> We appreciated the in–depth comments of Reviewer #1 and have rewritten much of the text, reordered the figures to present. We focus more on the time series of snowpack property change and have reduced the three layer-level detailed property plots to a single sample plot. We have added a simple densification model, as per the suggestion of the previous review of Reviewer #1. This model is calibrated on the experimental data, and evaluated on the operational dataset, with moderate success.

REVIEWER #1

The authors have made substantial changes to the original paper and addressed some of the concerns raised by the reviewers. While this has somewhat improved the quality of the work, the manuscript still requires major revisions to improve the presentation of the results and the discussion of their limitations and implications.
> As per this reviewer's previous comments, a bulk density change model has been created with the experimental data and evaluated on the operational data.

The introduction has in part been rewritten. Nevertheless, it still does not provide a clear context to explain why this study is requires and why one should be interested in the influence of snowmobile use on snow properties.
> We want to study the specifics of how snowmobile use impacts the snowpack, so the focus of the paper remains that. This is stated in the Introduction.

Does it affect the underlying vegetation, is it relevant for snow melt in the spring, does is stabilize the snow cover to reduce the avalanche danger?
> *in the Introduction we state that the amount of snowmobile use is increasing in many locations and that will further change the snowpack. We further add some text related to the impacts on underlying vegetation and potential avalanche risk.*

There is limited research on how snowmobile activity influences underlying vegetation (except Keddy et al., 1979), so the addition of snow due to snowmaking provides an indication of possible changes. It was found that there is often more 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). Model simulation have snow snowmelt can occur later due to a denser snowpack and more heat loss from the snowpack and underlaying soil (Fassnacht and Soulis, 2002); increased snow loading (Rixen et al., 2003) and manual compaction (Martz et al., 2016) yield cold soil.

Also, a changing climate could cause more compaction (Martz et al., 2016).

I suspect the last topic was what motivated the authors to perform these measurement. If so, this should clearly be stated in the introduction, and relevant studies which have investigated these effects should be discussed.
> We are not interested in how compaction can stabilize the snow cover to reduce the avalanche danger. In fact, we stated in the Discussion we caution against this method.

The presentation of the results has not improved much and still remains rather poor. Most figures

show vertical density, temperature, hardness and ramm hardness profiles for all sampling dates.
> *While we disagree about the detailed plots, we have reduced them to a single date to illustrate differences in layers or sampling intervals. We have added basal hardness and basal crystal/grain size and shape to the previous time series plot (Figure 4). It now shows the key results.*

These figures are illustrative but not easy to interpret.
> *The plots of density, hardness and ram resistance versus depth provide detailed differences between treatment methods. However, they have been reduce to one date (mid-February and mi-experiment) and the emphasis is now on the time series plot.*

Furthermore, the authors mainly discuss mean (bulk) properties or the properties of the basal layer. While the authors have now included a Figure showing the evolution of mean density, basal density, mean temperature gradient and mean hardness (Figure 8), this figure is only briefly mentioned at the end of the results section in a separate subsection (4.6).
> *We have now incorporated a more detailed summary of these time series results, and de-emphasized the individual layer-based results in the other four figures. The time series figure is presented prior to the other figures. We now use it as the basis of presenting the results and the use the other four for backing up specific points.*

Furthermore, many of the results shown in this figure are repeatedly discussed before. For instance, in lines 208 to 220 the authors discuss changes in bulk density and constantly refer to Figure 4, which shows the vertical density profiles. While reading this passage, I found myself repeatedly looking at Figure 8, and it would be much more efficient and intuitive for the reader to show the plots of the mean and basal properties in each respective subsection.
> *Figure 8 (time series) has been moved to before Figure 4 and the Results section has been rewritten using the time series as the starting point to illustrate overall differences with the other figures (previously 4 to 7) used to illustrate detailed differences. The Results is now a summary with less specifics on layers.*

Finally, the discussion and conclusion sections still need to be largely rewritten as it remains very scattered. Indeed, the authors need to do a much better job at putting their results into context, discuss the limitations of their methodologies and findings and highlight new insights. For instance, the hardness and ramm measurements have some peculiarities. In some pits specific layers sometimes have very high values which then disappear in subsequent pits. This is not observed in the control pits and highlight the difficulties in obtaining reliable hardness measurements in snow disturbed by snowmobiles. Such problems are not discussed at all by the authors even though they clearly highlight some of the limitations of this study.
> *The Discussion has been reorganized and various paragraphs have been combined. Much of the remaining text has been rewritten. A paragraph on Limitations has been added to the Discussion. The Conclusions have been rewritten.*

