# Snowmobile Impacts on the Physical and Mechanical Properties

Steven R. Fassnacht[1,2,3,4,5*], Jared T. Heath[1,6], Kelly J. Elder[7]
[1] Department of Ecosystem Science and Sustainability – Watershed Science, Colorado State University, Fort Collins, Colorado USA 80523-1476
[2] Cooperative Institute for Research in the Atmosphere, Fort Collins, Colorado USA 80523-1375
[3] Geospatial Centroid at CSU, Fort Collins, Colorado USA 80523-1019
[4] Natural Resources Ecology Laboratory, Fort Collins, Colorado USA 80523-1499
[5] Geographisches Institut, Georg-August-Universität Göttingen, 37077 Göttingen, Germany
[6] City of Fort Collins, Water Resources & Treatment, Fort Collins, Colorado USA 80521
[7] Rocky Mountain Research Station, US Forest Service, Fort Collins, Colorado USA 80526
**Corresponding author*: steven.fassnacht@colostate.edu; phone: +1.970.491.5454

Short title: **Snowpack Changes due to Snowmobile Use**

## Abstract

We ran a snowmobile over a series of test plot to examine the physical and material properties of the snowpack due to compaction from a snowmobile. We measured the snow density, temperature, stratigraphy, hardness, and ram resistance from snow pit profiles. Experiments were performed at two different experimental areas, specifically Rabbit Ears Pass near Steamboat Springs and at Fraser Experimental Forest near Fraser, Colorado USA. We examined the difference between no use and varying degrees of snowmobile use (low, medium and high) for different starts of snowmobile use, specifically on a shallow (the operational standard of 30 cm) and deeper snowpack (120 cm). Significant changes in snowpack properties were measured due to snowmobile use beginning on a shallow snowpack. These snowpack property changes were more pronounced where there was less snow accumulation. When snowmobile use started on a deeper snow, in particular at 120cm, there was less difference compared to the control case of no snowmobile use.

## 1. Introduction

In the United States, where annually snowmobiling accounts for between $7 billion (American Council of Snowmobile Associations, 2014) to $26 billion (International Snowmobile Manufacturers Association, 2016) in revenue, much of the snowmobile use is on public land. The United States National Forest System sees about 6 million annual snowmobile visits accessing about 327,000 km$^2$ of land (US Forest Service, 2010 and 2013a). As the number of people participating in winter recreation is increasing (Cook and Borrie, 1995; Winter Wildlands Alliance, 2006; US Forest Service, 2010; Nagler et al., 2012; US Forest Service, 2013a; Colorado Off-Highway Vehicle Coalition, 2016), the presence of activities like snowmobile use may influence snowpack properties in these seasonally snow-covered environments. Further, as the climate changes, there will be reduced land available for snowmobiling (Tercek and Rodman, 2016), likely increasing the impact of snowmobile traffic.

There have been limited studies regarding the influence of snowmobile use on snowpack properties (Keddy et al., 1979; Thumlert et al., 2013; Thumlert and Jamieson, 2015). Various studies examine how the snowpack changes due to snow grooming at ski resorts (Fahay et al., 1999; Keller et al., 2004; Spandre et al., 2016a), or to traction and mobility of wheeled vehicles across a snowpack (Abele and Gow, 1990; Shoop et al., 2006; Pytka, 2010). One of these few studies has been for snowmobile use on shallow snow (10 to 20 cm deep) that caused a doubling of fresh snow density, little impact on the underlying old snow, but had a highly significant effect upon natural vegetation below the snow (Keddy et al., 1979). Examining deeper snow, Thumlert et al. (2013) and Thumlert and Jamieson (2015) examined the distribution of stresses through the snowpack due to type of loading, depth and snowpack stratigraphy (Thumlert et al., 2013). We specifically examined the effect of snowmobile use on the physical and material properties of the snowpack. The objectives of this research were: (1) quantify changes to physical snowpack properties due to compaction by snowmobiles; and (2) evaluate these changes based on the amount of use, depth of snow when snowmobile use begins, and the snowfall environment where snowmobiles operate. This work examines both the entire snowpack and the basal layer. Since there are many snowmobile users and billions spent each year on snowmobiling this work will benefit land managers who need to make decisions about multi-use areas that are used by snowmobilers, among others.

## 2. Study Sites

During the 2009-2010 snow season a set of snow compaction plots were located near Rabbit Ears Pass (REP) in the Rocky Mountains of northern Colorado to southeast of the town of Steamboat Springs. REP is within the Medicine Bow-Routt NF (Figure 1) along the Continental Divide encompassing over 9,400 km$^2$ of land in Colorado and Wyoming. Rabbit Ears Pass is especially popular during the winter season and is heavily used by snowmobilers and other winter recreationalists due to the ease of access to backcountry terrain from Colorado Highway 40. Due to heavy use and conflict among users during the winter season, the Forest Service manages Rabbit Ears Pass for both non-motorized and motorized uses. The west side of pass is designated for non-motorized users and prohibits the use of motorized winter recreation and, the east side of the pass is a mixed use area and open to motorized users (Figure 1). If snowmobile use impacts the snowpack, as we examine in this paper, then differences in snowpack properties will be observed (e.g., Walton Creek versus Dumont Lakes and Muddy Pass in Figure 1).

Two REP experimental snow compaction study plots were located adjacent to one another within an open meadow north of Colorado Highway 40 at an elevation of approximately

3,059 m (Figure 1). The snow compaction sites were established within an area that prohibits motorized use to protect the study sites from unintended impacts of snowmobilers. The Columbine snow telemetry (SNOTEL) station, located at an elevation of 2,792 m, was used to show how 2009-2010 winter compared to other winters at REP. The SNOTEL network was established in the late 1970s across the Western United States by the Natural Resources Conservation Service to monitor snowpack properties (initially snow water equivalent and precipitation, and temperature and snow depth were added in the 1990s-2000s) for operational runoff volume forecasting (see <wcc.nrcs.usda.gov>).

Three operational sites that were not experimentally manipulated, i.e., where the specific amount of snowmobile use was unknown, were identified along Colorado Highway 40 on REP (Figure 1 left inset). The "natural" control site was Walton Creek, located west of Rabbit Ears Pass in an open meadow at an elevation of 2,895 m within a managed area that prohibits motorized use. Snowshoers, skiers, and snowboarders primarily use this area in the winter to access backcountry terrain. Two treatment sites were located east of REP at an elevation of about 2,900 m within an area managed for motorized and mixed uses; the Dumont Lakes and Muddy Creek sites were located in open meadows near their trailheads (Figure 1). These trailheads provide backcountry access to snowmobilers and snowmobile use in the meadows near the trailheads is medium to high, especially on weekends and over holidays (Skorkowsky, 2010). The meadow near the Muddy Creek trailhead is more heavily used by snowmobiles than the meadow near the Dumont Lakes trailhead.

Another experimental snow compaction plot was established at the Fraser Experimental Forest (FEF) near the town of Fraser, Colorado in the Rocky Mountains of Central Colorado (Figure 1). The 93 km$^2$ experimental forest is a research unit of the United States Forest Service

(USFS) Rocky Mountain Research Station (RMRS) located within the Arapaho NF. The FEF snow compaction site was located in a small meadow at an elevation of 2,851 m among lodgepole pine (*Pinus contorta*) forest. The Fraser Experimental Forest is closed to snowmobile use, but is used in the winter to access backcountry terrain by snowshoers, skiers, and snowboarders. The Middle Fork Camp SNOTEL station, located at an elevation of 2,725 m, was used to characterize the 2009-2010 winter at FEF.

## 3. Methods

### *3.1 Experimental snow compaction plots*

Snow compaction study plots were established in undisturbed areas at the REP and FEF experimental snow compaction study areas. Each plot was 22 m wide and 15 m long (Figures 2a and 2b). Plots were divided into equal width transects (2 m) and treated with low, medium (FEF only), or high snowmobile use, including a no treatment control transect representing an undisturbed snowpack. Two control transects were used at FEF to represent the undisturbed snowpack. Integrating two controls in the study plot allowed for replication and determination of variability. The location of control and treatment plots across each study site was randomly selected. Each transect was separated by a three meter buffer to eliminate the influence of compaction treatments on adjacent transects (Figures 2a and 2b).

Transects were treated by driving a Skidoo brand snowmobile weighing about 300 kg with the rider (Figure 2d) at 10 km/h over the length of each transect five, 25 (FEF only) or 50 times, representing low, medium (FEF only), and high snowmobile use, respectively. Treatments began (Figure 2c) when non-compacted snow depths were approximately 30 cm (12 inches) for both locations, and when unpacked snow depths equaled approximately 120 cm (48 inches) for

REP only (Figure 2a). Treatments were implemented (Figure 2e) monthly thereafter, until peak accumulation (Figure 3). Snowpack sampling was performed within a week after each treatment (Figures 2 and 3).

### *3.2 Snow pit analyses and data collection*

Snow pit profiles were used to examine the physical properties of the snowpack in all study sites. A vertical snow face was excavated by digging a pit from the snow surface to the ground. Measurements of snow density, temperature, stratigraphy, hardness and ram resistance were taken vertically along the snowpack profile. Total snow depth was measured from the ground up, and combined with density to yield snow water equivalent (SWE). Physical snowpack properties were compared between non-snowmobile (control) and varying degrees (low, medium (FEF), and high) of snowmobile use (treatment).

Density was measured at 10 cm intervals, from the surface of the snowpack to the ground, by extracting a 250 mL or 1000 mL snow sample using a stainless steel wedge cutter <snowmetrics.com> and measuring the mass on an electronic scale with a resolution of 1g. The density of the snow ($\rho_s$ in kg/m$^3$) was determined by dividing the mass of the snow sample by the volume of the wedge cutter. Snowpack density profiles were a continuous profile of discrete 10 cm measurements. The bulk snowpack density was determined by averaging the depth integrated density measurements through the entire depth of the snowpack. A mean of the density measurements for the bottom 10 cm of the snowpack were used to evaluate changes near the snow and ground interface (basal layer).

