EFFECTS OF BARK BEETLE ATTACKS ON SNOWPACK AND SNOW AVALANCHE HAZARD

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ABSTRACT: Unprecedented bark beetle outbreaks across western North America have resulted in the death of millions of trees, which profoundly affects snowpack in high elevation forests. Healthy, dense forests growing in avalanche terrain reduce the likelihood of avalanche release by inhibiting the formation of continuous weak layers, which are key for slab avalanche formation. Bark beetle outbreaks quickly change composition, structure, and functions of forest ecosystems and may alter the protective effect of forests against snow avalanches. We examined the snowpack under canopies of Engelmann spruce forest stands in the central Rocky Mountains in Utah, USA, using the SnowMicroPen (SMP). Biweekly-repeated SMP measurements along 20 m transects at 0.5 m intervals were recorded in winter 2015/16 in study plots beneath canopies of a recently infested trees (green), trees 3+-years after bark beetle infestation (gray), a harvested forest stand, and a non-forested meadow. We describe the evolution of the snowpack at our four study plots with two-dimensional snow density profiles as a measure of snow stratigraphy, which we derived from our high-resolution spatio-temporal SMP data. Our results indicate that at this relatively small spatial scale, differences in snow density layers between green and gray forest stands were not clearly observable. More homogeneous layering developed during periods of less to moderate snowfall where unloading or melting of intercepted snow from the canopy is reduced and snow metamorphism is the dominant process influencing snow stratigraphy. After harvesting, canopies of remaining smaller diameter trees and woody debris had no significant impact on snow stratigraphy, which needs to be addressed when planning silvicultural measures in protection forests and ski resorts. Considering changes in snowpack properties and local wind regimes following bark beetle attack is important for road and railroad safety, winter backcountry activities, avalanche forecasting, and protection forest and ski resort management.

KEYWORDS: subcanopy snow stratigraphy, avalanche protection forest, spruce beetle, SnowMicroPen

1. INTRODUCTION

In recent decades, billions of coniferous trees across millions of hectares in forests ranging from Mexico to Alaska have been killed by native bark beetles (Coleoptera: Curculionidae, Scolytinae; Bentz et al. 2010), profoundly affecting snowpack in high elevation forests (Pugh and Small 2012). Forests growing in avalanche terrain play an important role in avalanche protection by reducing the formation of continuous weak layers that contribute to slab avalanches. Forests modify snowpack properties through the interception of falling snow by tree crowns, the reduction of near-surface wind speeds, and changes to the energy balance beneath and around trees (Schneebeli and Bebi 2004). Together these processes lead to a highly variable snow stratigraphy (the characteristic microstructural layering within seasonal snowpack), which inhibits avalanche formation (Fig. 1). Bark beetle-induced tree mortality alters forest cover creating potential avalanche release areas where the forest previously protected settlements, infrastructure, ski slopes and backcountry snow recreationists against avalanches.

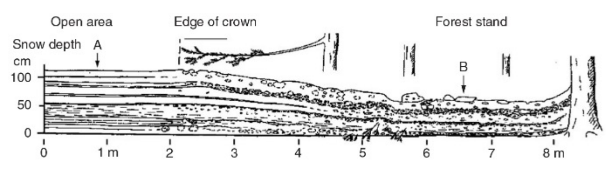

Fig. 1: Snow profile outside (A: homogenous snow stratigraphy) and beneath (B: heterogeneous snow stratigraphy) a spruce canopy. (Source: Schneebeli and Bebi 2004)

Native bark beetles are key agents of disturbance and change in coniferous forests of western North

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America. Bark beetles naturally shape forest ecosystems by removing old, decadent individuals allowing other tree species and age classes to establish (Veblen et al. 1991). However, many current outbreaks are among the largest and most severe in recorded history, with increasing evidence that outbreaks have moved higher in elevation than has been previously observed (Bentz et al. 2016). Bark beetle attack causes a rapid decrease in canopy bulk density without immediately altering the physical structure of the forest. The loss of needles reduces canopy interception, increases light transmission and wind speeds, and modifies the surface energy balance altering snow accumulation, melt and the microstructural properties of subcanopy snowpack and, therefore, snow stratigraphy with unknown consequences for avalanche hazard.

