, or SMP profiles that were classified as > "C2" according to the classification scheme of Pielmeier and Marshall (2009).

Similar results were observed throughout the winter of 2016, which, in contrast to the low snowpack in 2015, was an average snowfall year (Figs. 4 and 5). However, an increase in hardness with snow depth was more pronounced in the winter of 2016 in MEADOW and HARVEST plots compared to winter 2015, and compared to GRAY and GREEN plots caused by greater self-weight gravity snow settlement. At GREEN and GRAY plots, more homogeneous snow layers of different hardness were observed in the snowpack towards the end of the winter (Transects 5 to 7), but they were not as distinct during the beginning and the middle of the sampling period (Transect 1 to 4). Distinct and continuous hard layers, for example, buried sun, wind or melt-freeze crusts, and ice lenses (recorded as such in snow pit profiles) were present in the entire snowpack at HARVEST and MEADOW plots (Fig. 8).

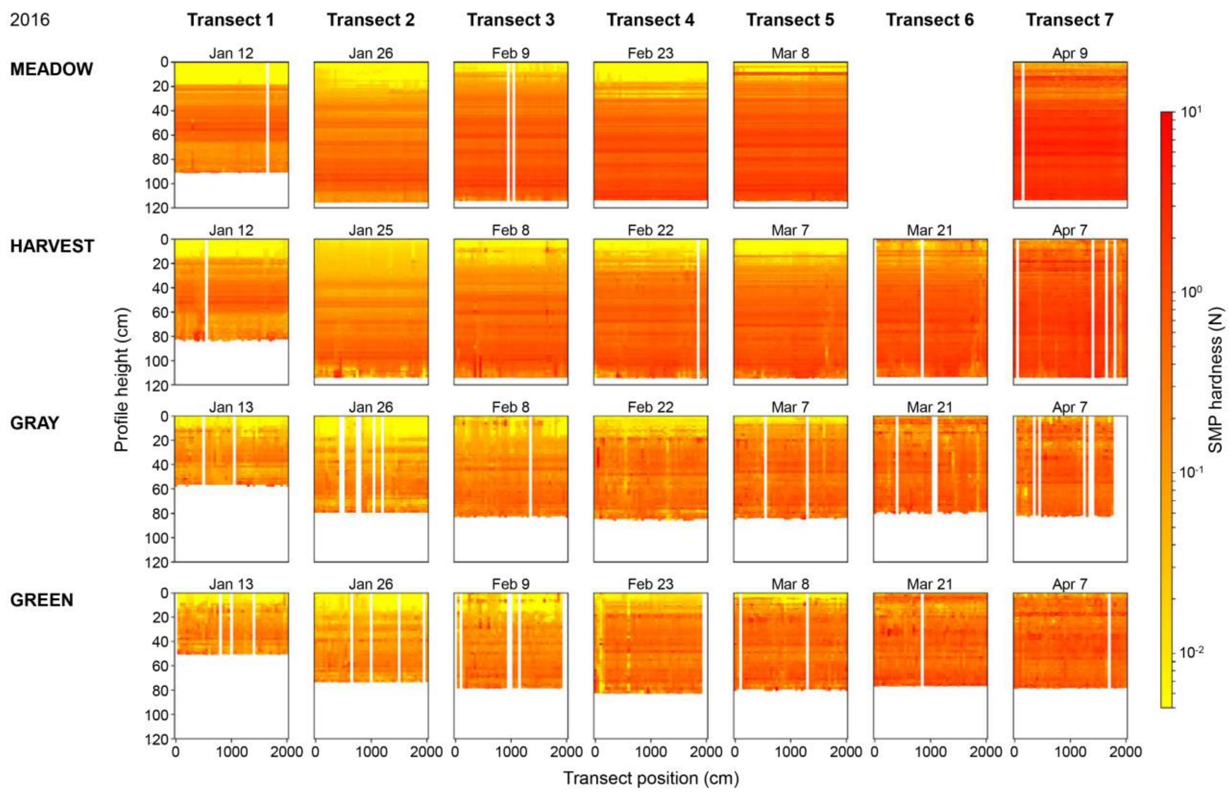

Fig. 8. Matched SMP profiles plotted side-by-side in the order taken in winter 2016 in the study plots MEADOW, HARVEST, GRAY and GREEN every 0.5 m along 20 m long transects. Snow hardness profile height corresponds to the snow height that was present at GREEN and GRAY plots. Except for Transect 1, snow height exceeded the maximum SMP probe length of 1.2 m at MEADOW and HARVEST plots. Missing SMP profiles (white columns) are either sampling points that were coinciding

with a tree bole, or SMP profiles that were classified as > "C2" according to the classification scheme of Pielmeier and Marshall (2009).

3.2.3 Quantification of variability in snow stratigraphy

In general, the computation of the similarity metric distance D revealed that SMP profiles that are closer in space have lower D values than SMP profiles that are more distant, which translates to a more similar snow stratigraphy from point to point (data not shown). Figure 9 shows a pair-wise comparison of the median D, that is, the median of all D for all matched SMP profiles pairs collected at one day in the respective study plots. Two main groups are clearly distinguishable: 1) the MEADOW and the HARVEST plots, and 2) the GREEN and the GRAY plots. Median D retrieved by matching and comparing SMP profiles collected in a study plot of one group with the SMP profiles from a study plot of the other group are clearly larger than D within both groups. This is especially true for the winter of 2015 where numerous SMP profiles collected in MEADOW and GRAY plots could not be matched for Transects 1, 2, 4, and 7 ($D > 2$) due to layer thickness variations that exceeded the set range of [-50%, +100%].