Temperature measurements were obtained at 5 cm intervals from the top to the bottom of the snowpack using a dial stem thermometer with ±1$^{o}$C accuracy. The repeatability in the temperature measurement was better than ±1°C, and temperature gradients are well represented by this instrument (Elder et al., 2009; American Avalanche Association, 2016). Snowpack temperature profiles and the corresponding bulk temperature gradient were compared. The temperature gradient ($T_G$ in °C/m) was calculated as the ratio of the change in temperature ($\Delta T$ in °C) from the snowpack depth where the temperature gradient was linear (upper boundary, 25-30 cm below the surface) and the temperature at 0 cm (lower boundary) with the distance ($d$ in m) over which the change in temperature occurred. For this study, the point of zero amplitude was used as the upper boundary to remove bias from diurnal fluctuations (Pomeroy and Brun, 2001). Basal layer temperatures (0 cm) were used to compare temperature changes near the snow and ground interface.

Stratigraphic measurements illustrate the evolution of the snowpack over time by characterizing the shape and size of snow crystals within each stratified layer of the snowpack. Classification of grain morphology was based on *The International Classification for Seasonal Snow on the Ground* (Fierz et al., 2009) and mean grain size was measured and recorded to the nearest 0.5 mm using a hand lens and a crystal card. The crystal forms were identified as fresh, rounded, faceted, and ice layers.

Hardness is the penetration resistance of the snowpack (Fierz et al., 2009), and is reported as the force per unit area required to penetrate the structure of the snowpack (McClung and Schaerer, 2006) due to microstructure and bonding characteristics of the snow grains (Shapiro et al., 1997). Hardness measurements were taken horizontally with a force gauge in each stratigraphic layer using a Wagner Instruments Force Dial gauge (<http://wagnerinstruments.com>) with maximum force measurements of 25 N and 100 N, and fabricated circular metal plate attachments of known area (20 $cm^2$) . The circular metal plate was pushed into the snow and the force required to penetrate the snow was recorded. The snow hardness ($h_i$ in N/m$^2$) for each stratigraphic layer was calculated as the force required to penetrate the snow ($F$ in N) per unit area of the circular metal plate ($A$ in m$^2$). The bulk snowpack hardness ($H_B$ in N/m$^2$) was determined by weighing each stratigraphic layer hardness measurement by the stratigraphic layer thickness. The hardness associated with the bottom stratigraphic layer for each transect was used to describe hardness changes in the basal layer of the snowpack.

The standard ram penetrometer is an instrument with a cone on the end of a tube onto which a hammer of known weight is dropped from a known height and the depth of penetration is recorded; it was used to vertically measure the relative hardness or resistance of a snow layers in order to assess the change in ram resistance due to compaction (American Avalanche Association, 2016). A ram profile measurement was taken 0.5 meters from the edge of the snow pit wall subsequent to snow pit profile measurements. The mean ram resistance ($S_B$ in N) was determined by weighting each stratigraphic layer's ram resistance value obtained from the standard ram penetrometer measurement with the layer thickness. The ram resistance value associated with the bottom stratigraphic layer was measured to describe changes in ram resistance in the basal layer of the snowpack .

### *3.3 Statistical analyses*

Data were analyzed using the Mann-Whitney-Wilcoxon rank sum test (Wilcoxon, 1945; Mann and Whitney, 1947). This determines the statistical significance between two datasets, herein different treatments compared to the control of no snowmobile use (Table 1). This statistical test is non-parametric and determines whether two samples were selected from populations having the same distribution. The sets of samples are comparable density, temperature, hardness, and ram resistance profiles for the five different monthly measurements. A statistical significance was determined to the 95% (significant) and 99% (highly significant) confidence interval ($p<0.05$, and $p<0.01$) and noted with an asterisk in Table 1.

## 4. Results

The 2009-2010 winter at REP had an average snow depth, based on the Columbine SNOTEL data (Figure 3a), while the peak SWE of 556 mm on 9 April was less than the historical average peak SWE at 93%. Maximum snow depth measured at the REP snow compaction study plot was approximately 1.5 m and for Colorado was deemed to represent a deeper snow cover environment. From the Middle Fork SNOTEL data, the 2009-2010 winter at FEF was less than average compared to the 15-year historical average (Figure 3b). The measured snow depth at the FEF snow compaction study plot never exceeded 1 m, similar to the Middle Fork Camp, and therefore was used to represent a shallower snow cover environment.

### *4.1 Density*

Bulk snowpack density increased at the REP snow compaction study site when low and high use compaction treatments began on 30 cm of snow (Figure 4a). As a result, low and high use compaction treatments were significantly different between these treatments (low and high) and the control, and compared to both low and high use compaction treatments beginning on 120 cm of snow (Table 1). The largest bulk snowpack density difference was observed on 6 February when the control bulk density was 246 kg/m$^3$, while the low and high use compaction treatments yielded an increase to 285 kg/m$^3$ and 328 kg/m$^3$, respectively (Figure 4a). In contrast, compaction treatments (low and high) beginning on 120 cm of snow (Figure 4b) did not significantly alter the bulk snowpack density compared to the control (Table 1). While the bulk snowpack density increased through the duration of the study period, by the last sampling date bulk snowpack density was similar between the control and treated transects (Figure 4av and 4bv). Treatment increased the density in the basal layer of the snowpack, with the largest difference of 75% (density of 351 kg/m$^3$) and 88% (377 kg/m$^3$) for low and high use compaction treatments observed on 12 December, respectively, compared to just over 200 kg/m$^3$ for the control (Figure 3ai). Snow compaction treatments had little impact on basal layer densities when treatments began on 120 cm of snow with the largest difference being observed on 6 February as 229, 234, and 268 kg/m$^3$ for the control, low and high treatments, respectively (Figure 4biii).

Bulk snowpack density also increased at the FEF snow compaction study site for all compaction treatments (low, medium, and high use) that began on 30 cm of snow (Figure 4c). Significant differences were observed between all treatments and the control. However, there were no significant differences between the varying treatments (Table 1). For low and medium use compaction treatments the largest difference in bulk snowpack density compared to the control was on 12 February when density was measured at 177, 296, and 311 kg/m$^3$, for the control, low and medium treatment, respectively (Figure 4ciii). Snowpack density measured for high use had the largest difference from the control on 22 January when bulk snowpack density was 341 kg/m$^3$ compared to a bulk density of 192 kg/m$^3$ for the control (Figure 4cii). Bulk snowpack density generally increased during the study period, but by the end of the study period there were minimal differences between the control and varying degrees of compaction (Figure 4cv). Basal layer density increased from all compaction treatments. After the first treatment on 27 December, the basal layer density increased by 148% (288 kg/m$^3$) for low use to about 190% of medium and high use, compared to 116 kg/m$^3$ for the control (Figure 4ci).

### *4.2 Temperature*

Low and high use compaction treatments at the REP snow compaction study site that began on both a shallow snowpack of 30 cm and on a deep snowpack of 120 cm did not result in significant changes in temperature gradient. The maximum temperature gradients were observed on 12 December as 18, 28, and 25$^{o}$C m$^{-1}$ for the control, low use, and high use compaction treatments that began on a shallow snowpack, while they were almost the same (23, 23, and 25$^{o}$C m$^{-1}$) for the control, low use, and high use compaction treatments that began on a deep snowpack. Temperature gradients for all treatments decreased throughout the winter season until all uses exhibited a temperature gradient approaching 0$^{o}$C m$^{-1}$ by 17 April. Basal layer temperatures increased throughout the winter season until all uses exhibited a basal layer temperature of -1$^{o}$C by 17 April.

Low, medium and high use compaction treatments at the FEF snow compaction study site did not significantly impact the temperature gradient. Maximum temperature gradients for low, medium, and high use were 30$^{o}$C m$^{-1}$, 13$^{o}$C m$^{-1}$, and 20$^{o}$C m$^{-1}$ on 27 December compared to 20$^{o}$C m$^{-1}$ measured at the control. Temperature gradients decreased throughout the winter season until all uses exhibited a temperature gradient near 0$^{o}$C m$^{-1}$ by 26 April (Figure 5b). The coldest basal layer temperature was for medium use on 22 January (-6$^{o}$C), with a basal layer temperature of -5$^{o}$C on 27 December for all other treatments. Basal layer temperatures increased for all uses throughout the winter season until basal layer temperatures reached -1$^{o}$C by 26 April (Figure 5b).

### *4.3 Hardness*

Mean snowpack hardness increased at the REP snow compaction study site following low and high use compaction treatments that began on 30 cm of snow (Figure 6a), but only for high use starting on a deeper snowpack (Figure 6b). Significant increases in hardness were observed between treatments that began on 30 cm of snow and the control, and between compaction treatments (low and high) that began on 120 cm of snow (Table 1). For the treatment that began on the shallow snowpack, the maximum mean hardness for the control was 82 kPa for the control on 17 April (Figure 6av) while for the low use treatment a maximum of 174 kPa was measured on 12 December and for the high use treatment, a maximum of 487 kPa was measured on 6 February. In contrast, mean snowpack hardness was not significantly impacted by snow compaction treatments that began on 120 cm of snow (Table 1). Mean snowpack hardness increased following the initial snow compaction treatments for low and high use, but subsequent compaction treatments did not appear to have a large effect (Figure 6b and Table 1). Mean snowpack hardness for low and high use was greater than the control following the initial snow compaction treatment for both initiation depths (30 cm and 120 cm), but there were minimal differences by the last sampling date (Figure 6av and 6bv).

Snow compaction treatments that began on 30 cm of snow increased basal layer hardness (Figure 5a), but treatments that began on 120 cm of snow did not impact basal layer hardness (Figure 5b). For the former, the maximum basal layer hardness was measured at 188 kPa (Figure 6ai) and 158 kPa (Figure 6aiii) for the low and high treatments, respectively. For both controls and all treatments that began on 120 cm of snow (Figure 6b), the maximum basal layer hardness was about 6 kPa.

Low, medium, and high use compaction treatments resulted in a significant increase in mean snowpack hardness following snow compaction treatments beginning on 30 cm of snow at the FEF snow compaction study site (Table 1). Hardness generally increased during the study period; however, hardness at the treated transects were approaching control values by the last sampling date (17 April; Figure 6c). For the control, the maximum mean snowpack hardness was about 25 kPa (on 26 March in Figure 6civ) while the maximum treatment hardness was one to two orders of magnitude higher at 395 kPa (low treatment on 22 January, Figure 6cii), 780 kPa (medium treatment on 26 March, Figure 6civ) and 4,627 kPa (high treatment on 26 March, Figure 6civ). Similarly, the maximum basal layer hardness for the control was only 4 kPa (on 26 March, Figure 6civ) and 138, 352 and 728 kPa for low, medium and high use, respectively (Figure 6cii, 6civ, and 6civ).