Investigating and monitoring the microstructural layering within subcanopy snowpack over space and time is key for assessing the impact of bark beetle-induced tree death on avalanche formation. However, snowpack observations in forested terrain are rare and typically describe layering and related microstructural properties such as hardness, grain size, and grain shape by point observations with snow pit profiles. Such observations emphasize and illustrate the heterogeneous stratigraphy of subcanopy snowpack (Fig. 1), but are not able to adequately describe forest-snowpack interactions in space and time. Furthermore, manual snow pit profiles disturb the snowpack such that repeat measurements are not possible, and are highly dependent on observer skills introducing uncertainty, if the snow pit is mischaracterized. In contrast, the SnowMicroPen (SMP) is a portable and minimally invasive instrument, which measures snow penetration resistance (the force required to break bonds between snow crystals) automatically and observer-independent every 4 µm to a depth of 1.2 m (Schneebeli and Johnson 1998).

We used the SMP to repeatedly examine the snowpack under canopies of spruce beetle (*Dendroctonus rufipennis* Kirby) infested Engelmann spruce (*Picea engelmannii* Parry ex Engelm.) forest stands in the central Rocky Mountains in Utah, USA, over the winter 2015/16. Spruce beetles cause drastic changes in community structure, composition, and functions of spruce dominated forests (Jenkins et al. 2014), which occur above 2400 m throughout the Intermountain Region of the US. Since the early 1990's, spruce beetles have affected >180,000 ha of Engelmann spruce forests in the Intermountain Region; recent spruce beetle outbreaks in Utah alone have killed over 1 million trees (data from Aerial Detection Surveys 1996-2015, USDA Forest Service-Forest Health Protection), including backcountry terrain and ski resorts. Using snowpack data and other observations as a guide, we discuss consequences of bark beetle-induced tree mortality and salvage logging strategies on snowpack and snow avalanche hazard. These considerations are important for protection forest and ski resort management, road and railroad safety, winter backcountry activities, and (forest) avalanche forecasting (Teich et al. 2013).

2. STUDY AREA

2.1 Study site and plots

Our study site is located in an Engelmann spruce-subalpine fir (*Abies lasiocarpa* (Hooker) Nuttall) forest at an elevation of approximately 2900 m in the Uinta Mountains, Utah, USA (Fig. 2).

