Snowmobile Impacts on Snowpack Physical and Mechanical Properties

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

Abstract

Snowmobile use is a popular form of winter recreation in Colorado, particularly on public lands. To examine the effects of differing levels of use on snowpack properties, experiments were performed at two different areas, Rabbit Ears Pass near Steamboat Springs and at Fraser Experimental Forest near Fraser, Colorado USA. Differences between no use and varying degrees of snowmobile use (low, medium and high) on shallow (the operational standard of 30 cm) and deeper snowpacks (120 cm) were quantified and statistically assessed using measurements of snow density, temperature, stratigraphy, hardness, and ram resistance from snow pit profiles. Snowpack property changes were more pronounced where there was less snow accumulation. When snowmobile use started in deeper snow conditions, there was less difference in density, hardness, and ram resistance compared to the control case of no snowmobile use. These results have implications for management of snowmobile use in times and places of shallower snow conditions where underlying natural resources could be affected by denser and harder snowpacks.

1. Introduction

In the United States snowmobiling accounts for between $7 billion (American Council of Snowmobile Associations, 2014) to $26 billion (International Snowmobile Manufacturers Association, 2016) in annual revenue, and much of the snowmobile use occurs on public land. The United States National Forest System records about 6 million snowmobile visits annually, accessing about 327,000 km^2 of land (US Forest Service, 2010 and 2013a). With continued increases in the number of people participating in winter recreation (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), activities like increased snowmobile use may influence snowpack properties in these seasonally snow-covered environments. Of additional concern, is that climate change will result in 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). Studies have however, examined 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 the few studies on snowmobile use examined effects on shallow snow (10 to 20 cm deep). The authors found a doubling of fresh snow density, little impact on the underlying old snow, but use was seen to significantly compress the natural vegetation below the snow (Keddy et al., 1979). Examining deeper snow cover, 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).

Changing snowpack from snowmobile use will have other impacts. Aside from the work done by Keddy et al. (1979), there is limited research on how snowmobile activity influences underlying vegetation. The addition of snow due to snowmaking provides an indication of possible changes. Changes from snowmaking include a greater occurrence of soil frost, ice layers may form at the base of the snowpack, and there is often a delay in vegetative growth due to extended snow cover (Rixen et al., 2003). Snowmelt can occur later due to compaction and there is greater heat loss from the snowpack and underlying soil (Fassnacht and Soulis, 2002; Rixen et al., 2003).

In our research, we specifically examined the effect of snowmobile use on the physical and material properties of the snowpack. The objectives were to: (1) quantify changes to physical snowpack properties due to compaction by snowmobiles; (2) evaluate these changes based on the amount of use, depth of snow when snowmobile use begins, and the snowfall environment where snowmobiles operate; and (3) create a simple model to estimate the change in snowpack density due to snowmobile use. This work examines not only changes to the basal snowpack layer, but also to the entire snowpack. Since there are many snowmobile users and billions of dollars are spent each year on snowmobiling, this work will benefit land managers who need to make decisions about which users (e.g., snowmobilers, non-motorized recreation such as backcountry skiers, snowshoers, and those on fat bikes) have access to portions of multi-use areas, especially when the information may be used to reduce conflict among recreationists.

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 National Forest (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 uses and prohibits motorized winter recreation while the east side of the pass is a mixed-use area and open to motorized users (Figure 1). This study area was selected to determine if differences in snowpack properties will be observed between the non-motorized and motorized use areas (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. Data from the Columbine snow telemetry (SNOTEL) station, located at an elevation of 2,792 m, was used to show how the 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 were monitored, temperature and snow depth were added in the 1990s-2000s to aid in operational runoff volume forecasting (see <wcc.nrcs.usda.gov>).

Three sites were not experimentally manipulated, i.e. the specific amount of snowmobile use was unknown, were identified as operational sites 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 sites, Dumont Lakes and Muddy Creek, were located east of REP at an elevation of about 2,900 m within an area managed for motorized and mixed uses; the sites were located in open meadows near their respective 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 during the same winter snow season of 2009-2010 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 surrounded by lodgepole pine (*Pinus contorta*) forest. The Fraser Experimental Forest is closed to snowmobile use, but is used 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 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 FEF study plot allowed for replication and determination of variability. The location of control and treatment plots across each study site were 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 including 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 usually within a week after each treatment (Figures 2 and 3). At FEF, snowpack sampling was performed prior to the first treatment to illustrate range of spatial variability across the plots (first set of points in Figure 4b).

3.2 Snow pit analyses and data collection

Snow pit profiles were used to examine the physical properties of the snowpack at both the experimental and at the operational 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 (ρ_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 created from a continuous profile of discrete 10 cm measurements. The bulk snowpack density was determined by averaging the depth integrated density measurements over 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. Temperature gradients are well represented by this instrument, and the repeatability of temperature measurements are better than ±1^{o}C (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 ^{o}C/m) was calculated as the ratio of the change in temperature (ΔT in ^{o}C) with the distance (d in m) over which the change in temperature occurred. The snowpack temperature gradient was approximated as linear from an upper boundary that was 25-30 cm below the surface to the lower boundary at 0 cm. 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 taken at 0 cm were used to compare temperature changes near the snow and ground interface.

Stratigraphic measurements were used to illustrate the evolution of the snowpack over time through characterization of 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 precipitation particles, rounded grains, faceted grains, 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). It is due to snowpack 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 20 cm^2 in area. 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). All layers thicker than 5 cm were identified using the 5-cm diameter of the plate. The bulk snowpack hardness (H_B in N/m^2) was determined by weighting 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 here to vertically measure the resistance of snow layers 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 the 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 compared were density, temperature, hardness, and ram resistance profiles for the five different monthly measurements. A statistical significance was determined for the 95% (significant) and 99% (highly significant) confidence interval ($p<0.05$, and $p<0.01$) and noted with an asterisk in Table 1.