### *4.4 Ram resistance*

Low and high use compaction treatments at REP caused an increase in mean snowpack ram resistance (Figure 7a and 7b), but the difference was only significant for treatments that began on 30 cm of snow (Table 1). The maximum mean snowpack ram resistance was measured as 128, 203, and 496 N for the control, low and high use, respectively (Figure 7av, 7av, and 7aiii). After the initial snow compaction treatments mean snowpack ram resistance for low and high use was greater than the control for the entire study period, but by the end of the study period minimal differences were observed between treatments. Basal layer ram resistance increased as a result of low and high use compaction treatments that began on both 30 cm (44, 614, and 1,297 N for control, low and high use) and 120 cm of snow (44, 270 and 90 N for control, low and high use).

Snow compaction treatments at the FEF snow compaction study site caused a significant increase in mean snowpack ram resistance (Figure 7c; Table 1). Maximum mean snowpack ram resistance for the control was 18 N (26 March, Figure 7civ), for low and medium use it was

544N and 591N (26 March, Figure 7civ) respectively, while for high use it was measured at 866N (on 12 February, Figure 7c). Basal layer ram resistance increased following the initial snow compaction treatments and continued to increase throughout the duration of the winter season, with maximums of 28 (26 March), 1,220, 1,220, and 3,220 N for the control, low, medium, and high treatments (on 12 February for all the use treatments).

### *4.5 Grain Size*

A decrease in crystal size was observed for both the deep and shallow snowpacks subjected to snowmobile use (Table 2). Specifically, depth hoar crystals for the controls at FEF reached a maximum average size of 9.0 mm. Low, medium, and high use resulted in average crystal sizes of 1.3 mm, 2.5 mm and 1.5 mm, respectively (Table 2).

### *4.6 Experimental Site Time Series*

A time series summary of the bulk density (Figure 8a), basal density (Figure 8b), temperature gradient (Figure 8c), and hardness (Figure 8d) illustrates the temporal evolution of the mean properties. The density increase due to snowmobile use is much more at Fraser (Figures 8aii and 8bii) and for the start on a low snowpack (30 cm) at Rabbit Ears initiation for the basal density (Figure 8bi), with density for the low use snowpack at FEF approaching the values measured for no use (Figure 8bii). Temperature gradients were not very different (Figure 8c) and not found to be significant (Table 1b). Increased hardness due to snowmobile use showed similar temporal patterns to densification (Figure 8d).

### *4.7 Operational Sites*

As illustrated by SWE (Figure 9d) and depth (Figure 9a), the amount of snow was similar for the snowpits dug at the three operational sites, but not the same since they were up to 6km apart (Figure 1). Also these were operational sites, i.e., the amount of treatment was not controlled and was based solely on permitted use. Patterns of increased density (Figure 9a), hardness (Figure 9b) and ram resistance (Figure 9c) were similar to the previous presented experiments (Figures 4, 6, and 7) with the non-snowmobile snowpits being less dense (Figure 9a) and having layers that were less hard (Figure 9b). For visual inspection, Muddy Creek had the most snowmobile use and thus had the highest density throughout the winter, and the hardest snowpack for mid-winter (Figure 9bii to 9biv) but at times was similar to Dumont Lakes.

## 5. Discussion

The increase in density and hardness is greatest compared to an untreated snowpack in early to mid-season (January) for a deeper snowpack (REP in Figures 4a, and 6a), and later into the snow season for the shallower snowpack (FEF in Figures 4c, and 6c). Similar differences were found due to ski run grooming in an Australia snowpack with a 400% increase in hardness early in the snow season but only about a 40% increase later in the winter (Fahey et al., 1999). Snow grooming increased the average density by up to 36% compared to non-groomed ski slopes (Fahey et al., 1999, Rixen et al., 2001).

Compaction of the snowpack changes in density, hardness and ram resistance (Figures 4, 6, 7, and 9), and results in deformation of snow through alterations in the ice matrix (bonding/grain contacts) (Shapiro et al., 1997). Since hardness depends predominantly on grain characteristics, such as bonding and grain contacts (Shapiro et al., 1997) and decreasing grain size results in increased density, then compaction due to snowmobile use may alter the microstructure of the snowpack (Table 2), directly influencing these physical and mechanical properties (Table 1). Such changes were observed for varying snowmobile use beginning on two different snow depths (REP only in Figures 4a, 6a, 7a versus Figures 4b, 6b, 7b) and for two different snow covered environments (Figures 4c, 6c, 7c).

For a deep snow cover environment (REP), compaction treatments beginning on a shallow snowpack (30 cm) resulted in a 15% and 33% increase in density for low and high use treatments, respectively (Figure 4a), observed mid-winter (early February), similar to maximum late season natural snowpack densities. Density differences were greatest for a shallow snow cover environment (FEF), with high use resulting in 78% greater density (Figure 4c). Conversely, no significant differences in density were observed when snowmobile use began on a deep snowpack (120 cm) (Figures 4b, Table 1). The snowpack density varies spatial and temporally, such as between 40 to 200 kg/m$^3$ for fresh snow (Fassnacht and Soulis, 2002), but this can double with just one pass of a snowmobile on a very shallow snowpack (Keddy et al., 1979), and even with more accumulation, density will increase, but the underlying snow increases in density (Figures 4 and 9a).

Increased densification of the snowpack due to snowmobile use influences snow hardness (Figure 6) and ram resistance (Figure 7). In this study, snow-hardness gauges and circular metal plates of known area were used (McClung and Schaerer, 2006), rather than the more simplistic in situ hand hardness test (American Avalanche Association, 2016). Snowmobile use beginning on a shallow snowpack (30 cm) for a deep snowpack (REP) resulted in a 2- and 6-fold increase in maximum snow hardness for low and high use compared to no use, whereas at a shallow snow study site (FEF), a 15-, 30- and nearly 200-fold increase in maximum snow hardness for low, medium, and high use was observed. A shallow snow environment is more susceptible to large changes in snow hardness due to varying snowmobile use.

Ram resistance values ranged from 0 N to just below 1000 N, which is a normal range for snowpack strength measurements (Colbeck et al., 1990). The precision of the ram penetrometer used in this study was 10N, so the ram resistance of a fresh snow and layers of the snowpack with limited metamorphism could not be measured as it is typically in the range of 0.5N (Pruitt, 2005). These values can increase to as much as 70N as a result of two passes with one person on a snowmobile (Pruitt, 2005). Similar to hardness observations, snowmobile use beginning on a shallow snowpack yielded ram resistance 1.5- and 4-fold greater than the natural snowpack (Figure 7). The impact of snowmobile use on a snowpack ram resistance (Figures 7 and 9c) has only been observed by Pruitt (2005).More frequent fresh snowfall events (REP, Figure 7a) with compaction treatments can produce a snowpack of stratified strong and weak layers, and a deeper snowpack is capable of lessening the effect of compaction from snowmobile use (Figure 7b).

As crystals become compacted due to snowmobile use, there is an increase in bonding between crystals and early compaction impedes further kinetic growth. Temperature gradients were as high as $33^{o}C\ m^{-1}$ at the beginning of the season, and approached $0^{o}C\ m^{-1}$ as the snowpack became isothermal at the end of the winter season. The temperature gradient was sufficient for kinetic growth metamorphism for most of the winter season ($T_G > 10^{o}C\ m^{-1}$), as seen by less dense lower snowpack layers for the controls (Figures 4a, 4c, 9a) and the deep snowpack where snowmobile use started at 120 cm (Figure 4b).

At rest, a snowmobile and its rider exert 4 to 10 kPa of pressure to the underlying snowpack (assuming a track length from 0.9 to 1.4 m, width of 0.50 m, a snowmobile weight of

200 to 350 kg, and a rider weight of about 100 kg, data from <polarisindustries.com>). There is an increase of less than an order of magnitude due to snowmobile movement (Thumlert et al., 2013 measured stresses of about 10 to 20 kPa at a depth of 30 cm below the surface of a deep snowpack). In comparison, fresh snow with a density of 100 kg/m$^3$ exerts a pressure of 0.003 kPa on the underlying snowpack (Moynier, 2006). Snowpack loading by wheeled vehicles on a shallow snowpack was much greater, peaking at about 350 kPa (Pytka, 2010). Grooming vehicles added a load similar to snowmobiles (Pytka, 2010), due to the larger track size and results may be transferrable.

While the temperature profile differences between control and snowmobile use were not significant, temperature gradients, and thus vapour pressure gradients, were still less decreasing depth hoar growth (Table 2). This trend was also observed on REP, but the difference in depth hoar crystal sizes between control and treatments was less (Table 2).

The overall increase in density, hardness and ram resistance (Figure 7) was statistically significant between the control (no snowmobile use) and all treatments, except when treatments were initiated on a deep snowpack (Figures 4b, 6b, and 7b, Table 1). The measured depth of influence for a snowmobile is about 90 cm (Thumlert et al., 2013). At 20 cm below the snow surface, the induced stress is already much less than 10 cm below the surface from a snowmobile (Thumlert et al., 2013) or a grooming machine (Pytka, 2010). Most ski resorts in the French Alps required a minimum snow depth of 40 cm to offer skiing, with a range from 60 cm in February to 40 cm in April (Spandre et al., 2016b). The US Forest Service (2013b) recommends a minimum of 30 cm before the use of snowmobiles. Increasing the minimum snow depth before allowing snowmobile traffic will reduce changes to the snowpack due to snowmobiles (Table 1). Where the experiments were undertaken, i.e., Colorado, there are 1.1 to 1.6 million annual snowmobile visits, with an increase from 580 thousand to 690 thousand between 2010 to 2013 in northern Colorado (Routt NF and Arapaho-Roosevelt NF) and southern Wyoming (Medicine Bow NF) (US Forest Service, 2010 and 2013a), with an annual economic impact of more than $125 million to each state (Nagler et al., 2012; Colorado Off-Highway Vehicle Coalition, 2016). Thus snowmobile use will continue to change to the snowpack, and the impacts are expected to become greater with the anticipated increases in snowmobile activity.