In contrast, median D within HARVEST and MEADOW, and between HARVEST and MEADOW plots are small, which indicates a smaller slope-parallel variability in snow stratigraphy and, therefore, a more homogeneous snow layering. Median D of GREEN and GRAY plots as well as between GREEN and GRAY plots are larger pointing to a greater slope-parallel variability, that is, a more heterogeneous snow stratigraphy.

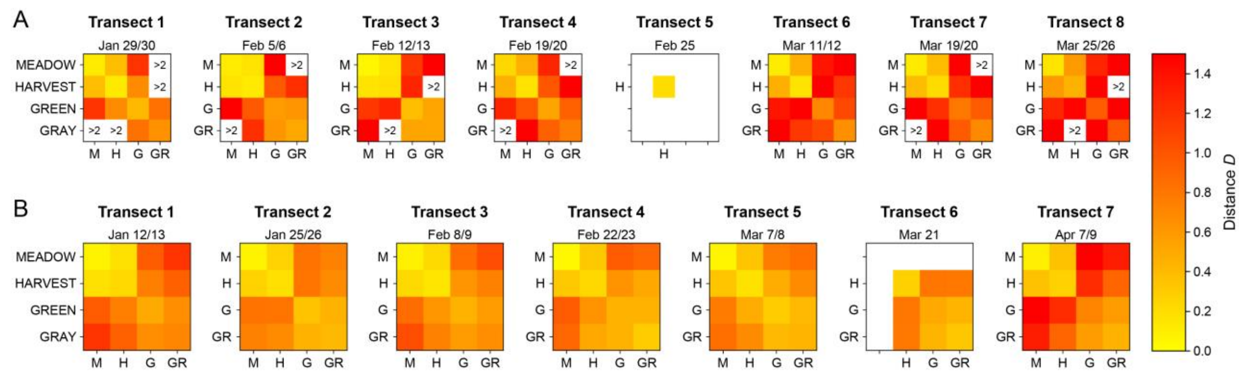

Fig. 9. Pair-wise comparison of the median of distance *D* computed from SMP profile pairs sampled along transects at GREEN (G), GRAY (GR), HARVEST (H), and MEADOW (M) study plots in A) 2015, and B) 2016.

This distinction between the two groups MEADOW/HARVEST and GREEN/GRAY is also visible in Figure 10, which shows the evolution of the intra-set variability *V* that was calculated for every transect collected at each of our four study plots. In both winters *V*, which quantifies how different the collected SMP profiles are, was found to be generally higher for transects sampled at GREEN/GRAY plots compared to MEADOW/HARVEST plots.

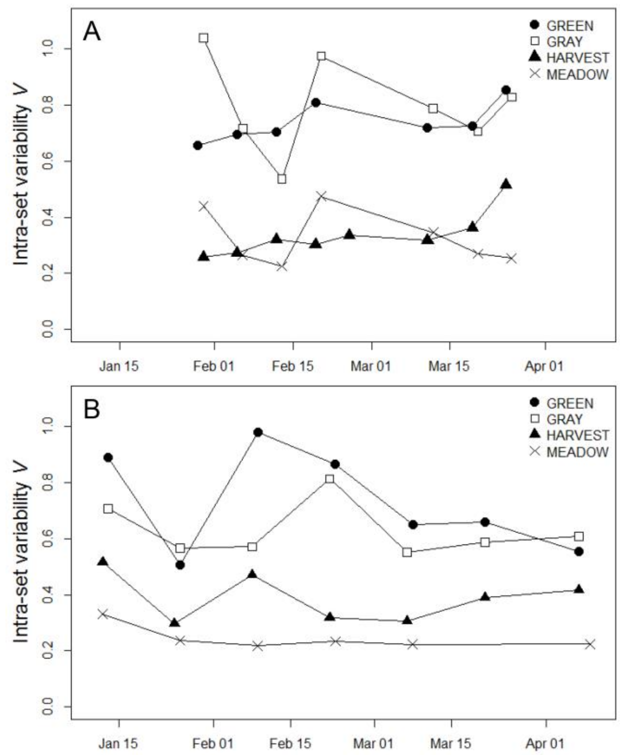

Fig. 10. Evolution over time of intra-set variability *V* calculated for transects sampled at GREEN, GRAY, HARVEST, and MEADOW study plots in A) 2015 (Transects 1 to 8), and B) 2016 (Transects 1 to 7, Table A1).

In 2016, values of *V* in the GREEN plot were mostly slightly higher than *V*-values calculated for the GRAY plot followed by HARVEST and MEADOW plots suggesting a decrease from a more heterogeneous to a more homogeneous snow stratigraphy in that order. For the latter one, we calculated the lowest *V*-values that changed only little over the course of the 2016 sampling period (Fig. 10B); however, greater fluctuations in *V* were found in 2015 (Fig. 10A). Values and range of *V* retrieved for the HARVEST plot were similar for both winters. Compared to 2016, *V* retrieved for transects collected at the GRAY plot in 2015 were higher with greater fluctuations over the sampling period (Fig. 10A). For the GREEN plot calculated *V*-values were found to be in a similar range in both years, but with greater fluctuations over the sampling period in 2016.