3.4 Bulk Snowpack Density Change Model

A multi-variate linear model was created to estimate the change in bulk snowpack density for various treatments compared to the control (no use) using the following snowpack properties: depth, bulk density, SWE, basal density, starting depth for treatments, number of passes, and time between treatment and sampling. The cross-correlation between variables was considered to reduce model over-fitting. The model was calibrated with the experimental data from REP and FEF, and evaluated using data from the operational sites with Walton Creek as the control, Dumont Lakes as medium use, and Muddy Creek as high use. The Nash Sutcliffe Coefficient of Efficiency (NSCE, Nash and Sutcliffe, 1970) was used to evaluate the fit of the model.

4. Results

4.1 The Measurement Winter

The 2009-2010 winter at REP had slightly less than the mean snow depth as compared to the 15-year average from 2003-2017, based on the Columbine SNOTEL data (Figure 3a). A peak SWE value 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 represents a deeper snow cover environment for Colorado. From the Middle Fork SNOTEL data, the 2009-2010 winter at FEF had less snow depth than 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.

4.2 Snowpack Properties

4.2.1 Density

Snowpack properties were very similar for all FEF plots prior to treatment, and were almost the same at the end of the sampling period in April (Figure 4ii). The mean snowpack density increased over the snow season (Figure 4a), with the exception of the FEF control and at the high use site on 12 Feb 2010 due to fresh snow deposition. At the REP snow compaction study site, bulk density for high use compaction treatments starting on 30 cm of snow was greater throughout the measurement period than the no use treatment throughout the winter (Figures 4ai, 5ai, and 5aii), while the bulk density from low use starting on the deeper snowpack of 120 cm was very similar to that measured for no use. The snowpack was more dense for low use on the shallower snowpack (start at 30 cm) than the control, expect for 13 March (Figure 4ai). Density differences are more pronounced for the basal layer (Figure 4bi); for compaction treatments starting at 30 cm, the lowest layers were much more dense (Figure 5a). Since the deeper snow (120 cm) treatment at REP was initiated on February 1st, these treatment densities (low and high use, start at 120 cm) were the same as the control (Figures 4ai and 4bi). After treatment, the high use treatment snowpack was more dense (Figures 4a and 4b). Densities for the compaction treatments starting at 30 cm were significantly different than the control and compaction treatments beginning at 120 cm of snow (Table 1). The density differences between the treatments on the deep snow (120 cm) and the control were not significantly different (Table 1).

Density increases due to snowmobile use were much greater at Fraser (Figures 4aii and 4bii) than Rabbit Ears. All treatments at FEF were significantly different than the control, but the difference among treatments was not significant (Table 1). The density differences among treatments are highlighted in the 10-cm individual density measurements (Figure 5a) and in the basal layer (Figure 4bii).

4.2.2 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 the earliest sampling date (12 December, Figure 4c) as 18, 28, and 25^{o}C/m 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) 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, and were isothermal at 0^{o}C/m by mid to late April (Figures 4ci and 4cii), since the snow had stared to melt (Figure 3). Overall, temperature gradients were not very different (Figure 4c) and were not found to be significant (Table 1b).

4.2.3 Hardness

The snowpack was harder for snowmobile use starting on 30cm than the control (no use) for both sites (Figures 4d and 4e). Mean snowpack hardness did not change much over time (Figure 4d), except once high use treatments started (06 Feb) on a deeper snowpack. However, basal layer hardness did decline at REP for both high and low use starting on 30 cm (Figure 4ei). With treatments at FEF, the hardness was always much higher than the control (Figure 4dii). Hardness initially increased at the REP snow compaction study site following low and high use compaction treatments that began on 30 cm of snow (Figure 4di), but these were about the same as the control by 17 Apr, when melt had started. 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). 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 (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 4ei).

Snow compaction treatments that began on 30 cm of snow increased basal layer hardness (Figure 4ei), but treatments that began on 120 cm of snow did not impact basal layer hardness (Figure 4ei). For both controls and all treatments that began on 120 cm of snow (Figure 4ei), the maximum basal layer hardness was about 6 kPa. Increased hardness due to snowmobile use showed similar temporal patterns to densification (Figures 4a and 4d). At REP, snowmobile use compacted the second layer below the surface, and high use (50 passes) made that layer about 10 times harder than the low use (5 passes) snowpack (Figures 5bi and 5bii). These results are also reflected in the ram resistance (Figures 5ci and 5cii).

4.2.4 Ram resistance

Low and high use compaction treatments at REP caused an increase in mean snowpack ram resistance, but the difference was not significant for treatments that began on deep snow (120 cm; Table 1). 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 and 120 cm of snow. Snow compaction treatments at the FEF snow compaction study site caused a significant increase (Table 1) in mean snowpack ram resistance. Basal layer ram resistance increased following the initial snow compaction treatments and continued to increase throughout the duration of the winter season.

4.2.5 Grain Size

Smaller crystals were observed for snowmobile use starting on a shallow snowpack compared to the control or starting on a deeper snowpack (Figure 4f). Rounded grains were observed during the first sampling at REP shallow depth snowmobile start, with faceted grains for the following three sampling dates (Figure 4fi). Rounding facets were observed on the last sampling day at both sites. At FEF, there were 3 to 4 mm faceted crystals prior to the treatments; the faceted crystals were fragmented in the basal layer of the treated plots until they began rounding by the last sampling date (Figure 4fii). The shallower snow at FEF enabled large faceted crystals to grow in the basal layer, up to 9 mm in size (Figure 4fii).

4.3 Operational Sites

As illustrated by SWE (Figure 6d) and depth (Figure 6a), the amount of snow was similar for the snowpits dug at the three operational sites, but not exactly the same since they were up to 6 km apart (Figure 1). Also since these were operational sites, the amount of treatment was not controlled and was based solely on permitted snowmobile use. Patterns of increased density (Figure 6a), hardness (Figure 6b) and ram resistance (Figure 6c) were similar to the patterns seen in the previously presented experiments (Figures 4, and 5) with the non-snowmobile impacted snowpits being less dense (Figure 6a) and having layers that were less hard (Figure 6b). From 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 6b), but at times the results for Dumont Lakes were similar.