Snowmobile use, starting with a shallow or thin (30 cm) snowpack, resulted in a denser and harder snowpack (Figure 8) with smaller basal grains (Table 2). This is expected, yet this paper does not suggest that snowmobiles can be used to strengthen the snowpack and prevent avalanches that fail on basal facets, similar to a boot packing program (e.g. Sahn, 2010). While this may be useful in very limited and small areas, it is very difficult to properly align the creation of repetitive tracks, as done here (Figure 2), nor to the same intensity. Do not try snowmobile use in the backcountry to reduce avalanche hazard.

Snowmobile use was found to have a highly significant effect upon natural vegetation below the snow (Keddy et al., 1979), with grooming shown to delay the blooming of alpine plants (Rixen et al., 2001) due to a later snowmelt and a significantly cooler soil (Fassnacht and Soulis, 2002). Deeper snowpack were found to not have a cooler soil temperature under the snowpack (Keller et al., 2004), but did melt out four weeks later (Keller et al., 2004). Since the snowpack changes due to snowmobile traffic on a shallow snowpack were significant (Table 1), the effects of snowmobile use on the soil and vegetation underlying a shallow snowpack should be further investigated.

Without wind, snow depth will be less for areas with snowmobile traffic (Figures 2d, 2e, and 4; Rixen et al., 2001; Spandre et al., 2016a). However, wind is often present in open areas where snowmobiling occurs. The local terrain features and position and extent of canopy influence how the wind interacts with the snowpack (Pomeroy and Brun, 2001). In an Australia case study, SWE increased by 45% in groomed areas (Fahey et al., 1999); at the Rabbit Ears Pass recreational use areas, SWE also increased (Figure 9d) likely due to snow blowing into the depressions created by snowmobile tracks (Figure 2d). The increased load could further impact the underlying snowpack properties. Further, snowmaking (Spandre et al., 2016a) to supplement natural snow conditions and /or grooming (Fahey et al., 1999; Rixen et al., 2001; Spandre et al., 2016a) compacts the snowpack below it, and alters the underlying snowpack properties (Howard and Stull, 2014; Spandre et al., 2016a; Spandre et al., 2016b). Also, a changing climate will likely reduce the extent of terrain and decrease the length of the winter recreation season (Laxar and Williams, 2008; Steiger, 2010; Dawson and Scott, 2013; Marke et al., 2015; Tercek and Rodman, 2016).

## 6. Conclusion

This study examined the effect of compaction from snowmobile use on snowpack properties. It showed that snowpack properties change with varying use of snowmobile use, annual snowfall (REP versus FEF), and the depth at which snowmobile use was initiation. Snowmobile use creates compaction that influences the physical and mechanical properties of the snowpack. In particular, this increases snowpack density, hardness, and ram resistance when winter recreational use occurs. The largest differences in snowpack properties are snowmobile use beginning on a shallow snowpack (30 cm) compared to no use, which increases snowpack density, hardness, and ram resistance. These increases are directly related to increasing snowmobile use (from low to medium to high). Conversely, snowmobile use that begins on a deep snowpack (120 cm) has a limited effect on snowpack properties as seen by density, temperature, hardness, and ram resistance measurements comparable to an undisturbed snowpack.

## Author contribution

The experiments were designed by J.T. Heath and S.R. Fassnacht with input from K.J. Elder. J.T. Heath performed the experiments with assistance from K.J. Elder at the Fraser site. All authors contributed to the writing of the manuscript, with S.R. Fassnacht doing all the revisions to the text. S.R. Fassnacht generated the figures.

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## References

Abele, G., Gow, A.: Compressibility Characteristics of Undisturbed Snow. Research Report 336, U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire, 1975.

American Avalanche Association: Snow, Weather and Avalanches: Observation Guidelines for Avalanche Programs in the United States (3rd ed.). Victor, ID, 104pp, 2016.

American Council of Snowmobile Associations: Economic Impact of the Snowmobiling Industry, URL: <http://www.snowmobilers.org/>, last accessed 4 April 2017, 2014.

Auerbach, N. A. and Halfpenny, J. C.: Snowpack and the subnivean environment for different aspects of an open meadow in Jackson Hole, Wyoming, USA, Arctic and Alpine Research, 23, 41-44, 1991.

Burakowski, E., and Magnusson, M.: Climate Impacts on the Winter Tourism Economy in the United States, Natural Resources Defense Council and Protect Our Winters, 33pp, 2012.

Colbeck, S.C.: An Overview of Seasonal Snow Metamorphism, Reviews of Geophysics and Space Physics, 20(1), 45-61, 1982.

Colbeck, S.C.: Theory of metamorphism of dry snow, Journal of Geophysical Research, 80(9), 5475-5482, 1983.

Colbeck, S.C.: A review of the metamorphism and classification of seasonal snow cover crystals, Avalanche Formation, Movement and Effects, IAHS Pub. 162, 3-34, 1987.

Colorado Off-Highway Vehicle Coalition: Economic Contribution of Off-Highway Vehicle Recreation in Colorado, Report by Pinyon Environmental, Lakewood, CO USA, URL: <http://www.cohvco.org/>, last accessed 4 April 2017, 2016.

Cook, B. and Borrie, W.: Trends in Recreation Use and Management of Wilderness, International Journal of Wilderness, 1(2), 30-34, 1995.

de Quervain, M.R.: On Metamorphism and Hardening of Snow under Constant Pressure and Temperature Gradient, IUGG General Assembly of Toronto, IASH Publication No. 46, pp 225-239, 1958.

Colorado Ski Country USA: Economic Study Reveals Ski Industry's $4.8 Billion Annual Impact to Colorado, Summary of RRC Associates, Boulder, Colorado report on the Colorado ski industry, 9 December, 2015, Denver, CO, USA. URL: <http://coloradoski.com/media_manager/mm_collections/view/183>, last accessed 4 April 2017, 2015.

Dawson, J., and Scott, D.: Managing for climate change in the alpine ski sector, Tourism Management, 35, 244-254, 2013.

Diamond, M., and Lowry, W.P.: Correlation of density of new snow with 700 mb temperature, Snow, Ice and Permafrost Research Establishment Research Paper 1, US Army Corps of Engineers, 3 pp, 1953.

Fassnacht, S.R., and Soulis, E.D.: Implications during transitional periods of improvements of snow processes in the Land Surface Scheme – Hydrological Model WATCLASS, Atmosphere-Ocean, 40(4), 389-403, 2002.

Fahey, B., Wardle, K., and Weir, P.: Environmental effects associated with snow grooming and skiing at Treble Cone Ski Field. Part 2. Snow properties on groomed and non-groomed slopes, Science for Conservation, 120B, 49-62, 1999.

Fierz, C., Armstrong, R.L., Durand, Y., Etchevers, P., Greene, E., McClung, D.M., Nishimura, K., Satyawali, P.K. and Sokratov, S.A.: The International Classification for Seasonal

Snow on the Ground, IHP-VII Technical Documents in Hydrology N°83, IACS Contribution N°1, UNESCO-IHP, Paris, 2009.

Gold, L.W.: Changes in a shallow snow cover subject to a temperate climate, Journal of. Glaciology, 3, 218-222, 1958.

Giddings, J.C., and LaChapelle, E.: The Formation Rate of Depth Hoar, Journal of Geophysical Research, 67(6), 2377-2383,1962.

International Snowmobile Manufacturers Association: Snowmobiling Fact Book. ISMA, URL: <http://www.snowmobile.org/>, last accessed 4 April 2017, 2016.

Howard, R., and Stull, R.: Piste : A snow-physics model incorporating human factors for groomed ski slopes, Journal of Hydrometeorology, 15, 2429–2445, [doi :10.1175/JHM-D-14-0013.1], 2014.

Keddy, P., Spavold, A., and Keddy, C.: Snowmobile impact on old field and marsh vegetation in Nova Scotia, Canada : An experimental study, Environmental Management 3, 409–415, [doi: 10.1007/BF01866580], 1979.

Keller, T., Pielmeier, C., Rixen, C., Gadient, F., Gustafsson, D., and Stähl, M.: Impact of artificial snow and ski-slope grooming on snowpack properties and soil thermal regime in sub-alpine ski area, Annals of Glaciology, 38, 314-318, 2004.

Lazar, B., and Williams, M.W.: Climate change in western ski areas: Potential changes in the timing of wet avalanches and snow quality for the Aspen ski area in the years 2030 and 2100, Cold Regions Science and Technology, 51(2-3), 219-228, 2008.

Marke, T., Strasser, U., Hanzer, F., Stötter, J., Wilcke, R. A. I., and Gobiet, A.: Scenarios of future snow conditions in Styria (Austrian Alps), Journal of Hydrometeorology, 16, 261-277, doi:10.1175/JHM-D-14-0035.1, 2015.

Longley, R.W.: Snow depth and density at Resolute, Northwest Territories, Journal of Glaciology, 3, 733-738, 1960.

Mann, H.B., and Whitney, D.R.: On a Test of Whether one of Two Random Variables is Stochastically Larger than the Other, Annals of Mathematical Statistics, 18(1), 50–60, [doi:10.1214/aoms/11777304919], 1947.

McClung, D., and Schaerer, P.: The Avalanche Handbook, 3rd Edition, The Mountaineers Books, Seattle, Washington, 342 pp, 2006.

Moynier, J.: Avalanche Aware: The Essential Guide to Avalanche Safety, Morris Book Publishing, LLC, Guilford, Connecticut, 90 pp, 2006.

Nagler, A.M., C.T. Bastian, D.T. Taylor, and T.K. Foulke: 2011-2012 Wyoming Comprehensive Snowmobile Recreation Report, Report to the State of Wyoming, Department of State Parks and Cultural Resources, prepared by Department of Agricultural and Applied Economics, University of Wyoming, Laramie WY, 172pp, 2012.Pomeroy, J. W., and Brun, E.: Physical properties of snow, in Jones, H. G., Pomeroy, J. W., Walker, D. A., and Hoham, R. W. (eds.), Snow Ecology. Cambridge: Cambridge University Press, 45-126, 2001.

Pruitt, W. O.: Why and how to study a snowcover, Canadian Field-Naturalist, 119(1), 118-128, 2005.

Pytka, J.: Determination of snow stresses under vehicle loads, Cold Regions Science and Technology, 60, 137-145, [doi :10.1016/j.coldregions.2009.10.002], 2010.