Repeated measures ANOVA and pairwise t-tests conducted with data combined for both winters revealed no significant difference in *V* for GREEN (*M* = 0.73, *SD* = 0.13) and GRAY (*M* = 0.71, *SD* = 0.16) plots; t (14) = -0.14, p = 0.88, and between HARVEST (*M* = 0.36, *SD* = 0.08) and MEADOW (*M* = 0.29, *SD* = 0.08) plots; (t (14) = -1.86, p = 0.08). However, *V* differed significantly between the two distinguished groups GREEN/GRAY (*M* = 0.72, *SD* = 0.14) and MEADOW/HARVEST (*M* = 0.33, *SD* = 0.09) plots; (t (27) = -13.25, p < 0.001).

Based on the similar and, therefore, robust results from both metrics median *D* and *V*, the above findings suggest that differences in the spatial variability in snow stratigraphy are related to different canopy effects of green and gray stage spruce forest stands. In contrast, the canopy cover of salvage-logged forests stands can be reduced to a degree where it has almost no effect on the snowpack.

3.3 Predictors of variability in snow stratigraphy

Through model selection based on the AICc and *F*-tests we found that variations in *V* were best explained by the percentage of canopy covering each transect observed on the SMP sampling day according to the best-fit model containing data for both years. The percentage of canopy cover was also the most important significant variable in combination with T_a1 and N1 for 2015, and in combination with T_a3 and N3 for 2016. Conditional R^2-values for the best-fit models range between 0.71 and 0.88 (Table 4). Two-way interactions of the chosen variables had no significant effects on variations in *V*.

Table 4

Model formulas, AICc, marginal R^2 (R^2_m), and conditional R^2 (R^2_c) for the three best-fit models selected for 2015, 2016, and for both years combined

Year	Model formula[*]	AICc	R^2_m	R^2_c
2015[**]	$V = f\{\,\mathbf{CANOPY} + (1\vert\text{PLOT})\,\}$	-70.9	0.61	0.71
and	$V = f\{\,\mathbf{CANOPY} + \text{HS} + (1\vert\text{PLOT})\,\}$	-70.4	0.63	0.71
2016	$V = f\{\,\mathbf{CANOPY} + \text{HS} + \text{N3} + \text{T}_a1 + (1\vert\text{PLOT})\,\}$	-70.0	0.65	0.73
2015	$V = f\{\,\mathbf{CANOPY} + \mathbf{T_a1} + \mathbf{N1} + (1\vert\text{PLOT})\,\}$	-37.3	0.67	0.87
	$V = f\{\,\mathbf{CANOPY} + \mathbf{T_a1} + \text{N1} + \text{HS} + (1\vert\text{PLOT})\,\}$	-36.5	0.69	0.88
	$V = f\{\,\text{CANOPY} + \mathbf{T_a1} + \text{HS} + (1\vert\text{PLOT})\,\}$	-36.2	0.71	0.85
2016	$V = f\{\,\mathbf{CANOPY} + \mathbf{T_a3} + \mathbf{N3} + (1\vert\text{PLOT})\,\}$	-38.1	0.82	0.82
	$V = f\{\,\mathbf{CANOPY} + (1\vert\text{PLOT})\,\}$	-36.8	0.77	0.77
	$V = f\{\,\mathbf{CANOPY} + \mathbf{T_a1} + \Delta\text{T}_a3 + \mathbf{N3} + (1\vert\text{PLOT})\,\}$	-35.6	0.82	0.82

[*]Parameters in bold have significant coefficients ($p < 0.05$).

V = intra-set variability; CANOPY = percentage of canopy cover per transect; HS = mean height of the snowpack; N3 = accumulated precipitation 1 to 3 days prior to measurements; T_a1 = average air temperature 1 day prior to measurements; N1 = accumulated precipitation 1 day prior to measurements; T_a3 = average air temperature within a 3-day period prior to measurements; ΔT_a3 = average air temperature difference between 1 and 3 days prior to measurements; PLOT = plot categories GREEN, GRAY, HARVEST and MEADOW; the parentheses indicate the term is a random effect (*re*), all other terms are fixed effects; (1|*re*) indicates that the intercept was allowed to vary randomly. Parameters are listed in order of importance.

[**]modelling YEAR as additional random effect (1|YEAR) did not enhance model fit.

Including the year sampled as random effect did not enhance the performance of the model including data for both years. Therefore, we excluded "YEAR" and treated "PLOT" as the only random effect for the models for both winters. The variance explained by the random effect PLOT, which can be interpreted as the effect of the stage within the spruce bark beetle outbreak cycle and its associated canopy condition GREEN, GRAY, HARVEST or MEADOW, ranged between 0% in 2016 and 23% in 2015 (Table 4, calculated as fraction of the difference between marginal R^2 and conditional R^2 of the conditional R^2). Since it was also only 14% for the best-fit model including both years' data, we, in addition, used linear regression to test for linear correlation between percentage of canopy cover and *V*. A highly significant positive correlation was found for both years' data (Fig. 11), but also between percentage of canopy cover and *V* that were observed in 2015 (R^2 = 0.70; p < 0.001), and in 2016 (R^2 = 0.77; p < 0.001). No linear correlations were found either between T_a1 and *V* or between N1 and *V* (variables in the 2015 best-fit LMM) as well as between T_a3 and *V* or N3 and *V* (variables in the 2016 best-fit LMM).