4.4 Bulk Snowpack Density Change Model

The snowpack started to melt by the last sampling date (Figure 3) and the difference in density between the control and treatments was small (Figure 4a). Thus, these data were not used in creating the change in bulk snowpack density model. Treatments starting on a deep snowpack at REP were not significantly different than the control (Figure 4a, Table 1) so these data were also excluded. The number of passes per treatment, depth, and bulk density were not cross-correlated ($R^2<0.04$), so these variables were used to create the model. Change in bulk density due to snowmobile use is a function of the number of passes and bulk density, but it is inversely related to snow depth (Figure 7a). The optimal model had a NSCE of 0.69 (Figure 7a), which is considered reasonable (Morasi et al., 2007). The model fit the FEF data better than the REP data (Figure 7a). When applied to the operational sites, the model results appear reasonable (Figure 7b), with the exception of the first sampling day (11 Dec). It is likely that snowmobile use was limited this early in the season, resulting in minimal differences between compaction levels (Figures 7b). The NSCE for the last 4 dates is 0.39 (Figure 7b), which can be improved to 0.71 if the number of passes is allowed to vary for different dates. This may be reasonable, as the amount of use, especially between sampling dates, is ultimately not known at the operational sites.

5. Discussion

Snowpack changes were observed for varying snowmobile use beginning with two different snow depths (REP only in Figure 4 or 5i and 5ii) and for two different snow-covered environments (Figures 4 and 5). 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 4ai and 4di), and later into the snow season for the shallower snowpack (FEF in Figures 4aii and 4dii). Similar differences were found from 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 due to snowmobile use increased densification of the snowpack which influences snow hardness (Figure 4) and ram resistance. Compaction deformed fresh snow (Figure 5), fragmented faceted grains (Figure 4fii), and reduced the growth of faceted grains (Figure 4f). In this study, snow-hardness gauges and circular metal plates of known area were used for hardness testing (McClung and Schaerer, 2006), rather than the more simplistic in situ hand hardness test (American Avalanche Association, 2016). However, the hardness of thin layers could not be measured as the circular metal plate used for measurements had a diameter of 5 cm, omitting the possible measurement of thin ice layers. Snowmobile use beginning on a shallow snowpack (30 cm) for an overall deeper snowpack (REP) resulted in a 2- and 6-fold increase in maximum snow hardness for low and high use compared to no use (Figures 4di and 4ei), 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 (Figures 4dii and 4eii).

The impact of snowmobile use on snowpack ram resistance has only been observed by Pruitt (2005), who stated that the ram resistance of fresh snow and layers with limited metamorphism was less than 1N and could increase by 70N due to two passes of a snowmobile. The change in ram resistance mirrored what was observed with changes in hardness (Figures 5c and 6c). The snowpack properties of a shallow snow environment can be more greatly affected by snowmobile use than those for an area that receives more snow (e.g., Figure 3b versus Figure 3a). Density differences were greatest for a shallow snow cover environment (FEF), while no significant differences in density were observed when snowmobile use began on a deep snowpack (120 cm) (Figure 4a, Table 1). Snowpack density does vary spatial and temporally, 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). With more accumulation, density will also increase, but high levels of snowmobile use will tend to increase the density above what is observed with non-snowmobile impacted snow (Figures 4 and 6). Densification of the snowpack at the start of testing from snowmobile impacts led to a decrease in grain size throughout the season, until rounded crystals were observed with the last observations (Figure 4f).

At rest, a snowmobile and its rider exert 4 to 10 kPa of pressure to the underlying snowpack. This assumes 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. Grooming vehicles add a force similar to snowmobiles (Pytka, 2010) based on mass and track size; the snowpack property changes observed herein could also be translated to such vehicles. Snowpack loading by wheeled vehicles on a shallow snowpack was much greater than that of a snowmobile, peaking at about 350 kPa (Pytka, 2010). 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).

Snowmobile use was found to have a highly significant effect upon natural vegetation below the snow (Keddy et al., 1979), and by extension through snowmaking (Rixen et al., 2003). Ski grooming has been 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 snowpacks were found to not have cooler soil temperatures under the snowpack (Keller et al., 2004), but melted out four weeks later than thinner snowpacks (Keller et al., 2004). Since the 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.

Snowmobile use, starting with a shallow or thin (30 cm) snowpack, resulted in a denser and harder snowpack with smaller basal grains (Figure 4). If compaction penetrates deep enough into the snowpack, it could impact weak layers that cause avalanches (Saly et al., 2016). While this may be useful in very limited and small areas, such as that performed in boot packing programs (e.g. Sahn, 2010) to strengthen snowpacks likely to fail on basal facets, it is very difficult to properly align and reproduce the intensity of repetitive tracks, as done experimentally here (Figure 2). Do not try snowmobile use in the backcountry to reduce avalanche hazard.

Other factors acting in concert with snowmobile traffic to affect snowpack properties include wind, snowmaking/grooming, and a changing climate. Without the effects of wind, snow depth will generally be lower 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. Local terrain features and position and extent of canopy cover influence how the wind interacts with the snowpack (Pomeroy and Brun, 2001). In an Australian 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 6d) 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 snow-covered 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).

A total of 101 snowpits (50 at REP, 15 at the operational sites, and 36 at FEF) were dug and sampled for this work. Future investigations could focus on specific aspects of this study, such as using a finer temporal resolution, but with few treatments. Monthly variability was observed (Figure 4), with the mean snowpack density being less in February (Figure 5) than January. From the operational sites, specific hard layers and high values of ram resistance were measured that did not persist until the next monthly sampling (Figure 6; and observed in the experimental treatments not shown). These variations were possibly a combination of naturally occurring spatio-temporal snowpack variability and sampling errors; it can be difficult to obtain reliable hardness measurements in snow disturbed by snowmobiles.

Since starting treatments on 120 cm showed no significant difference from the control (Table 1), different starting depths, such as 30, 60 and 90 cm, could be used to identify the depth when snowmobile use has no significant impact. Inter-annual variability of snowpack patterns can be large in Colorado (Fassnacht and Hultstrand, 2015; Fassnacht and Records, 2015; Fassnacht et al., 2017), and should be included in long term motorized use land management considerations. At FEF, all treatments had a significant impact, so one treatment could suffice, especially if additional sites with different snow accumulation patterns are considered. Density and temperature were measured at 10-cm intervals using the Snowmetrics wedge cutter. A different sampler could be used to measured the density over each layer. Due to the equipment used for hardness sampling, hardness could not be measured for thin ice layers, thus bulk hardness was under-estimated, different equipment may resolve this issue. Also, due to compaction of the snow grains by the high use 30-cm start treatment at REP the hardness could not be measured (Figure 4di).