Rixen, C., Stoeckli, V., Huovinen, C., and Huovinen, K.: The phenology of four subalpine herbs in relation to snow cover characteristics, Soil-Vegetation-Atmosphere Transfer Schemes and Large-Scale Hydrological Models (Proceedings Sixth IAHS Scientific Assembly Symposium S5, Maastricht, July 2001), IAHS Pub., 270, 359-362, 2001.

Sahn, K.: Avalanche risk reduction in the continental climate: How to implement an effective boot packing program, Proceedings of the 2010 International Snow Science Workshop, p. 296-301, 2010.

Spandre, P., Morin S., Lafaysse M., Lejeune Y., François H., and Lejeune, Y.: Integration of snow management processes into a detailed snowpack model, Cold Regions Science and Technology, 125, 48-64, [doi:10.1016/j.coldregions.2016.01.002], 2016a.

Spandre, P., François, H., George-Marcelpoil, E., and Morin, S.: Panel based assessment of snow management operations in French ski resorts, Journal of Outdoor Recreation and Tourism, 16, 24-36, [doi: 10.1016/j.jort.2016.09.002], 2016b.

Shapiro, L. H., Johnson, J. B., Sturm, M., and Blaisdell, G. L.: Snow Mechanics: Review of the State of Knowledge and Applications, USA Cold Regions Research and Engineering Laboratory (CRREL), Research Report 97-3, 1997.

Shoop, S.A., Richmond, P.W., Lacombe, J.: Overview of cold regions mobility modeling at CRREL, Journal of Terramechanics, 43 (1), 1-26, 2006.

Skorkowsky, R., 2010. Personal communication. Hahns Peak/Bears Ears Ranger District, Routt Nationa Forest, U.S. Forest Service.

Sommerfeld, R. A., and LaChapelle, E.: The Classification of Snow Metamorphism, Journal of Glaciology, 9(55), 3-17, 1970.

Sturm, M., Taras, B., Liston, G. E., Derksen, C., Jonas, T., and Lea, J.: Estimating Snow Water Equivalent Using Snow Depth Data and Climate Classes, Journal of Hydrometeorology, 11, 1380-1394, 2010.

Tercek, M., and Rodman, A.: Forecasts of 21st Century Snowpack and Implications for Snowmobile and Snowcoach Use in Yellowstone National Park, PLoS ONE, 11(7), e0159218, [doi:10.1371/journal.pone.0159218], 2016.

Thumlert, S., and Jamieson B.: Stress measurements from common snow slope stability tests, Cold Regions Science and Technology, 110, 38-46, [doi:10.1016/j.coldregions.2014.11.005], 2015.

Thumlert, S., Exner, T., Jamieson, B., and Bellaire, S.: Measurements of localized dynamic loading in a mountain snow cover, Cold Regions Science and Technology, 85, 94-101, [doi :10.1016/j.coldregions.2012.08.005], 2013.

US Forest Service: National Visitor Use Monitoring Results, USDA Forest Service National Summary Report Data collected FY 2008 through FY 2012, US Department of Agriculture, URL: <http://www.fs.fed.us/recreation/programs/nvum/>, last accessed 4 April 2017, 2013a.

US Forest Service: Modifications Made to Medicine Bow National Forest Winter Travel Special Order - Release date Nov. 15, 2013, Medicine Bow National Forest, URL: <https://www.fs.usda.gov/detail/mbr/news-events/?cid=STELPRDB5440798>, last accessed 7 April 2017, 2013b.

US Forest Service: National Visitor Use Monitoring Results, USDA Forest Service National Summary Report Data collected FY 2005 through FY 2009, US Department of Agriculture, URL: <http://www.fs.fed.us/recreation/programs/nvum/>, last accessed 4 April 2017, 2010.

Wahl, K. L.: Evaluation of trends in runoff in the western United States: Managing water resources during global change, Proceedings of the Annual Conference and Symposium, Reno, NV, American Water Resources Association, 701-710, 1992.

Wilcoxon, F.: Individual comparisons by ranking methods, Biometrics Bulletin, 1(6), 80-83, [doi:10.2307/3001968], 1945.

Winter Wildlands Alliance: Winter Recreation on Western National Forest Lands: A Comprehensive Analysis of Motorized and Non-Motorized Opportunity and Access, Winter Wildlands Alliance, Boise, Idaho, 44 pp, 2006.

**Table 1.** Statistical difference (p-values) between no snowmobile use (control) and varying snow compaction treatments on snowpack properties at the study plots located at Rabbit Ears Pass (REP) and Fraser Experimental Forest (FEF), Colorado during the 2009-2010 winter season for a) density, b) temperature, c) hardness, and e) ram resistance. Statistically significant differences at the p<0.05 confident level are highlighted in grey, and highly significant (p<0.01) difference are denoted with an asterisk.

| a) Density | | | control | Shallow initiation depth (30 cm) | | |
|---|---|---|---|---|---|---|
| | | | | Low | Medium | High |
| REP | Shallow initiation depth (30 cm) | Low | <0.01* | | | <0.01* |
| | | High | <0.01* | <0.01* | | |
| | Deep initiation depth (120 cm) | Low | 0.44 | <0.01* | | <0.01* |
| | | High | 0.24 | <0.01* | | <0.01* |
| FEF | Shallow initiation depth (30 cm) | Low | <0.01* | | 0.29 | 0.30 |
| | | Medium | <0.01* | 0.29 | | 0.98 |
| | | High | <0.01* | 0.30 | 0.98 | |

| b) Temperature | | | No use | Shallow initiation depth (30 cm) | | |
|---|---|---|---|---|---|---|
| | | | | Low | Medium | High |
| REP | Shallow initiation depth (30 cm) | Low | 0.22 | | | 0.11 |
| | | High | 0.70 | 0.11 | | |
| | Deep initiation depth (120 cm) | Low | 0.77 | 0.34 | | 0.50 |
| | | High | 1.00 | 0.22 | | 0.70 |
| FEF | Shallow initiation depth (30 cm) | Low | 0.12 | | 0.89 | 0.10 |
| | | Medium | 0.14 | 0.89 | | 0.13 |
| | | High | 0.64 | 0.10 | 0.13 | |

| c) Hardness | | | No use | Shallow initiation depth (30 cm) | | |
|---|---|---|---|---|---|---|
| | | | | Low | Medium | High |
| REP | Shallow initiation depth (30 cm) | Low | <0.01* | | | 0.16 |
| | | High | <0.01* | 0.16 | | |
| | Deep initiation depth (120 cm) | Low | 0.42 | <0.01* | | <0.01* |
| | | High | 0.06 | 0.02 | | <0.01* |
| FEF | Shallow initiation depth (30 cm) | Low | <0.01* | | 0.36 | 0.01 |
| | | Medium | <0.01* | 0.36 | | 0.08 |
| | | High | <0.01* | 0.01 | 0.08 | |

| d) Ram resistance | | | No use | Shallow initiation depth (30 cm) | | |
|---|---|---|---|---|---|---|
| | | | | Low | Medium | High |
| REP | Shallow initiation depth (30 cm) | Low | <0.01* | | | 0.08 |
| | | High | <0.01* | 0.08 | | |
| | Deep initiation depth (120 cm) | Low | 0.32 | <0.01* | | <0.01* |
| | | High | 0.07 | 0.01 | | <0.01* |
| FEF | Shallow initiation depth (30 cm) | Low | <0.01* | | 0.33 | <0.01* |
| | | Medium | <0.01* | 0.33 | | <0.01* |
| | | High | <0.01* | <0.01* | <0.01* | |

**Table 2.** Depth hoar grain size at the snow compaction study plots located at Rabbit Ears Pass (REP) and Fraser Experimental Forest (FEF), Colorado during the 2009-2010 winter season.

| | | date | Basal layer grain size [mm] | | | |
|---|---|---|---|---|---|---|
| | | | control | Low | Medium | High |
| REP | Shallow initiation depth (30 cm) | 12/12/2009 | 3.0 | 1.0 | | <0.5 |
| | | 01/09/2010 | 2.0 | 3.0 | | 1.0 |
| | | 02/06/2010 | 3.0 | 1.5 | | 1.0 |
| | | 03/13/2010 | 3.0 | 3.0 | | 1.0 |
| | | 04/17/2010 | 1.5 | 1.5 | | 1.0 |
| | Deep initiation depth (120 cm) | 12/12/2009 | 3.0 | 3.0 | | 3.0 |
| | | 01/09/2010 | 2.0 | 3.0 | | 1.5 |
| | | 02/06/2010 | 3.0 | 3.5 | | 3.0 |
| | | 03/13/2010 | 3.0 | 3.0 | | 3.5 |
| | | 04/17/2010 | 1.5 | 1.5 | | 1.5 |
| FEF | Shallow initiation depth (30 cm) | 12/27/2009 | 4.0 | 3.0 | 1.0 | 1.0 |
| | | 01/22/2010 | 3.0 | 1.0 | 2.0 | 1.5 |
| | | 02/12/2010 | 4.5 | 2.0 | 2.0 | 1.5 |
| | | 03/26/2010 | 9.0 | 1.0 | 2.5 | 1.5 |
| | | 04/26/2010 | 5.0 | 1.5 | 3.0 | 3.0 |

## List of Figures

**8.** Time series for the different sampling dates of a) mean snowpack density, b) basal snowpack density, c) snowpack temperature gradient, and d) mean snowpack hardness for i. Rabbit Ear Pass and ii. Fraser Experimental Forest. Note that the snow at the low and high use start at 30 cm could not be adequately tested for hardness on the first sampling date at the REP treatment plots.

**9.** Snowpit data for Walton Creek (no snowmobile use), Dumont Lakes (moderate snowmobile use) and Muddy Creek (high snowmobile use) in the Rabbit Ears Pass recreational use areas illustrating a) density, b) hardness, c) ram resistance, and d) SWE.