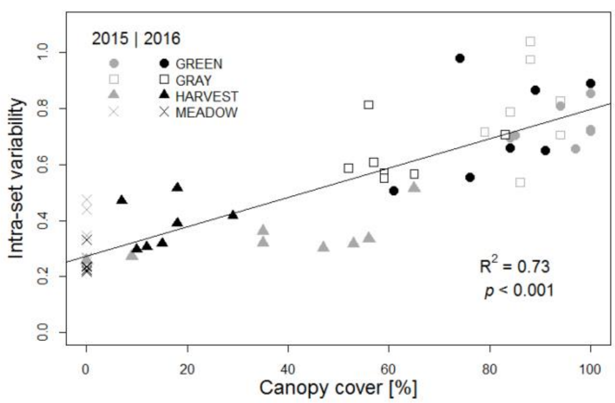

Fig. 11. Intra-set variability *V* plotted against percentage of canopy cover for transects measured at GREEN, GRAY, HARVEST and MEADOW plots in 2015 and 2016. The R^2 and *p*-value are for the linear regression model that only includes percentage of canopy cover as explanatory variable. Regression line is shown for the significant linear relationship between canopy cover and *V*.

4. Discussion

4.1 Effects of spruce bark beetle infestation on forest snowpack

Our first hypothesis that, following spruce bark beetle infestation, the spatial variability in snow stratigraphy decreases gradually from a more heterogeneous snowpack to a more homogeneous snowpack among non-infested to gray stage to salvage-logged spruce forest stands, is not supported by our findings. The variability in snow stratigraphy (quantified by the similarity metrics intra-set variability *V* and distance *D*) that we observed in winters of 2015 and 2016 over 10 and 20 m long transects, did not differ significantly between green and gray stage Engelmann spruce forest stands. However, the snowpack in both stands was significantly more heterogeneous compared to the snow stratigraphy that developed in salvage-logged and non-forested areas. This heterogeneous layering of sub-canopy snowpack translates to disrupted and discontinuous snow layers and weaknesses, and is the main reason why slab avalanche release from dense healthy forest is inhibited (Gubler and Rychetnik, 1991; Schneebeli and Bebi, 2004; Schneebeli and Meyer-Grass, 1993). We found that the percentage of canopy cover (out of all tested forest and weather variables) was the main predictor that influenced the spatial variability in subcanopy snow stratigraphy. Heterogeneity in snow stratigraphy increased with increasing forest canopy cover. The method we used to determine the presence of canopy did not depend solely on the presence of needles, but included additional canopy elements such as branches and twigs. That is, the spatial variability in snow stratigraphy did not depend on only the reduction in needle mass (i.e., the stage during the outbreak cycle) four to five years after the spruce beetle infestation. In contrast, salvage logging that reduced the canopy cover to ~25%, led to a more homogeneous snow stratigraphy. The snow stratigraphy found in this study plot was similar to observations in the non-forested (meadow) plot where distinct and continuous slope-parallel soft and hard snow layers including sun or wind crusts, ice lenses and weak layers (that we identified as such in snow pit profiles) are generally more likely to form (Schweizer et al., 2003).

These differences in the spatial heterogeneity of snowpack properties between gray stage and harvested areas was also found in a modeling study (Perrot et al., 2014); however, we did not observe a clear decrease in the heterogeneity of the snowpack with the progression of foliage loss (i.e., green to gray stage). This is especially true for the winter of 2015, which was characterized by a below average snowpack and warm January and February mean air temperatures. Compared to 2016, variability in snow stratigraphy of green and gray stage stands was more similar despite the greater difference in the proportion of live canopy. Moreover, differences between the two distinguished groups that had a similar variability in snow stratigraphy (i.e., green/gray stage stand, and salvage-logged/non-forested area) were very distinct. These differences were also found in 2016 but less pronounced suggesting the influence of typical snow and meteorological patterns that were present in each year. Linear mixed models that were fit to the data of each year separately revealed contributions of mean air temperature and accumulated precipitation, but no significant linear relationship between either of those variables and V was found.

We therefore examined air temperature and snow depth measurements (see Fig. 4) that were present prior to field campaigns where greater differences in V between green and gray stage stands were found (see Fig. 10). Three campaigns stand out: January 29/20 (Transect 1) and February 19/20 (Transect 4) in 2015, and February 8/9 (Transect 3) in 2016. In January 2015, mean air temperatures were above 0°C and no new snow had fallen in the study region since the middle of the month. We therefore assume that more melt-freeze snow may have been formed in locations in less shaded areas along the transect in the gray stage stand compared to the green stand, which could have led to a greater spatial variability in snow stratigraphy. In the gray stand's snow hardness profile, a discontinuous harder layer close to the snow surface can be identified, but also small areas of very hard snow at a depth of 10 cm (Fig. 7). According to our field notes and in field observations, these areas could be ice clumps that were a result of refrozen melt water dripping from the canopy into the snowpack (Fig. 12C). The same process could have also influenced the greater variability in snow stratigraphy observed in the gray stage stand in February of the same year. Prior to that campaign, little snow had fallen, and air temperatures had increased suggesting that snow intercepted by dead trees melted faster compared to snow that was intercepted in live canopies. Meltwater dripping from branches forms meltwater channels in the snowpack which, after refreezing, are assumed to interrupt continuous snow layers with low tensile strength and to have a stabilizing effect on the snowpack (Gubler and Rychetnik, 1991). Schweizer et al. (1995) performed snowpack stability tests below the area projected by the crowns of larch trees and found that such a snowpack has greater tensile strength compared to areas just outside the projected crown area. The snowpack stabilizing effect of canopy drip is therefore restricted to the projected crown (Bründl et al., 1999). However, in contrast to the parts of protection forests at the upper tree line that mainly consist of larch with tree distances often exceeding 15 m, gray stage spruce stands still remain the physical structure of the original dense forest. Therefore, the snowpack stabilizing effect of increased canopy drip below crowns of larch trees is also present in gray stage spruce stands and even more pronounced because of the usually higher stem and canopy densities.