The significant change to snowpack properties by snowmobiles, except when treatments/use was initiated on a deep snowpack (Table 1), could impact land management decisions for multi-use public lands. 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 snowmobile traffic (Table 1). Where the experiments for this study were undertaken, on public lands in 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) alone. The an annual economic impact of snowmobile use is more than $125 million to each state (Nagler et al., 2012; Colorado Off-Highway Vehicle Coalition, 2016). Snowmobile use is likely to continue to increase, and economic gains need to be balanced with potential impacts to the landscape, particularly in those times and places where snowpacks are shallow.

6. Conclusion

Snowmobiling is a multimillion dollar industry that impacts local and regional economies and public recreation lands. There have been limited studies regarding the influence of snowmobile use on snowpack properties. We examined the effect of snowmobile use on the physical and material properties of the snowpack at sites with varying snowmobile use and seasonal snow conditions. Low, medium, and high snowmobile use was simulated on experimental transects and snowpack sampling results from the treated sites were compared to the snowpack properties observed at undisturbed control sites and at operational sites with varying levels of use. The largest differences in snowpack properties occur with 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 the snowpack properties of density, temperature, hardness, and ram resistance as compared to an undisturbed snowpack. These results suggest that from a management standpoint, it may be desirable to limit snowmobile use in shallower snow conditions to avoid increases in density, hardness, and ram resistance that could possibly impact land resources below the 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 and N.B.H Venable completing the revisions to the text. S.R. Fassnacht generated the figures and created the density model.

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Guillaume Chambon provided additional comments and an important citation that helped reformulate the discussion.

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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*	

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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, as are 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 annual snowfall in 2009-2010 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.

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 colors used for the control and treatment plots are used in Figures 4 through 7.

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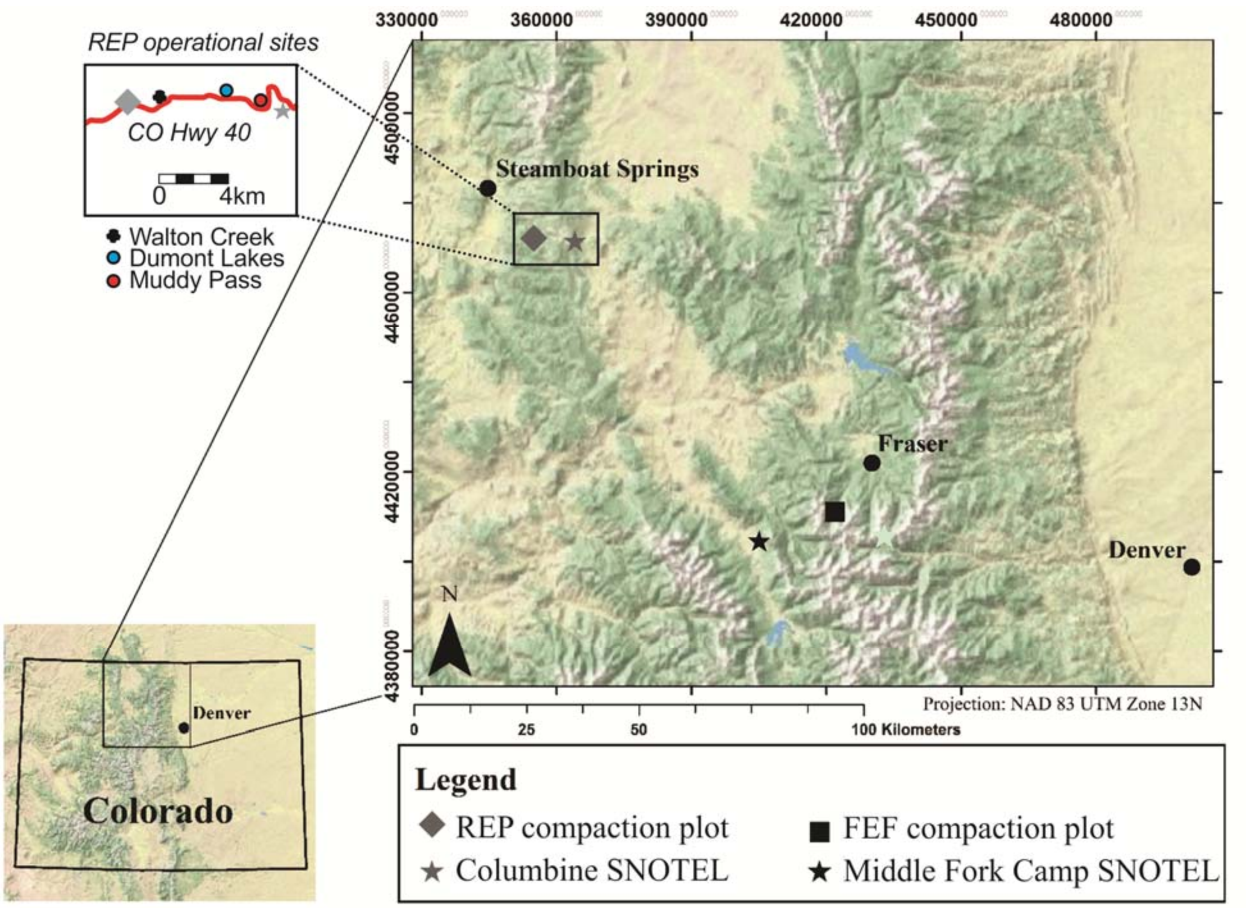
4. Time series for i. Rabbit Ear Pass (REP) and ii. Fraser Experimental Forest at the different sampling dates of a) mean snowpack density, b) basal snowpack density, c) snowpack temperature gradient, d) mean snowpack hardness, e) basal layer hardness, and f) mean basal crystal size and shape. The crystal shape is included as per Fierz et al. (2009), with the exception of the fragmented faceted crystals. Note that the snowpack 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.