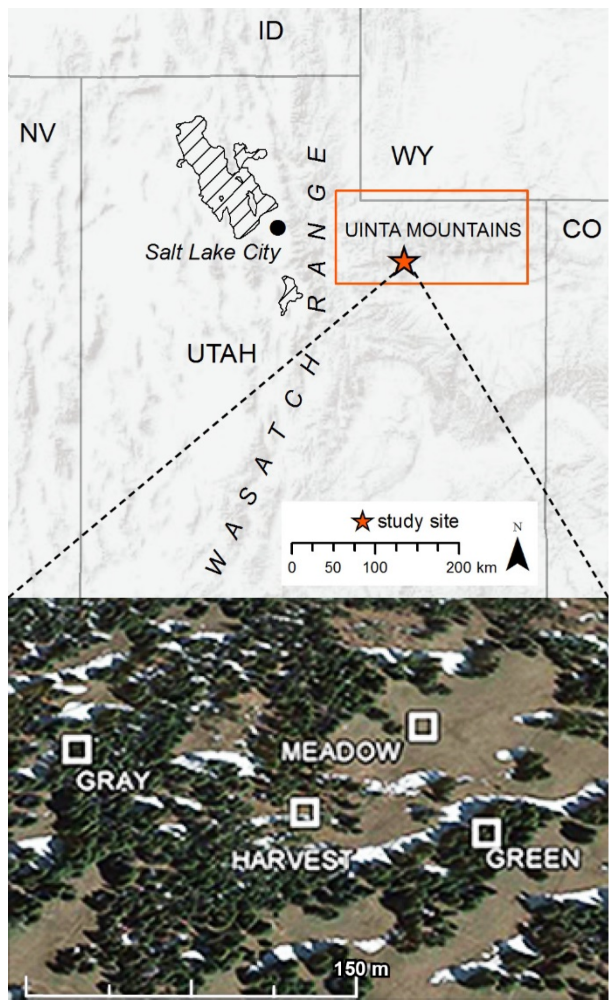

Fig. 2: Study site and study plots locations.

Four study plots were established in close proximity to each other characterizing different stages during a spruce beetle outbreak cycle. We chose three plots beneath trees, which were (1) recently infested by spruce beetles (GREEN), (2) infested more than three years ago (GRAY), and (3) salvage logged (HARVEST). A non-forested plot was installed and fenced in a meadow as the control exemplifying a total removal of the forest cover (OPEN; Fig. 2, Tbl. 1).

Tbl. 1: Forest and site characteristics of selected study plots measured October 2014.

	Green	*Gray*	*Harvest*	*Open*
Stem density [no./ha]	1234	596	509	-
Total basal area [m^2]	82.7	55.1	13.8	-
Average tree height [m]	20.1	18.9	14.6	-
Average DBH [cm]	33	36	19	-
Average crown diameter [cm]	411	428	295	-
Average height to crown [m]	7.0	4.8	8.4	-
Canopy density [%]	85	81	55	-
Green canopy [%]	89	37	100	-
Elevation [m asl]	2909	2901	2909	2896
Slope (º)	5	5-10	10	10-12
Aspect	N-NE	N	NW	N

After plot selection in September 2014, some trees in the GREEN plot showed signs of spruce beetle infestation, i.e. reddish-brown boring dust had accumulated at beetle entrance and emergence holes and on the ground around trunks, but the needles were still green and not fading (Fig. 3). During winter 2014/2015, the infested trees were partially debarked by woodpeckers leaving layers of bark flakes on the snow surface around the trunks, which were subsequently buried throughout the snow season (Fig. 4a, b). Needles of infested trees started to turn yellowish-green and release during winter 2015/2016 enhancing the litter content of upper snow layers. As we revisited the GREEN plot in July 2016, almost all trees were infested, where some had lost the majority of their needles, while few trees were already dead.

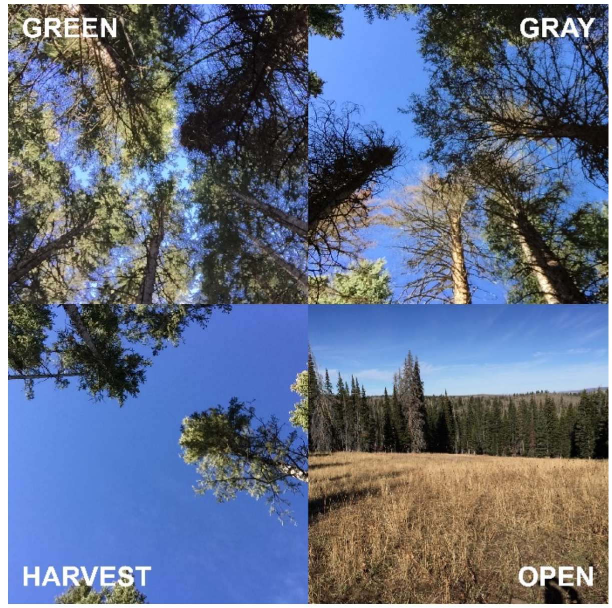

Fig. 3: Views upward in the canopies of study plots in September 2014.

Fig. 4: a) Bark flakes accumulated around woodpecker-debarked trunks of beetle-infested trees at the GREEN plot, which were b) subsequently buried in the snowpack. c) Needles dropped onto snow surface at the GRAY plot, and dense ice clumps emerging at the snow surface. d) Woody debris left after salvage logging at the HARVEST plot.