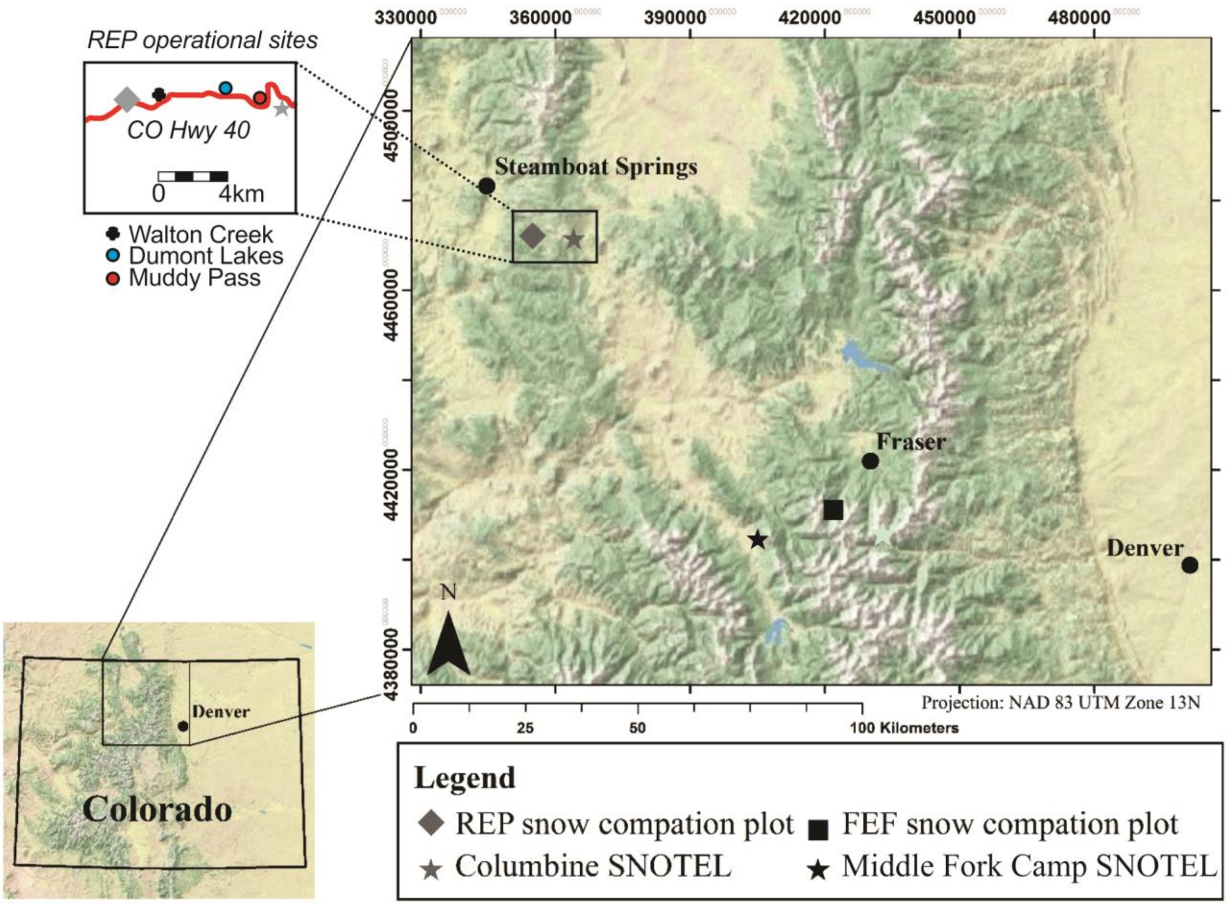


**Figure 1.** The snow compaction study plots are located in north-central Colorado. The Rabbit Ears Pass (REP) site is within the Routt National Forest near the town of Steamboat Springs, and the three operational (non-experimentally manipulated) sites (Walton Creek with no use, Dumont Lakes with low to medium use, and Muddy Pass with high use based on field observations). The Columbine snow telemetry (SNOTEL) station was used to identify the amount of snowfall compared to the long-term average. The Fraser Experimental Forest (FEF) site is within the Arapaho-Roosevelt National Forest near the town of Fraser. The Middle Fork Camp SNOTEL site was used to represent the year's snowfall.

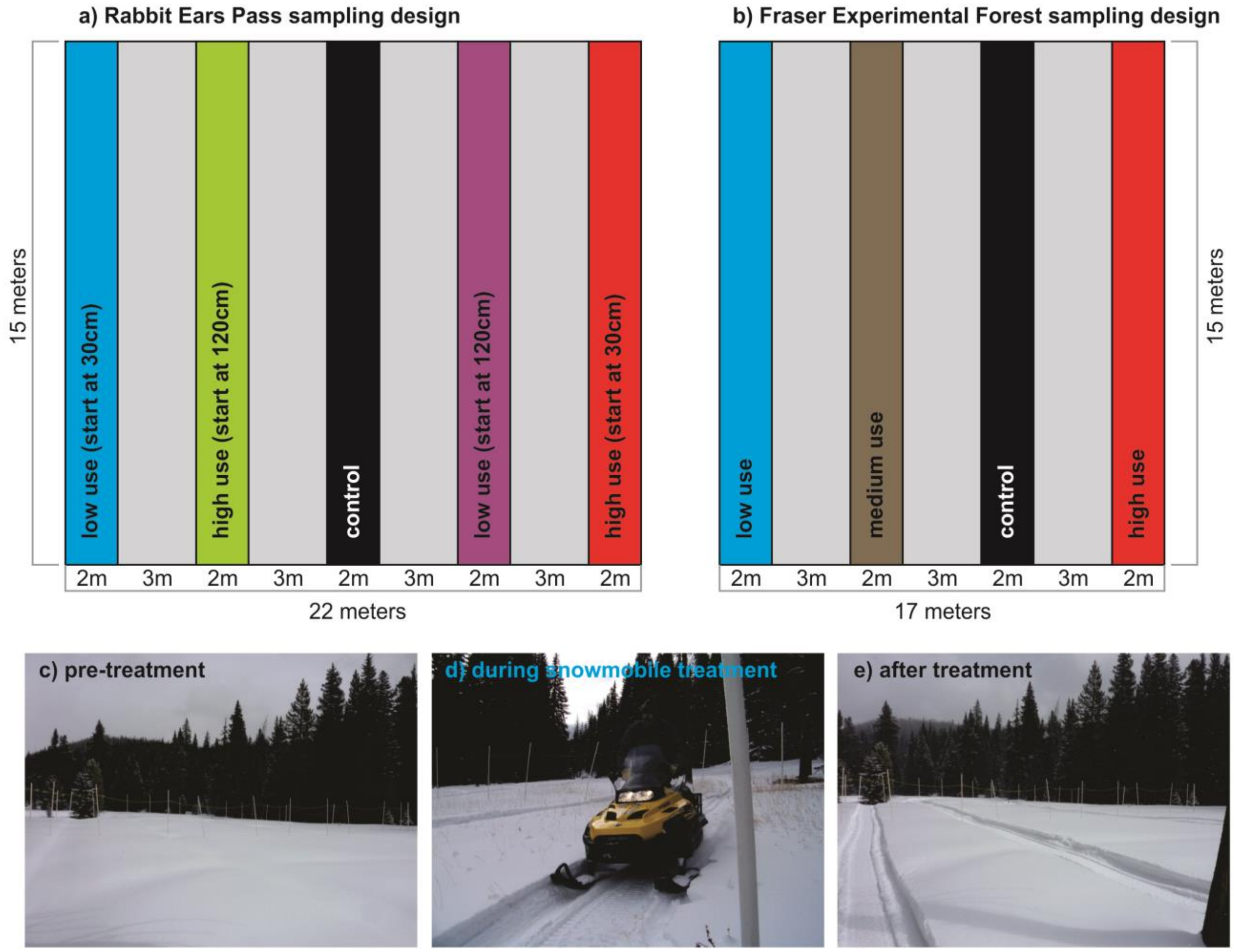


**Figure 2.** The sampling design for the snow compaction plots at a) Rabbit Ears Pass, b) Fraser Experimental Forest, and photographs of the study plots c) pre-treatment, d) during treatment, and e) after treatment. The color used for the control and treatment plots are used in Figures 4 through 7.

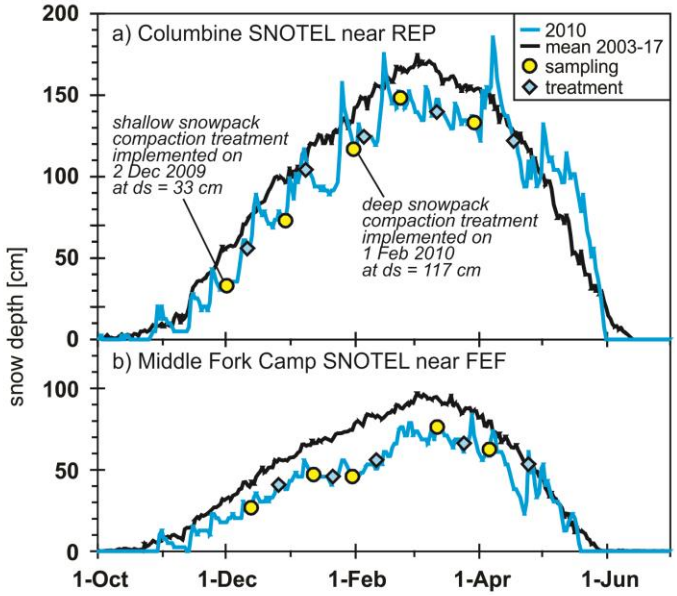


**Figure 3.** Mean snow depth from 2003-2017, and for the 2010 water year (WY2010) measured at a) the Columbine SNOTEL site near Rabbit Ears Pass (REP), Colorado and b) the Middle Fork Camp SNOTEL near Fraser Experimental Forest (FEF). Data were obtained online from the Natural Resource Conservation Service (NRCS) National Water and Climate Center (http://www.wcc.nrcs.usda.gov/).