5. a) Density, b) hardness, and c) ram resistance profiles for the February sampling dates (06 Feb at REP and 12 Feb at FEF) measured at the REP snow compaction study plot for no (control), low, and high use treatments beginning on i) 30 cm and ii) 120 cm of snow, and iii) 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.

6. 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.

7. Bulk snowpack density change model for different amounts of use compared to the control of no use a) calibrated for the two experiment sites (Rabbit Ears Pass, REP and Fraser Experimental Forest, FEF), and b) applied to the operational sites (Dumont Lakes and Muddy Creek), compared to the no use Walton Creek site. The calibrated model is presented in a) with the Nash Sutcliffe Coefficient of Efficiency (NSCE). The NSCE is presented in b) for two different time periods.



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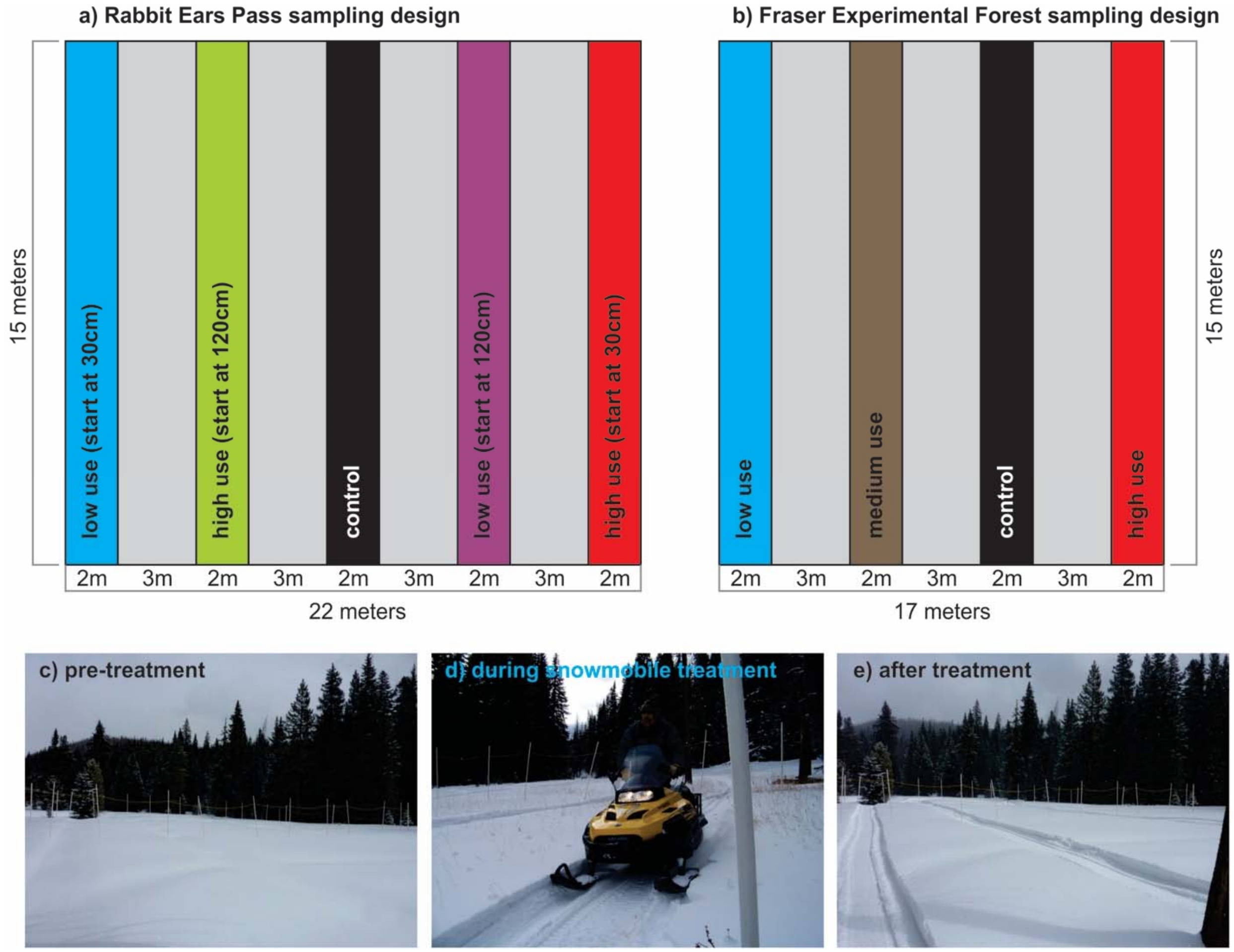

a) Rabbit Ears Pass sampling design

b) Fraser Experimental Forest sampling design

c) pre-treatment

d) during snowmobile treatment

e) after treatment

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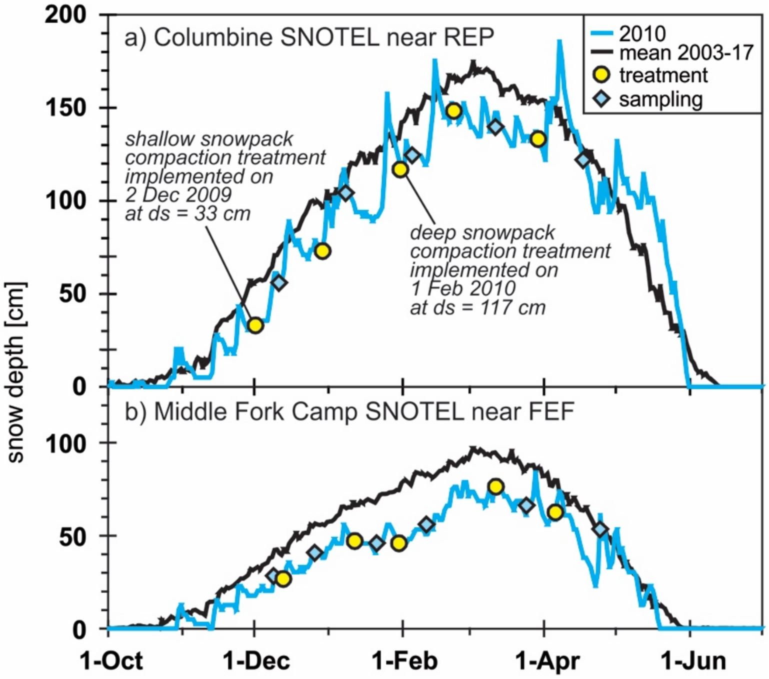