The majority of trees in the GRAY plot were attacked prior to 2014 and had already dropped needles at the time of study plot establishment leaving the upper crowns of exposed twigs with a gray hue (Fig. 3). Gray trees were interspersed with few green-infested trees consistently dropping needles onto the snow surface during winter 2015/16 (Fig. 4c).

Salvage logging is a post-disturbance forest management strategy designed to recoup wood product value, reduce hazardous fuels and enhance regeneration. The HARVEST plot was salvage logged by removing dead overstory spruce and retaining live overstory and understory trees with diameters <15 cm, which are less prone to bark beetle attack (Fettig et al. 2007). The logging increased the surface roughness with effective woody debris heights up to 0.95 m (Fig. 4d).

2.2 Meteorology

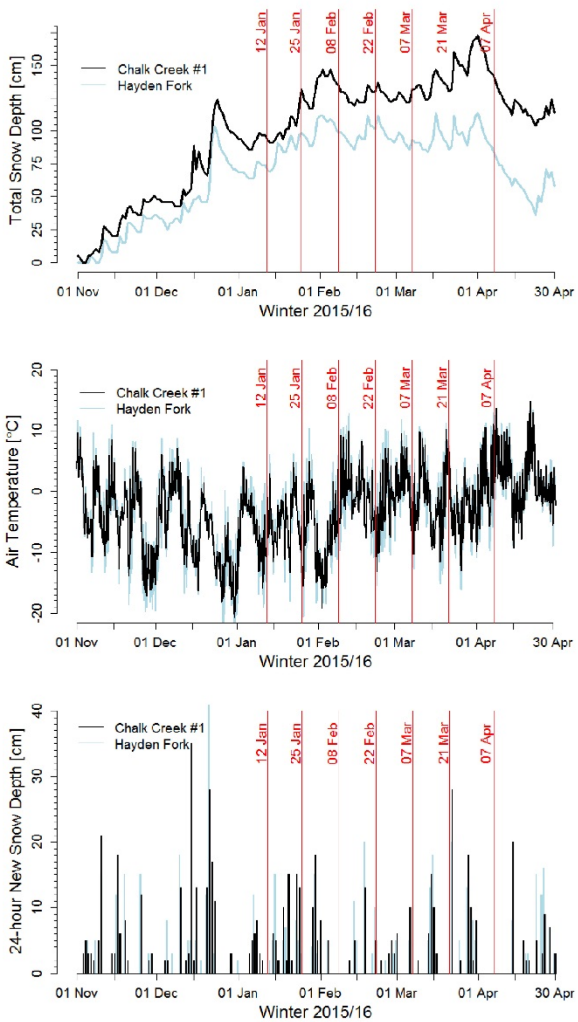

Fig. 5: Total snow depth (at 6:00 am), hourly air temperature and 24-hour new snow depth measured at SNOTEL Stations Chalk Creek #1 and Hayden Fork. Red lines indicate days of field campaigns.

The climate at the study area is typical of a continental subalpine site in the western US, with the majority of precipitation falling as snow during the winter months. Meteorological data are measured hourly by four Natural Resources Conservation Service Snowpack Telemetry (SNOTEL) stations near the study site. The two closest SNOTEL stations at elevations similar to the study site are Chalk Creek #1 (2741 m asl, 8.2 km to the west) and Hayden Fork (2808 m asl, 8 km to the southeast). The two stations measure air temperature, snow depth and precipitation accumulation (Fig. 5).