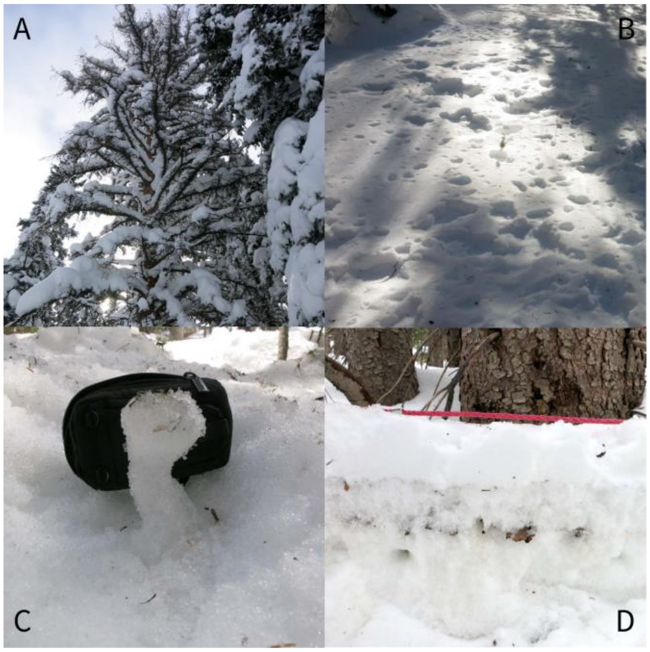

Fig. 12. Processes influencing subcanopy snow stratigraphy in forests after spruce beetle infestation: A) Snow intercepted by crowns of dead (gray) Engelmann spruce; B) Depressions at the snow surface created by unloading or melting of intercepted snow; C) Melt water that dripped from branches created melt channels in the snowpack and, after refreezing, emerged at the snow surface during snowmelt; D) Bark flakes that accumulated around woodpecker-debarked trunks of beetle-infested trees got subsequently buried in the snowpack. Photos: Michaela Teich

Beginning of February 2016, mean air temperatures were very low (~-15ºC) and snow fall was reported during this cold period prior to our data collection, but mean air temperatures had increased to ~-5ºC at the time of sampling (we measured 1ºC in the afternoon at the study site). The amount of snow initially intercepted by a crown depends on branch structure and is influenced by wind, temperature, and solar radiation during deposition (Sturm, 1992). Therefore, this combination of cold temperatures and snow fall could have reduced snow interception by dead tree crowns while more snow may have been intercepted in the green stand that unloaded as relatively dense snow clumps with increasing air temperatures (Hedstrom and Pomeroy, 1998;

Schmidt and Pomeroy, 1990). These effects of green versus gray canopy interacting with low temperatures during snowfall followed by an increase in temperature could have resulted in the observed greater spatial variability in snow stratigraphy in the green compared to the gray stage stand. For example, Pfister and Schneebeli (1999) showed how temperature influences the interception efficiency on wooden boards of different sizes and shapes, which can be interpreted as differences between green and gray stage spruce forest stands. Because adhesion of snow to twigs increases as temperature rises toward the freezing point, differences between live and dead trees may be more important when temperature during snowfall is low. In addition to the influence of the canopy coverage itself, these interactions could have also led to the greater differences in snow depth measured on February 8/9, 2016 between the gray stage stand ($M = 94$ cm) and the green stand ($M = 90$ cm) as well as on March 7/8 that year (green: $M = 94$ cm; gray: $M = 88$ cm). The snowfall prior to our measurements in early-March 2016 was accompanied by a decrease in air temperature (see Fig. 4), although differences in the variability in snow stratigraphy were rather low.

Our second hypothesis is, therefore, not fully supported by our findings. Forest canopy condition was not found to be the main predictor for changes to the spatial variability in snow stratigraphy. Even with the majority of foliage absent from the canopy of gray stage spruce forests, the standing dead snags still affect snow stratigraphy similarly to green forest stands. We attribute this to the small fine branches and twigs still present in the canopy influencing snow interception, snow unloading and canopy drip (Fig. 12), and moderating wind and solar radiation. However, canopy related processes, which contribute to a higher or lower snowpack heterogeneity may differ under specific meteorological conditions as well as on different slope aspects and angles. Therefore, future long-term studies that in particular include winters with well above average snow fall are needed to further investigate the protective capacity of gray stage avalanche protection forests. In addition, influences on snow stratigraphy due to energy balances associated with varying slope angles and aspects coupled with forest canopy loss requires further investigation.