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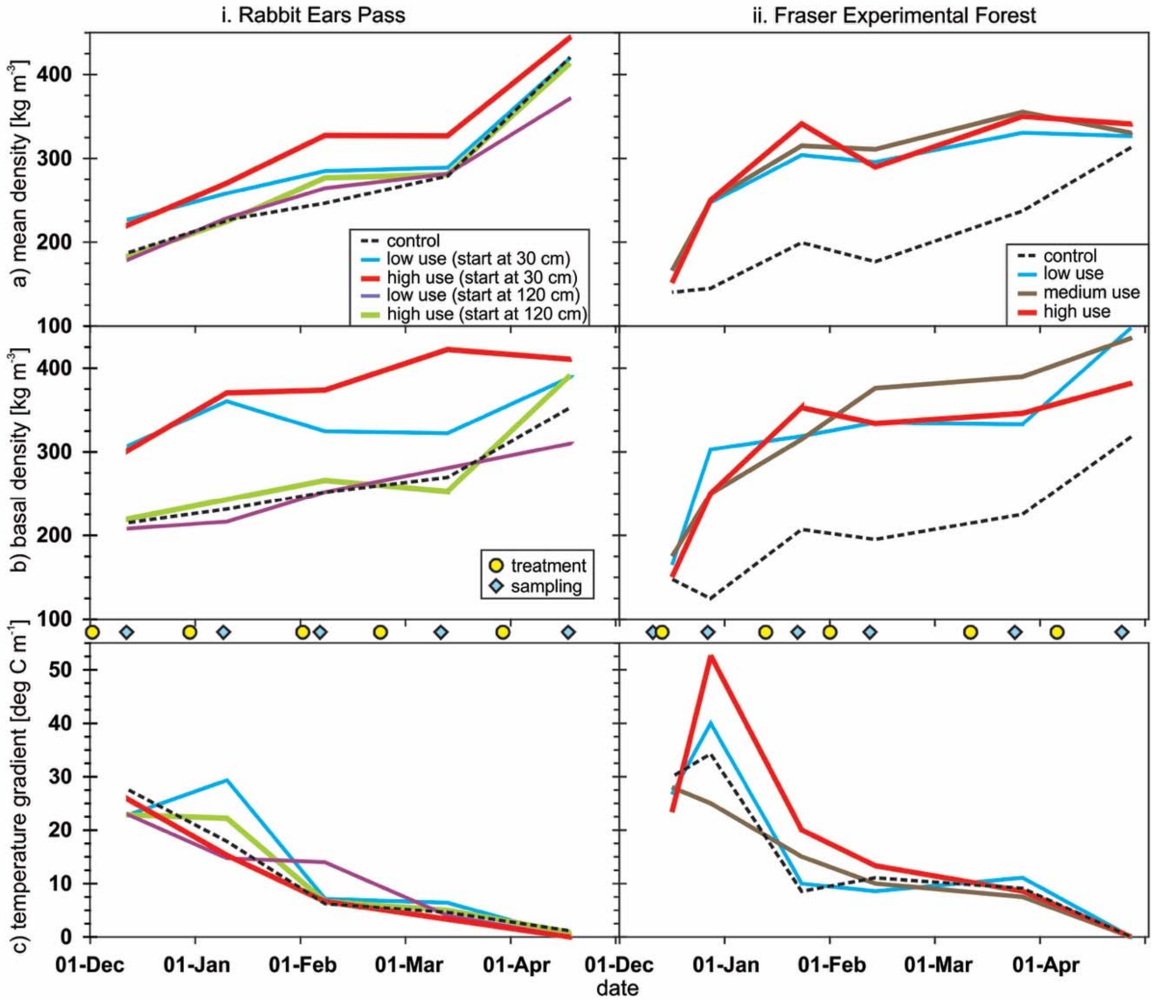
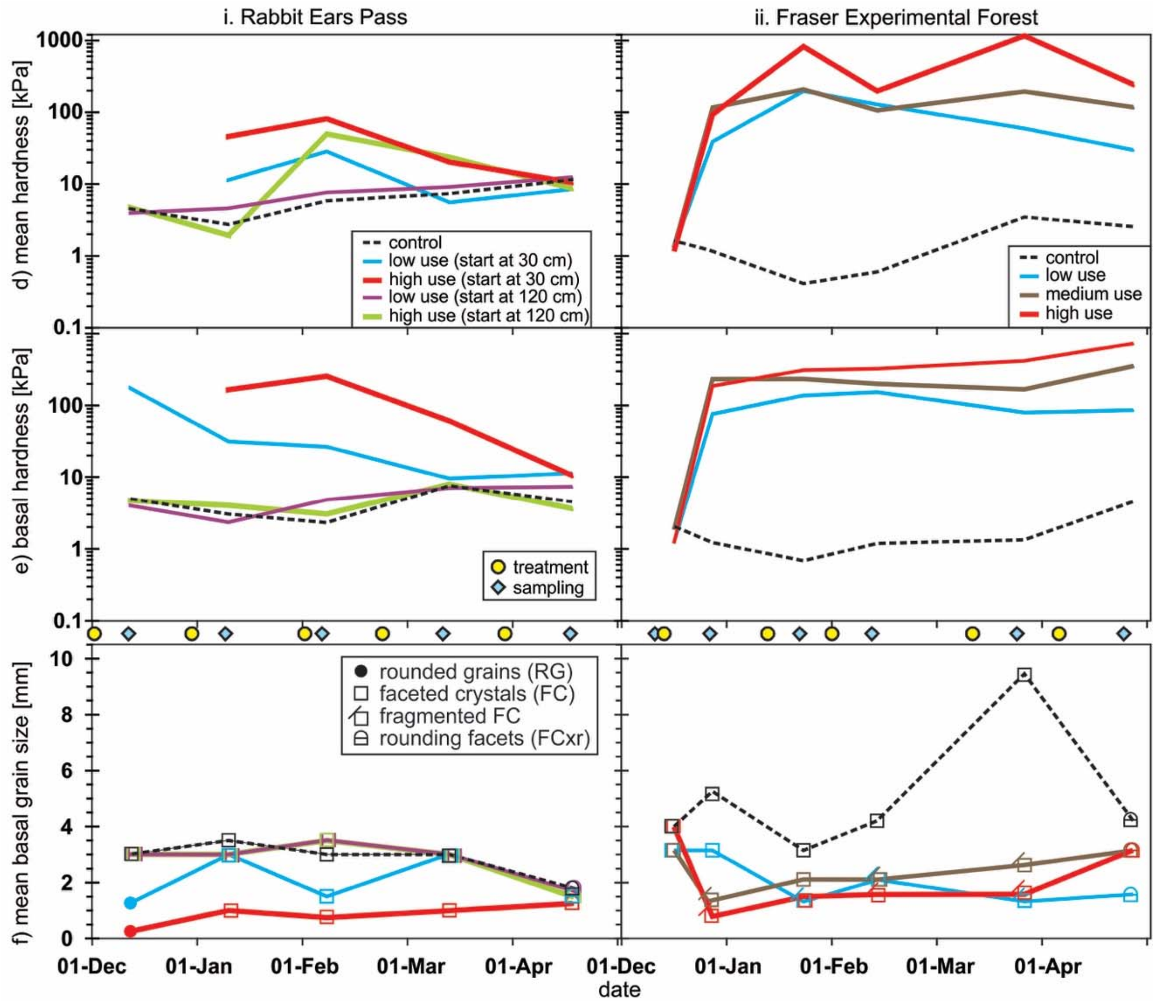
1