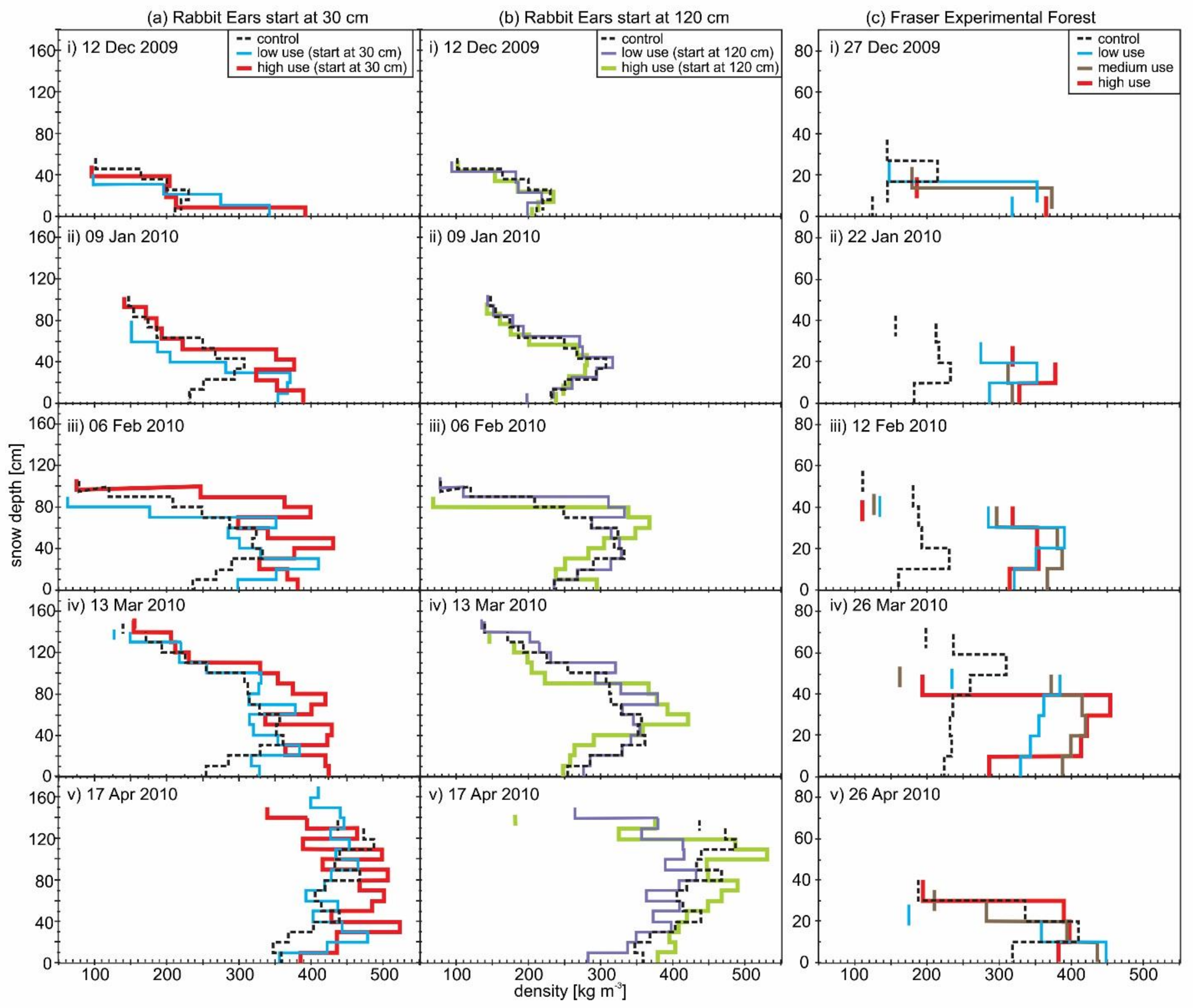


**Figure 4.** Density profiles for five dates (i to v) measured at the REP snow compaction study plot for no (control), low, and high use treatments beginning on a) 30 cm and b) 120 cm of snow, and c) the FEF snow compaction study plot for no (control), low, medium, and high use treatments beginning on 30 cm of snow. Note that free floating measurements represent overlapping density measurements. The ground is at zero snow depth.

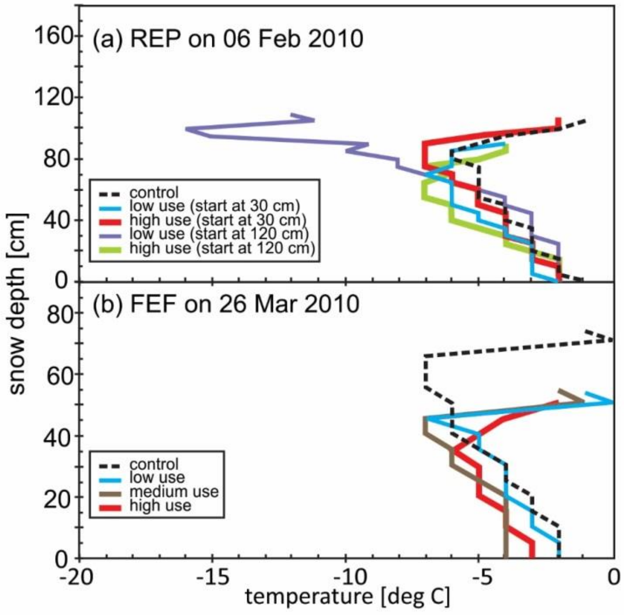


**Figure 5.** Temperature profiles measured at a) the REP snow compaction study plot on February 06, 2010 for no, low, and high use treatments beginning on 30 cm and 120 cm of snow and b) the FEF snow compaction study plot on March 26, 2010 for no, low, medium, and high use treatments beginning on 30 cm of snow.

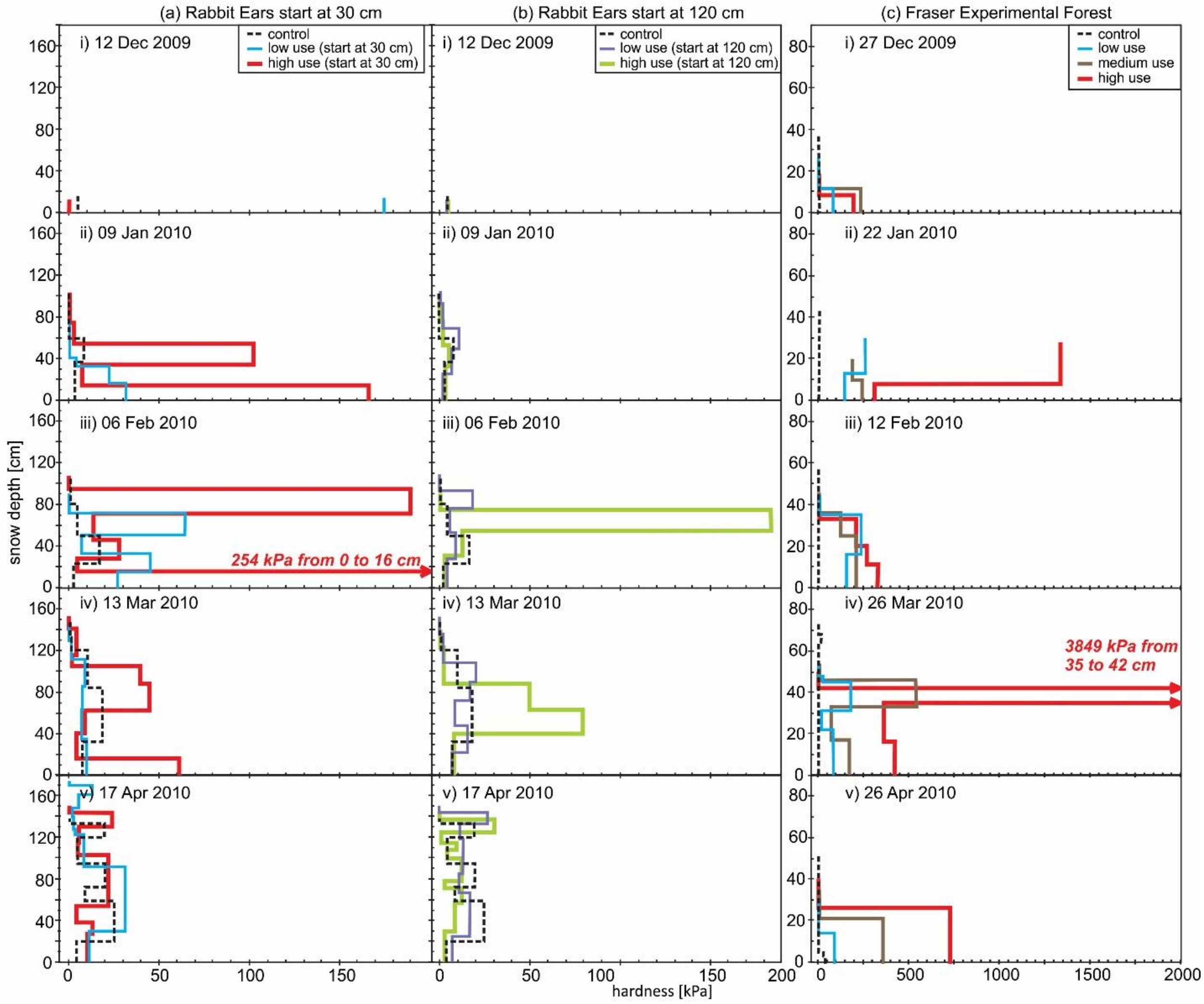


**Figure 6.** Hardness profiles for five dates (i to v) measured at the REP snow compaction study plot for no, low, and high use treatments beginning on a) 30 cm and b) 120 cm of snow, and c) the FEF snow compaction study plot for no, low, medium, and high use treatments beginning on 30 cm of snow.