Similarly, the authors put a lot of weight on a 9 mm grain size measurement in one pit (section 4.5 and line 399 in the discussion) to discuss the influence of snow mobile travel on grain size. I have dug many snow pits and have looked at countless layers of depth hoar in various snow climates (from coastal to continental), and have seldom seen depth hoar crystals of that size. This

particular measurement is therefore rather surprising to me and could very well be an outlier, and the authors should be more cautious with their interpretation.
> *The reviewer states that they have “seldom” seen depth hoar crystals of 9 mm in size, which implies that they have seen crystals this large. We have rewritten this point to emphasize that it is the difference in crystal size between the control and treatment that is relevant, not the actual size. We actually dug two control pits on that date and the size range was 8 to 10 mm for both pits.*

Specific comments:
lines 37-38: it is not clear to me why I should be interested in changes in snow properties due to snowmobile travel. The context is missing.
> *text has been added*

lines 47-48: ‘had a highly significant effect’ In what way did this effect manifest itself?
> *The vegetation was compressed. This sentence has been changed.*

line 57-58: ‘land managers need to make decisions’. What kind of decisions do they need to make that this study will help improve?
> *This sentence has been changed to describe the decisions of which users use what areas.*

line 147: ‘where the temperature gradient was linear’ it is not very clear what the authors mean here. The temperature gradient between two temperature measurements is always ‘linear’.
> *This has been reworded. A linear segment was used from the snow-soil interface to a distance below the snow surface where temperature increases. We have removed the temperature plots, but could add them back in if it helps clarify this method.*

line 157: ‘fresh’ is not an official crystal form. ‘Precipitation particles’ should be used.
> *changed*

line 168: ‘for each stratigraphic layer’. I assume that for thin layers this was not possible. Please state the minimum layer thickness where these hardness measurements could be made.
> *I think line 162 is meant. A sentence has been added “All layers thicker than 5 cm were identified due to the 5-cm diameter of the plate.”*

line 175: what do the authors mean by ‘relative hardness’?
> *This has been removed.*

lines 195-197: I would say that even for REP the snow depth was somewhat below average.
> *yes, this has been changed.*

Section 4.1: include a figure showing the temporal evolution of the mean and basal layer density over the season (from Figure 8), as most of the discussion centers around bulk and basal layer density and not the vertical profiles.
> *This Figure (was 8, now 4) has been moved earlier, and is cited much more.*

Section 4.2: include a figure showing the temporal evolution of the temperature gradient and the

basal layer temperature.
> *We are examining the temperature gradient and have removed the discussion of basal layer temperatures. The temperature gradient is a relative measure, and we feel it is more important than the basal temperature. The basal temperature varied little (-1 to 0C).*

line 255: 'by April 26 (Figure 5b)': this figure only shows values for 26 March.
> *This figure has been removed and the text has been changed.*

Section 4.3: include a figure showing the temporal evolution of the mean and basal layer hardness over the season.
> *The time series of mean hardness was included in the last version. The temporal evolution of basal hardness has been added to the time series plot.*

Section 4.4: include a figure showing the temporal evolution of the mean and basal layer ram resistance over the season.
> *Less emphasis is put on the ram resistance.*

Section 4.5: include a figure showing the temporal evolution of grain size over the season. This is much more illustrative than a table. It also more clearly shows that the 9 mm measurement is likely an outlier, and that the most marked differences in grain size were at the FEF site and for the high use site at REP (see figures below)
> *This has been added with crystal shape and Table 1 has been removed.*

Section 4.5: this section seems redundant as all these results were already addressed in the sections above.
> *this section has been removed and the text is included in the individual sections.*

line 331: 'were similar' in what way? Describe the similarities and differences more precisely.
> *This sentence has been reworded.*

Section 5: The discussion requires extensive rewriting to more clearly discuss some of the limitations of the employed methodology, highlight the main findings and discuss the results in context with other studies.
> *The objectives have been revisited.*

lines 339-345 Here you provide a general statement on observed densification and compare it with results from another study. In lines 355-361 you again discuss the observed densification more quantitatively. Clearly, these two sections should be combined.
> *Most of the first paragraph has been deleted and the remainder has been combined with other sentences.*

lines 348-352: I don't think that compacting the snow with a snowmobile alters the snow microstructure, unless you are compacting new snow. What was the snow type when you first compacted the snow in December? Also, snow hardness is predominantly determined by density, and not grain characteristics.
> *agreed. We have rewritten this based on what we saw: compaction of fresh snow and*

fragmenting of faceted crystals. At REP there was new snow every day we sampled.