i. Rabbit Ears Pass
ii. Fraser Experimental Forest
a) mean density [kg m^{-3}]
b) basal density [kg m^{-3}]
c) temperature gradient [deg C m^{-1}]
100
200
300
400
0
10
20
30
40
50
control
low use (start at 30 cm)
high use (start at 30 cm)
low use (start at 120 cm)
high use (start at 120 cm)
control
low use
medium use
high use
treatment
sampling
01-Dec
01-Jan
01-Feb
01-Mar
01-Apr
date



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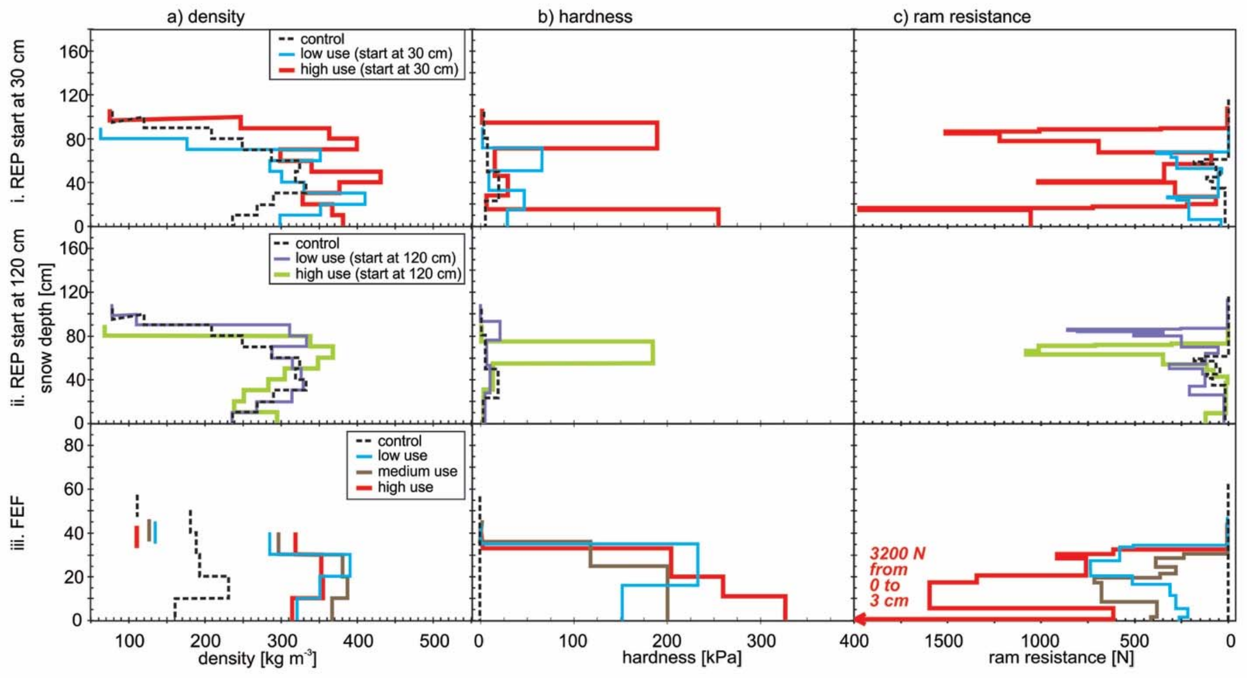
2