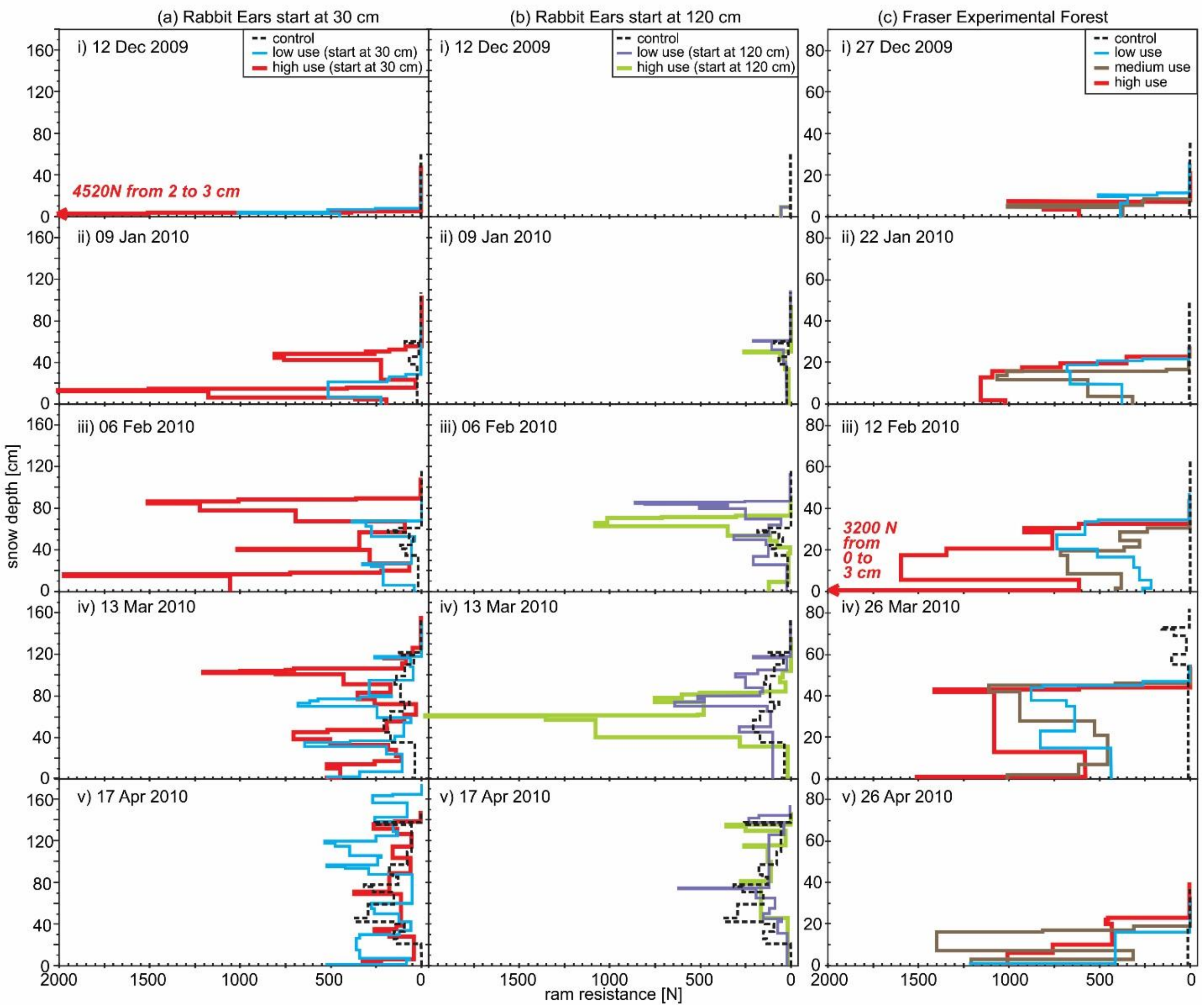
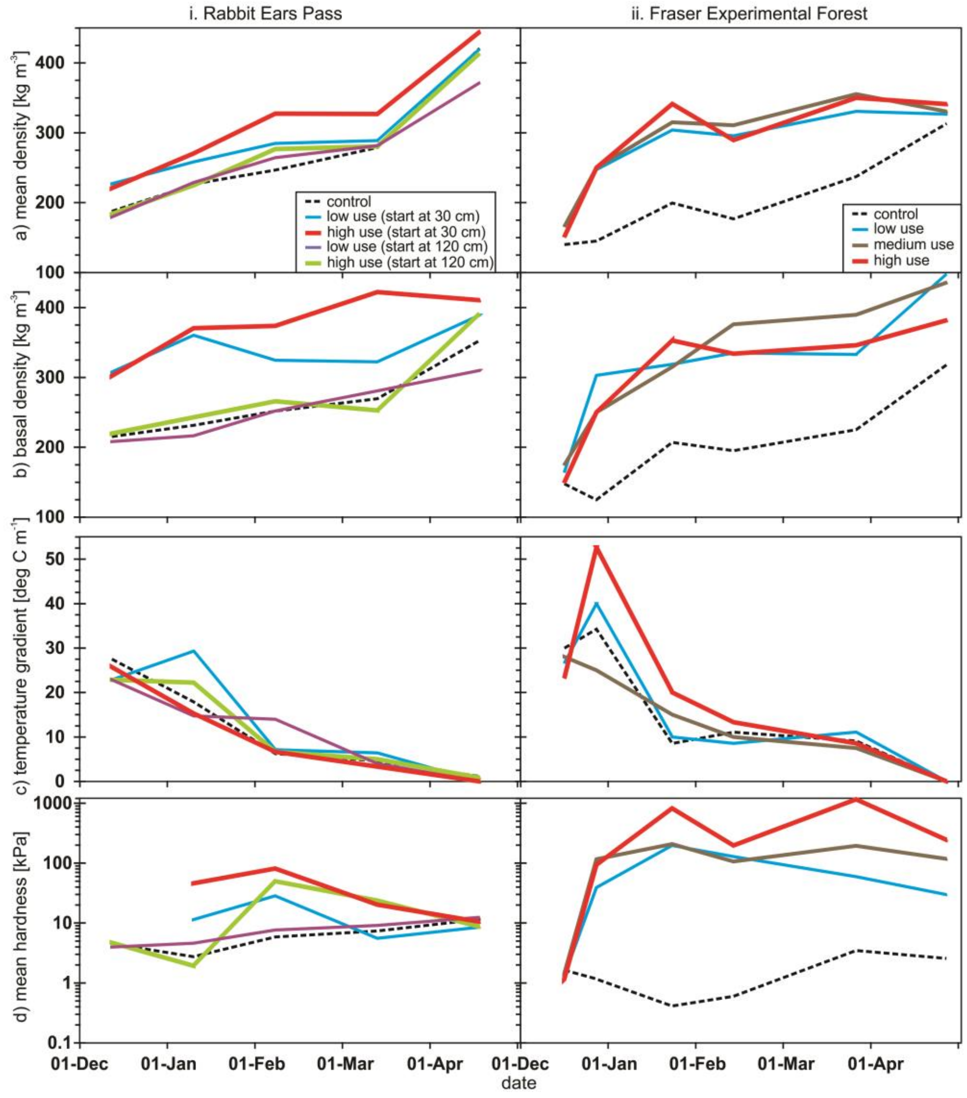


**Figure 7.** Ram resistance for five dates (i to v) profiles measured at the REP snow compaction study plot for no, low, and high use treatments beginning on a) 30 cm and b) 120 cm of snow, and c) the FEF snow compaction study plot for no, low, medium, and high use treatments beginning on 30 cm of snow.



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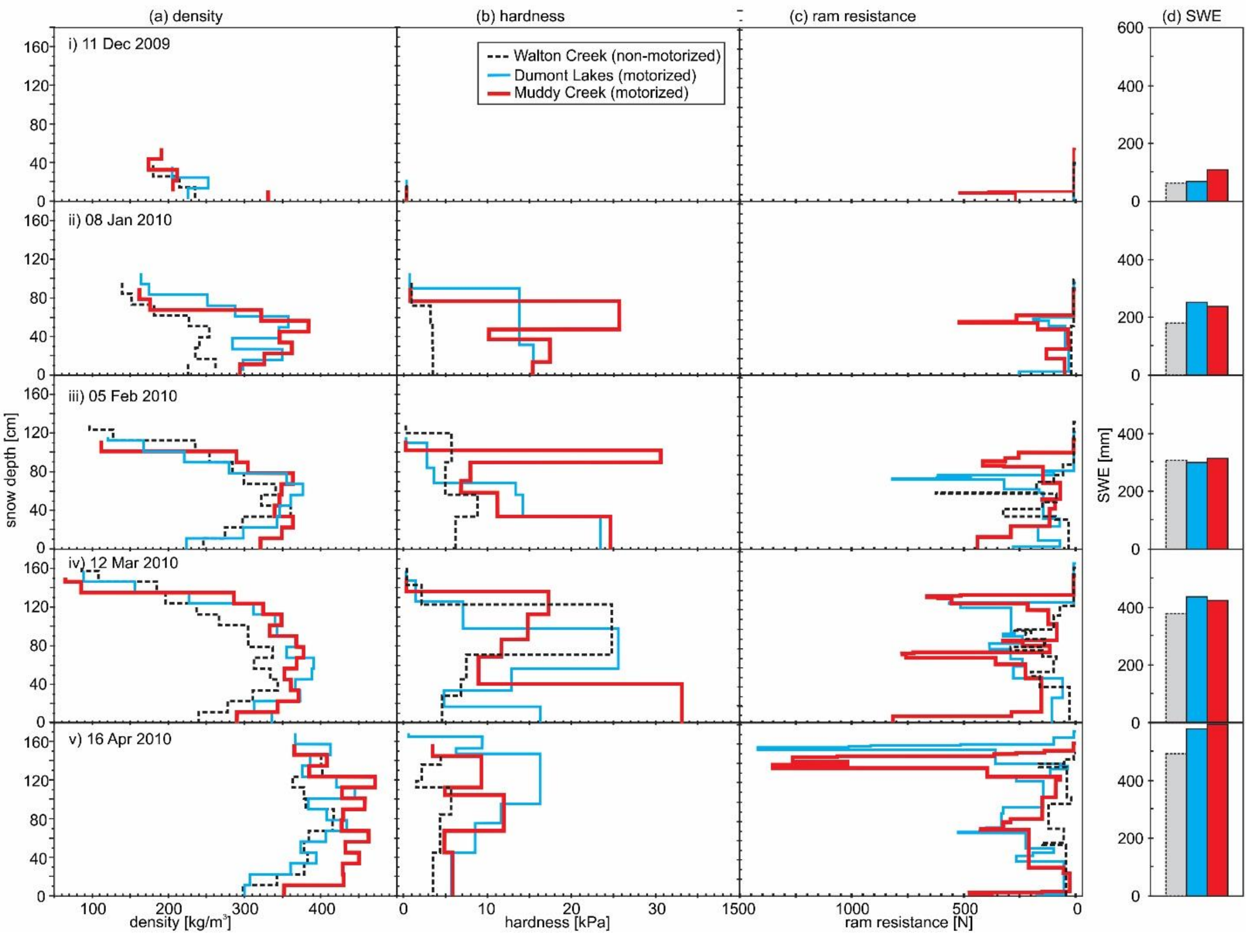

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