3. FIELD METHODS

3.1 Snowpack measurements

We used the SMP to examine the microstructural properties and to monitor the evolution of the snowpack in our four study plots in a spatial and temporal resolution. In the first winter field campaign on January 12 and 13, 2016, we defined and marked start and endpoints of the first transect (Transect 1) in each of the four plots, which served as reference for all following field campaigns. Each transect was 20 m in length running in an east-west direction. We recorded SMP measurements at 0.5 m intervals along each transect resulting in a maximum of 41 sampling points per study plot and sampling date (sample points were omitted, if obscured by a tree). In addition to SMP recordings, snow depth was measured and forest cover was estimated in 25% increments by two observers using a GRS Densitometer at each SMP sampling point. Every two weeks, transect endpoints were moved 0.5 m south from the previous point and measurements were repeated. In total, we sampled along seven transects throughout winter 2015/16 spanning a period of 14 weeks from mid-January to early April (Fig. 6).

During each field campaign, additional snow pit profiles were excavated in the OPEN plot. The International Classification for Seasonal Snow on the Ground (Fierz et al. 2009) was used to manually assess and classify layering, grain shape and size, and hand hardness. Snow temperature and density were measured every 5 cm with a digital thermometer and a 250 cc wedge cutter, respectively. Three SMP measurements were taken each time ~15 cm behind the pit walls.

3.2 Forest measurements

In July 2016, tree locations were mapped from the starting point of the first transect (position 0,0) with a compass and measuring tapes. A tape was laid east to west along Transect 1 (Fig. 6). The perpendicular angle to that tape was determined by sighting a target tree with a mirror compass and the distance from that tape to each tree was then measured with a second tape. For each mapped tree, we recorded the diameter at breast height (DBH measured 1.37 m above ground), tree height, height from the ground to the first green branches, and crown width. We also estimated the percentage green of total crown volume (two observers) and assigned a class of infestation (green/uninfested, green-infested/fading, gray/dead).

4. DATA PROCESSING

The SMP measures the penetration force (N) with a constant speed of 20 mm s^{-1} 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. All SMP recordings were checked for signal errors and quality according to the classification scheme of Pielmeier and Marshall (2009). Only signals which were classified as "C1" (no error), and "C2" signals (trend or offset in absolute SMP force) 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 signal processing from the SMP signal leaving only the signal recorded within snowpack.

We further processed SMP signals collected along each transect and at each sampling date (+/-41 signals per transect and date) using a statistical model developed by Proksch et al. (2015). This bilinear regression model estimates snow density based on the SMP parameters structural element length L (the mean distance between two rupturing elements), which is computed from the fluctuating SMP penetration force signal using the stochastic model from Löwe and van Herwijnen (2012), and the logarithm of the median penetration force ln ($\tilde{F}$). We filtered SMP parameter profiles with a sliding window size of 2.5 mm width and 50% overlap, yielding an estimate of L and $\tilde{F}$ for each window, and derived two-dimensional snow density profiles as a measure of snow stratigraphy without digging a snow pit (Fig. 7).