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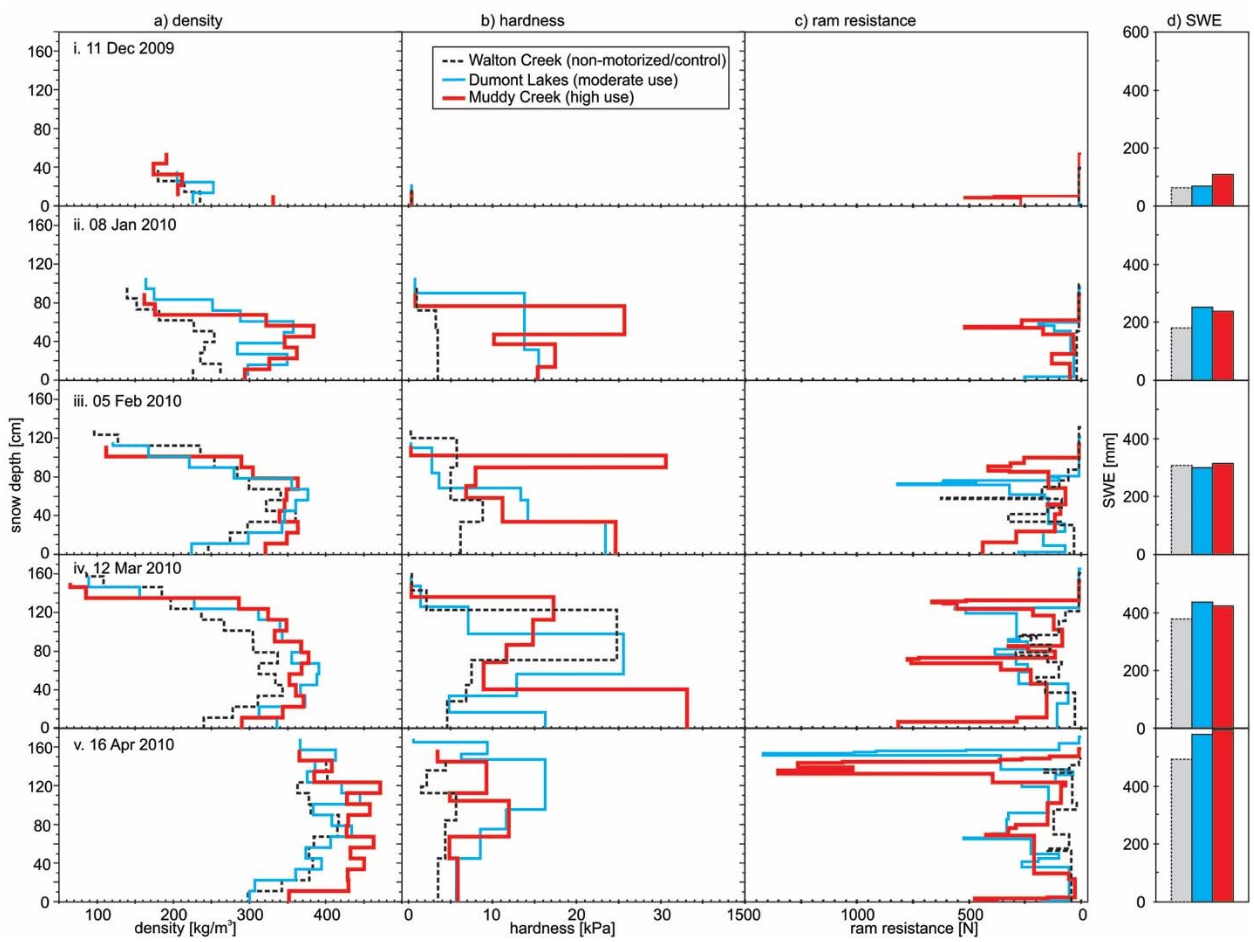

Figure 6. Snowpit data for Walton Creek (no snowmobile use), Dumont Lakes (moderate snowmobile use) and Muddy Creek (high snowmobile use) in the Rabbit Ears Pass recreational use areas illustrating a) density, b) hardness, c) ram resistance, and d) SWE.

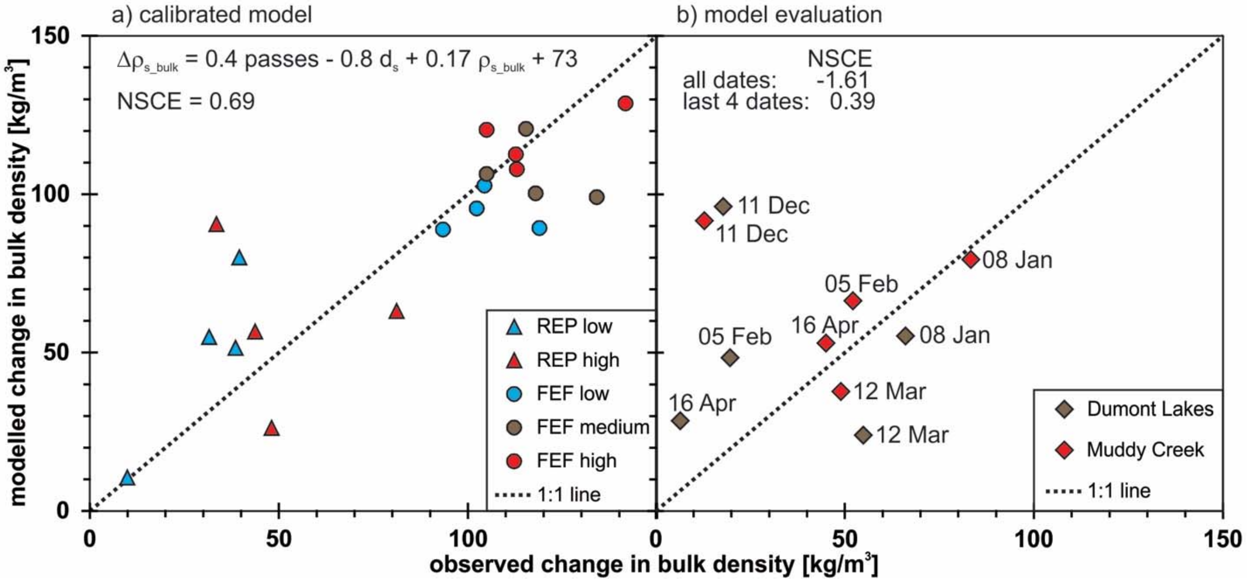

Figure 7. Bulk snowpack density change model for different amounts of use compared to the control of no use a) calibrated for the two experiment sites (Rabbit Ears Pass, REP and Fraser Experimental Forest, FEF), and b) applied to the operational sites (Dumont Lakes and Muddy Creek), compared to the no use Walton Creek site. The calibrated model is presented in a) with the Nash Sutcliffe Coefficient of Efficiency (NSCE). The NSCE is presented in b) for two different time periods.