Our third hypothesis that surface roughness in terms of the amount and height of CWD is linked to snowpack heterogeneity was not supported by our findings. We measured the highest volume of sound CWD at our salvage logged plot compared to the other forested plots, but the snow stratigraphy was found to be homogeneous and similar to a non-forested area. However, although surface roughness was increased through remaining logging slash, this slash was mainly composed of FWD fuel classes, which can be easily buried during the initial early season snow fall. The sound CWD was mostly comprised of pieces of tree limbs and branches, and the majority of large CWD pieces such as tree boles were removed from this stand. The maximum height of CWD was fairly consistent among the three forested plot types, but only few dead and down tree boles were present mainly in the gray stage stand. Therefore, increasing roughness by leaving wood in a gray stand after salvage logging may only help to disrupt continuous layers and weaknesses in the snowpack, if large stems and/or high stumps and root plates are kept in the stand (McClung, 2001).

4.2 Potential impacts on avalanche formation

Based on our findings and personal observations while revisiting the study plots every week or every other week over two consecutive winter seasons, we conclude that spruce forest stands up to at least five years after the initial infestation are capable of providing adequate protection against avalanche formation and release. The processes of the canopy interacting with certain snow and weather conditions may differ between the different stages during a spruce bark beetle outbreak cycle but lead to the same result: a heterogeneous snow stratigraphy that is less prone to avalanche release. In Figure 13 and below, we summarize the most important processes for each stage during a spruce bark beetle outbreak cycle and discuss implications for avalanche protection forest management after spruce bark beetle infestation.

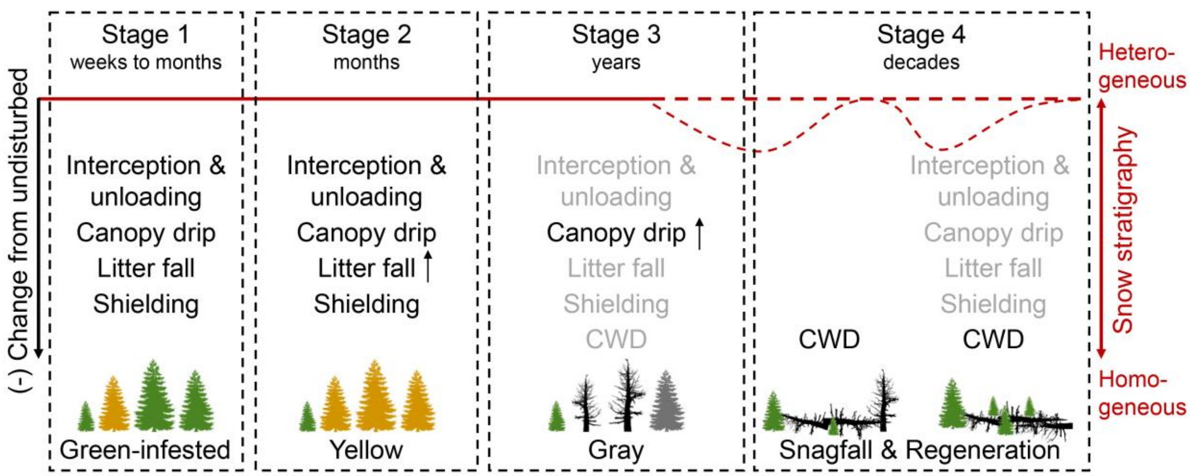

Fig. 13. Conceptual model of avalanche formation following spruce bark beetle outbreak for the stages 1) green-infested (current year's attack), 2) yellow (previous year's attack), 3) gray (approximately three to five years post infestation), and 4) snagfall and regeneration. Processes that do not change compared to undisturbed forests are shown in black. Processes that decrease in importance relative to undisturbed forests are shown in gray. Arrows indicate an increase relative to non-infested stands. Depending on the rate of snagfall between Stages 3 and 4, the probability for avalanche formation may decrease temporarily (especially during periods of heavy snow fall accompanied by cold air temperatures). The same is true, if decay rates of logs are faster than the establishment of sufficiently advanced regeneration. See Section 4.2 for further descriptions.

Stage 1 – Green-infested (current year's attack): Dense and mature spruce forest stands without canopy gaps wider than 20 m provide avalanche protection through canopy interception and subsequent unloading of intercepted snow (Bebi et al., 2009; Schneebeli and Meyer-Grass, 1993). Snow clumps dumping from branches embedded in the snowpack as well as meltwater dripping into the snowpack below canopies disrupt the snow stratigraphy and, therefore, prevent the formation of continuous snow layers and weaknesses, which is the prerequisite for avalanche formation in forests (Bründl et al., 1999; Schweizer et al., 2003). The wind shielding effect of forests reduces snow redistribution and compaction, and therefore the formation of a fine slope-parallel layering and hard- or wind-compacted snow slabs (Gubler and Rychetnik, 1991). Wind speed reduction and shading of the snowpack by the canopy also change the energy balance at the snow surface leading to more moderate temperature fluctuations, which reduces the formation of weak layers (Schneebeli and Bebi, 2004).