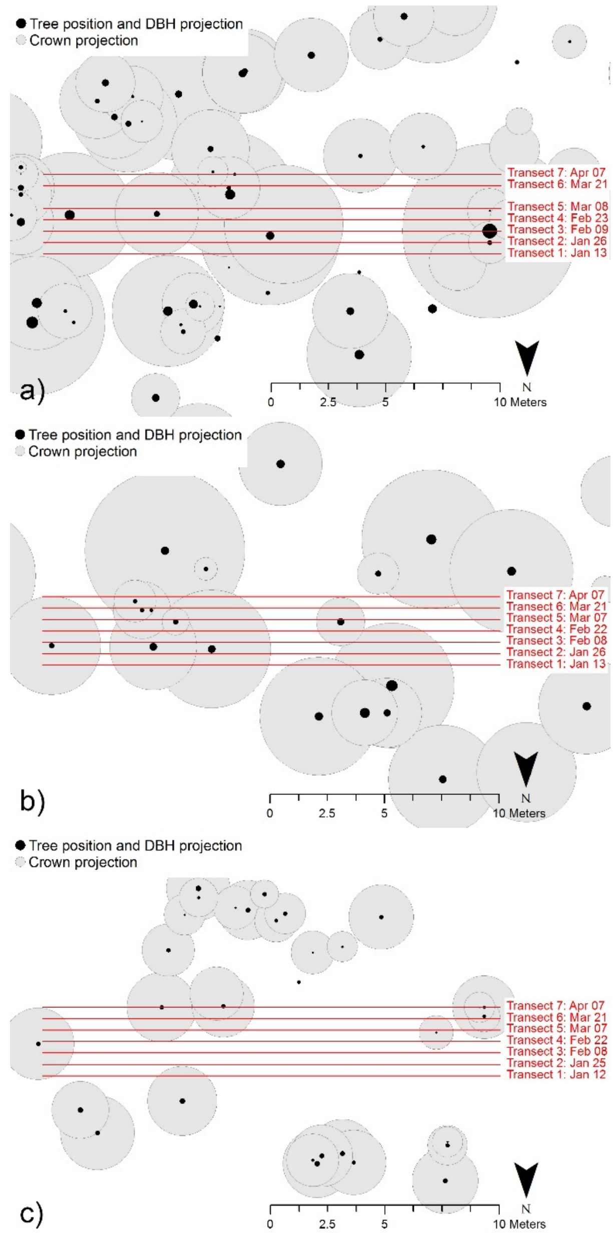

Fig. 6: Maps of tree locations, projected tree trunks (DBH measured at 1.37 m above ground) and crowns, and transects and sampling dates (in red) for study plots: a) GREEN, b) GRAY, and c) HARVEST. Note that N-S direction is rotated by 180°.

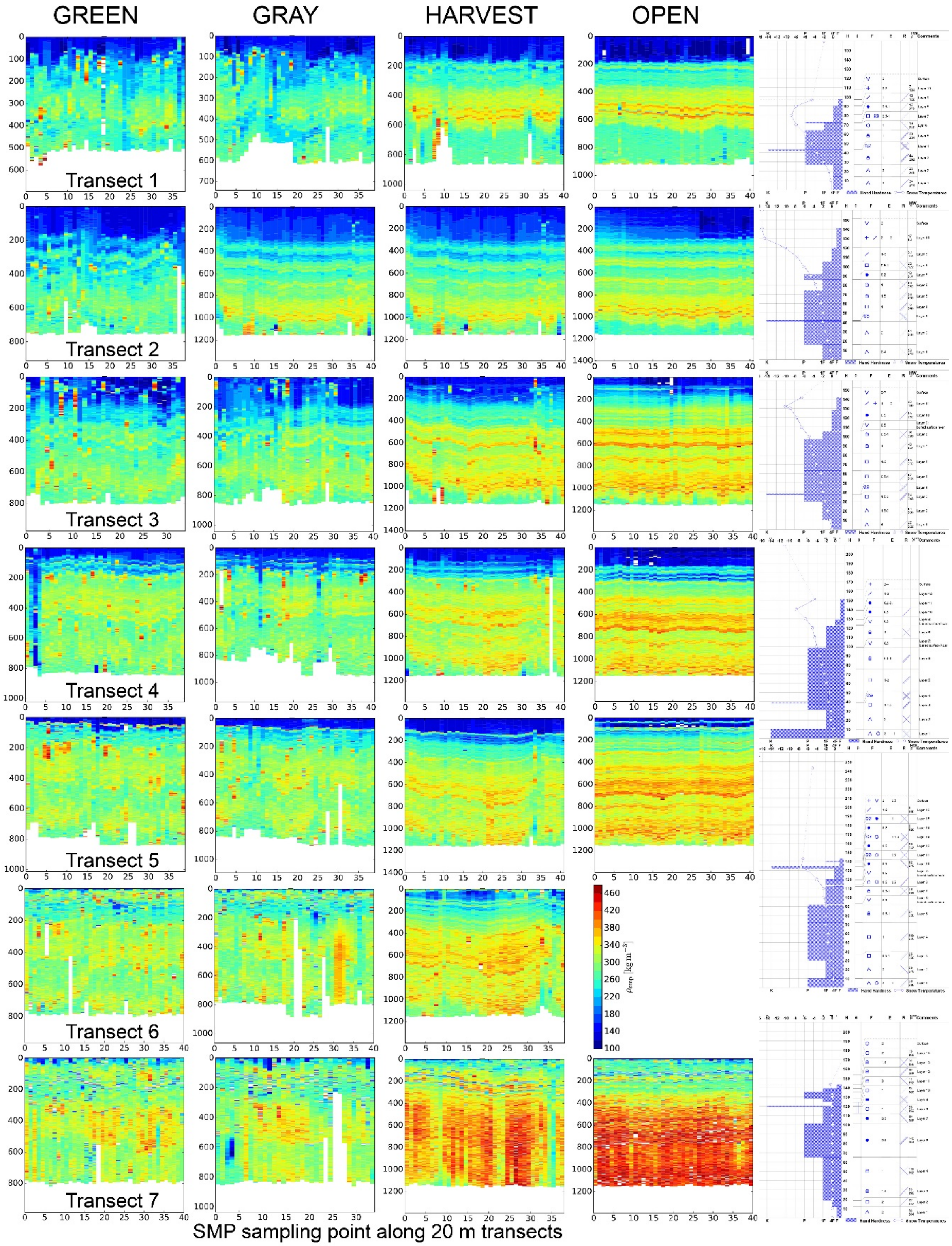

Fig. 7: SMP-derived densities (ρSMP), and manual snow profiles (right column) taken at the OPEN plot. Density plots are composites of +/-41 SMP measurements taken at 0.5 m intervals.
Note that the model from Proksch et al. (2015) was developed based on the SMP version 3 and might be incompatible with the newest hardware version 4 of the SMP used in this study. Therefore, actual snow density values might be slightly different from the computed ones. We will calibrate the model with densities sampled in the snow pits at 5 cm intervals and SMP measurements taken ~15 cm behind the pit walls.

5. RESULTS

In general, Figure 7 highlights the small-scale, but substantial differences in snow density and layering between our four study plots emphasizing the changing canopy effects during different stages of a spruce beetle outbreak cycle. Starting with the first transects sampled on January 12, GREEN and GRAY plots showed a highly variable snow stratigraphy. In contrast, continuous layers of different densities were recorded at HARVEST and OPEN plots. A continuous snowpack covered the study area since mid-November 2015 with a period of more intense snowfall and cold minimum air temperatures of -25°C in the second half of December 2015. Beginning January, mean air temperatures increased to -0.5°C followed by another cold period and minimal snowfall (Fig.5). The accumulated snow is, therefore, less dense and, shaded by trees, remained less dense in the upper layers of GREEN and GRAY plots. In contrast, continuous higher density layers were already detected in HARVEST and OPEN plots. Throughout the snow season, snowpack in all plots settled with higher densities at the bottom, but this process was much more dominant in the HARVEST, and especially the OPEN plot, which showed a continuous layering and homogenous snow stratigraphy each time sampled. The generally heterogeneous snow stratigraphy at GREEN and GRAY plots became more homogeneous at Transects 3 and 4 sampled in February. Transect 3 was collected following a period of moderate snowfall and cold air temperatures; Transect 4 received less snowfall and warmer temperatures of up to 10°C, which decreased towards the sampling date of February 22 to a minimum of -10°C. Canopy cover along these transects were similar to the ones sampled before and after (Fig. 6).

After we sampled Transect 4, total snow depth stayed at a similar height driven by altering positive and negative air temperatures and smaller amounts of accumulated snow. One bigger snow storm affected the area on March 22, just after we sampled Transect 6 and two weeks before our last field campaign. After this snow event, air temperatures started to increase towards our last field campaign where we recorded 8.5°C on April 7 causing the isothermal snowpack, and wet and dense snow layers observed at OPEN and HARVEST plots. Snow densities at GREEN and GRAY plots were much lower and especially the upper snow layers were highly disturbed.