Stage 2 - Yellow (previous year's attack): In general, the same processes as in green-infested stands apply. In addition, needle release begins and debarking of infested trees by woodpeckers may occur, depositing needles and bark flakes onto the snow surface, which are subsequently buried in the snowpack throughout the snow season (Fig. 12D). The increase in the amount of organic material modifies the albedo and the radiation regime at the snow surface (Pugh and Gordon, 2013; Winkler et al., 2010), and creates flow channels for dripping meltwater (Bründl et al., 1999). Because needles and bark flakes have a lower albedo than snow they absorb more heat and emit long-wave radiation, which creates little melt depressions acting as entry ways for preferential flow. A layer of organic material buried in the snowpack can create an uneven boundary between snow layers, which also favors preferential flow of meltwater in the snowpack. Dripping meltwater, vertical flow and refreezing in the snowpack prevent the formation of weak layers and increase the stability of the snowpack.

Stage 3 - Gray (approximately three to five years post-infestation): At the beginning of this stage (at least up to five years after infestation), small branches and twigs that remain in the canopy as well as falling needles and branches provide similar protective benefits as green, green-infested and yellow stands. Although snow interception might be reduced during snow fall with air temperatures well below freezing level (Pfister and Schneebeli, 1999), unloading and an increase in canopy drip and preferential flow result in a similar heterogeneous snow stratigraphy as found in green, green-infested and yellow stands (Bründl et al., 1999). The stabilizing effect of gray trees may even exceed the snowpack stability found beneath larch crowns (Schweizer et al., 1995), since spruce stands are usually higher in density. Once small branches start to release and the canopy structure starts to breakup through the loss of bigger branches and limbs, an increase in homogeneity in snow stratigraphy is expected to reach its maximum as the canopy is no longer shading the snowpack, and canopy drip is significantly reduced.

Stage 4 – Snagfall and regeneration (decades after initial infestation): Once snagfall occurs, snow stratigraphy may gradually become more heterogeneous again as large diameter tree boles contribute to discontinuous snow layers, if the remaining standing and downed woody debris are spatially distributed without gaps larger than 20 m (Schönenberger et al., 2005; Feistl et al., 2014). It was found that areas in avalanche protection forests that were disturbed by wind and not cleared after the event occurred, effectively prevented avalanche release for at least ten and up to 20 years following the disturbance (Frey and Thee, 2002; Wohlgemuth et al., 2017). In contrast to windthrow, which occurs during one single event, snagfall in forests following spruce bark beetle disturbance is often more gradual, but such stands are also prone to additional wind disturbance. Kupferschmid Albisetti et al. (2003) found that 75% of snags in a Norway spruce mountain forest that was killed by European spruce bark beetle were already broken four to eight years after infestation caused by a storm event and increased wind speeds. They concluded that leaving such stands unharvested is likely to result in effective protection against avalanche release for about 30 years after infestation. The protective effect of woody debris will increasingly be replaced by future regeneration once seedlings and saplings are twice as high as the expected maximum snow height, and forest succession moves from stem initiation to stem-exclusion and closed-canopy stages. However, a critical ‘‘protection gap period’’ with reduced overall protection against natural hazards as suggested against rockfall after wind disturbance may occur (Frey and Thee, 2002), if snagfall and decay rates of logs are faster than the establishment of sufficiently advanced regeneration. In addition, the establishment of new seedlings and saplings on decaying Norway spruce logs may be hindered by the presence of brown-rot-causing fungus *Fomitopsis pinicola* (Fr.) Karst. in European spruce bark beetle killed forests (Bače et al., 2012).

4.3 Implications for avalanche protection forest management

Following spruce bark beetle infestation, it is common practice to implement some form of salvage logging or sanitation felling to reduce localized beetle population pressure and the buildup of hazardous fuels, and to recoup some economic value from infested trees (Collins et al., 2012; Jenkins et al., 2014; Stadelmann et al., 2013). In Norway spruce forests of the European Alps, reducing the spread of a European spruce bark beetle infestation within and into adjacent stands can be critical to prevent the extent of an outbreak throughout an avalanche protection forest (Stadelmann et al., 2014). When spruce bark beetle populations have reached epidemic phases, decisions about optimal management strategies (within a reasonable time and at reasonable costs) become thus more challenging.

For such forest areas where the maintenance of the protective effect is the highest priority, our results suggest that it is often more appropriate to leave dead trees in place. Results from our salvage-logged study plot, which had a lower stem density and, more importantly, a lower overall canopy cover, show that the snow stratigraphy that developed at this plot was homogeneous and similar to the stratigraphy found in the adjacent un-forested meadow. This indicates an insufficient protective effect in harvested stands where the majority of overstory large diameter trees was removed, which is comparable to clear-cut areas (McClung, 2001). On a larger spatial scale, removing infested and dead trees can affect local wind regimes resulting in higher wind speeds, which can increase snow drift and compaction, and loading of slopes that were previously shielded by forests (Teich et al., 2016). Consequently, post-outbreak harvest management decisions can greatly influence the future snow stratigraphy and thus avalanche formation.

We recognize that in areas where the European spruce bark beetle pressure is endemic, management activities such as removal of infested trees through sanitation felling, and individual and small group salvage logging would be appropriate. These areas include, for example, important designated protection forest stands, recreation areas such as ski resorts, and viewsheds that are important for tourism to limit the loss and impact on these resources from future beetle infestations. Although, removing infested trees can be difficult and costly (e.g., by helicopter-assisted logging operations) due to the often limited accessibility to the terrain.