6. DISCUSSION

Healthy dense forest growing in avalanche terrain and starting zones can inhibit the formation of continuous weak snow layers and protect people, settlements and infrastructure against snow avalanches. After bark beetle attack, snow stratigraphy beneath dead trees is likely to change driven by reduced canopy interception, and increased wind speeds and light transmission, which modify the energy balance at the snow surface, but if these forests are still able to fulfill their protective function is uncertain. Therefore, monitoring and quantifying changes to snow deposition and metamorphism following bark beetle attack is of value, especially since outbreaks are likely to increase in frequency and magnitude at high elevations in North America and Europe under projected warming temperatures (Bentz et al. 2016, Seidl et al. 2014).

The layers detected by the SMP were also found in the manual snow profiles taken at the same day in our OPEN plot, but SMP-derived density profiles are of much higher resolution and detail. This highlights the advantages of the SMP in providing fast, minimally invasive and observer-independent information on microstructural properties of snow.

Our results indicate that at this relatively small spatial scale, differences in snow density layers between green (recently infested) and gray (3+-years post-infestation) forests are not clearly observable (Fig. 7). However, we do see a more homogeneous layering in the generally variable snow stratigraphy following periods of low to moderate snowfall where unloading or melting of intercepted snow from the canopy is reduced and snow metamorphism is the dominant process influencing snow stratigraphy. In contrast, warm temperatures after heavier storm events lead to an increase in unloading and, especially in gray forest stands, to an increase in drip from defoliated branches disturbing the upper layers of the snowpack. Additional field observations showed higher amounts of refrozen dense ice clumps in the snowpack at the gray forest stand (Fig. 4c), leading to the assumption that the needle loss could increase concentrated canopy drip, additionally disturbing the formation of continuous snow layers.

Following bark beetle disturbance, infested stands are often salvage logged to reduce hazardous fuels and to use infested stems for timber products. One logging strategy is to remove dead overstory and to retain trees with diameters <15 cm, which often results in woody debris increasing surface roughness. Surprisingly, canopies of small trees and remaining woody debris with effective heights up to 0.95 m had no significant impact on snow stratigraphy at the harvested forest stand. Therefore, logging operations and silvicultural measures after bark beetle disturbance in forests with a protective function have to be planned and carried out carefully, possibly accompanied by additional protection from avalanches and snow drift such as wooden fences.

On a larger spatial scale, removing infested and dead trees affects local wind regimes resulting in higher wind speeds, which can increase snow drift and loading of slopes previously shaded by forest. For example, high wind speeds and subsequent lift closures are a major problem at Brian Head ski resort in southwestern Utah, which lost up to 80% of their total trees during a recent spruce beetle outbreak (Utah Adventure Journal 2013). In addition to the potential increase in avalanche danger after bark beetle attack, loss of shade from the canopy results in earlier snow melt and poorer snow conditions for tree skiing. Stems, bark flakes, dead needles and other debris influences snow metamorphism often turning snow to "rot". Additionally, beetle killed trees in the backcountry can pose a serious threat to recreationists from standing dead snags and buried debris.

7. CONCLUSIONS

Changes in snowpack properties after bark beetle attack should be considered in protection forest and ski resort management as well as for road and railroad safety, and winter backcountry activities. Based on our one-winter/small-scale observations, significant changes in snow stratigraphy beneath recently infested trees compared to trees 3+-years post-infestation were not detected. However, the increasing homogeneity in snowpack layers in infested stands that were salvage logged, needs to be addressed when planning silvicultural measures in protection forests and ski resorts.

ACKNOWLEDGEMENTS

We thank the USDA Forest Service’s Intermountain Region-Forest Health Protection group, and especially Darren Blackford and Liz Hebertson for their help. We are grateful to Ted Scroggin and Mark Nelson from the USDA Forest Service for providing snow machines and additional support in the field. This study was funded by the USU Department of Wildland Resources and the USDA Forest Service. Michaela Teich is supported by an individual fellowship from the Swiss National Science Foundation (grant P2EZP2-155606).

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