Strategies to increase resistance (decreased susceptibility) and resilience to a spruce bark beetle infestation, demand to manipulate stand structure and species composition (Brang, 2001; Jenkins et al., 2014; Motta and Haudemand, 2000; Schmid and Frye, 1977; Temperli et al., 2014). In order to decrease the susceptibility to infestations and to foster advanced regeneration, forest managers could supplement regeneration cuts with planting to increase species diversity and the proportion of non-host species (Wohlgemuth et al., 2017). This would also create more structural diversity, that is, uneven and multi-layered stands with a mosaic of tree sizes and age classes, which are ideal for long-term avalanche protection (e.g., Bachofen and Zingg, 2001; Ott et al., 1997; Motta and Haudemand, 2000). Following spruce bark beetle outbreak, it may be necessary to help accelerate forest succession in avalanche prone areas while also increasing future species diversity by local planting (Wohlgemuth et al., 2017). In high-risk areas where protective effects of the remaining gray stage stand and additional planting are still not considered to be sufficient, additional protection measures against avalanche formation and snow drift (e.g., wooden snow fences and tripods) may be required.

In addition to sanitation felling and planting, forest managers must consider how to manage the CWD load following spruce bark beetle infestation. Although our findings did not support our hypothesis that increased CWD as observed in the salvage-logged forest stand would lead to a more heterogeneous snow stratigraphy, the majority of the present CWD were not tree boles. Moreover, our gray stage stand had yet to reach the snagfall stage and almost all dead trees remained standing. It has been found that retaining fallen trees after wind disturbance in Norway spruce dominated avalanche and rock fall protection forests still provides protective capacity through increased surface roughness (Schönenberger et al., 2005; Wohlgemuth et al., 2017). Moreover, these studies were conducted in wind disturbed forests where the predominant direction of snagfall is related to the wind direction in contrast to spruce bark beetle killed stands without subsequent wind disturbance. This approach is easier and less expensive than active management, and often maintains adequate protection against avalanches (Kulakowski et al., 2017; Kupferschmid Albisetti et al., 2003). Additionally, in cases where only groups of trees are infested as in an endemic phase, individual trees could be felled and debarked to prevent further spread of spruce bark beetles (Jenkins et al., 2014), and left in place as a snowpack stabilizing element. In order to further improve the protective effect by CWD, it may be necessary to strategically orient (i.e., 30 to 45º to the slope direction) and anchor these logs, and to periodically check their position, anchoring and decay rate (BAFU, 2008).

4.4 Conclusions

With climate change, more frequent and severe bark beetle outbreaks are expected. Mountain forests, which often serve an important role in avalanche protection are therefore prone to drastically increasing disturbances by spruce bark beetle, with uncertain consequences for the avalanche hazard.

Our findings from studying the temporal and spatial variability of snow stratigraphy in non-infested, gray stage and salvage-logged Engelmann spruce forest stands show that snow stratigraphy under canopies of non-infested and gray stage stands is similar and generally more heterogeneous compared to salvage-logged forests and non-forested areas. The small fine branches and twigs that are still present in the canopy five years after the initial attack maintain snow interception and unloading, and especially increase canopy drip. However, such canopy related processes that stabilize the snowpack may be reduced during specific meteorological conditions, that is, during extended periods of snowfall accompanied by cold air temperatures and in winters with above average snowfall. Salvage logging that reduced the canopy cover to ~25%, led to a homogeneous snow stratigraphy similar to the layering found in non-forested areas, which is prone to avalanche formation. Residual logging slash did not increase the surface roughness enough to affect the snow stratigraphy; however, increased surface roughness after snagfall is a more effective protection measure.

Thus, our study suggests to leave dead trees and downed woody material in place, especially in protection forests where bark beetle populations have reached epidemic phases. Additionally, in cases where only groups of trees are infested as in an endemic phase, felling and debarking individual trees and anchoring of large debarked logs can prevent further spread of spruce bark beetles and stabilize the snowpack. Overall, logging operations and silvicultural measures after bark beetle disturbance in forests with a protective function have to be planned and carried out carefully. To provide sustainable long-term protection against avalanches, forest management decisions in spruce dominated forests must focus on increasing structural and species diversities and thus resilience to mitigate the severity of future attacks.

Future long-term studies are needed to address questions of how long and under what meteorological conditions the protective effect of gray stage stands will be sufficient as canopy structure declines with time since the initial outbreak.

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Appendix

Table A1

Sampling dates for Transects 1 to 8 in 2015 and Transects 1 to 7 in 2016 at four study plots GREEN, GRAY, HARVEST, and MEADOW at the study site in the Uinta Mountains in Utah, USA.

		Sampling date and plot			
Transect no.	**Year**	**GREEN**	**GRAY**	**HARVEST**	**MEADOW**
Transect 1	**2015**	January 29	January 30	January 30	January 30
Transect 2		February 5	February 6	February 5	February 6
Transect 3		February 12	February 13	February 12	February 13
Transect 4		February 19	February 20	February 19	February 20
Transect 5		NA	NA	February 25	NA
Transect 6		March 11	March 12	March 11	March 12
Transect 7		March 19	March 20	March 19	March 20
Transect 8		March 25	March 26	March 25	March 26
Transect 1	**2016**	January 13	January 13	January 12	January 12
Transect 2		January 26	January 26	January 25	January 26
Transect 3		February 9	February 8	February 8	February 9
Transect 4		February 23	February 22	February 22	February 23
Transect 5		March 8	March 7	March 7	March 8
Transect 6		March 21	March 21	March 21	NA
Transect 7		April 7	April 7	April 7	April 9