lines 352-354: ‘such changes’ unclear what this refers to. Be more specific.
> [line 345] This sentence has been removed.

lines 361-365: unclear what the point is here.
> I think that this has been removed - I am not exactly sure what is being referenced here.

lines 373-374: I don’t agree with this statement. Your results show that for the FEF site there were very little differences between the amount of use as the densification and grain size changes were similar for low, medium and high use. For the REP site, on the other hand, the differences were more pronounced.
This is one of the main findings of your work which should be highlighted and discussed much more clearly.
> That is not what we found - see Figure 4. Specifically the influence was much more at FEF than REP and there were differences between the amount of use.

lines 384-386: provide an explanation why the effect of snowmobile travel is less for deeper snow covers. To me, this would mean that the initial impact of snowmobile travel, when the snow cover is still very shallow, is decisive.
> Most of this paragraph has been removed.

lines 387-388: I do not believe that compaction impeded faceting. However, the resulting faceted snow is likely stronger (better bonded). Did you observe differences in grain type at the base of the snow cover?
> We observed fragmentation of faceted crystals at REF.

lines 390-393: it is unclear to me how less dense snow at the base of the control plots indicates that more metamorphism took place. You can still have kinetic growth in denser snow.
> This has been removed.

lines 401-403: ‘results may be transferable’: what results do you mean?
> In the previous reviewer, the reviewer asked how the results were transferable. This sentence has been rewritten.

lines 404-407: I do not follow your reasoning here. The results clearly show that there was no significant difference in temperature gradient. You can therefore not conclude that the vapor pressure gradients and depth hoar growth was slower since you did not measure those. All you can say is that the densification at the start led to a decrease in grain size throughout the season.
> This paragraph has been deleted. The sentence “densification at the start led to a decrease in grain size throughout the season” was added earlier in the Discussion.

lines 408-424: The point of this section is not clear to me. Suggest rewriting.
> This paragraph describes the land management decision implications of snowmobile use on multi-use lands. This has been slightly rewritten and moved to the end.

lines 425-431: This is the first time where a context for the measurements is given. This should also be mentioned in the introduction, as this seems the main reason why these measurements were performed.
> The Introduction has been partially rewritten to provide more context. This paragraph has been moved to earlier in the Discussion.

lines 440-453: this last section does not seem very relevant to me.
> We feel that this paragraph helps explain some of the results that we saw. It has been moved and a new first sentence has been added to set its context.

Section 6: The conclusions have to be rewritten to better highlight the main findings and their implications.
> The Conclusions section has been rewritten.

> *New citations added:*

Rixen, C., Stoeckli, V., and Ammann, W.: Does artificial snow production affect soil and vegetation of ski pistes? A review, Perspectives in Plant Ecology, Evolution and Systematics, 5(4), 219-230, 2003.

Saly, D., Hendrikx, J., Birkeland, K., Challender, S., and Leonard, T.: The Effects of Compaction Methods on Snowpack Stability, Proceedings of the 2016 International Snow Science Workshop, Breckenridge, Colorado, 716-720, 2016.

Snowmobile Impacts on ~~the~~Snowpack Physical and Mechanical Properties ~~of Different~~

Steven R. Fassnacht[1,2,3,4~~,5~~]*, Jared T. Heath[1,~~6~~5], Kelly J. ~~Elder~~[~~7~~]Elder[6], Niah B.H. Venable[1,3]

[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~~3] Natural Resources Ecology Laboratory, Fort Collins, Colorado USA 80523-1499
[~~5~~4] Geographisches Institut, Georg-August-Universität Göttingen, 37077 Göttingen, Germany
[~~6~~5] City of Fort Collins, Water Resources & Treatment, Fort Collins, Colorado USA 80521
[~~7~~6] 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~~Snowmobile use is a ~~snowmobile over a series~~popular form of ~~test plot to~~winter recreation in Colorado, particularly on public lands. To examine the ~~physical and material properties~~effects of ~~the~~differing levels of use on snowpack ~~due to compaction from a snowmobile. We measured the snow density, temperature, stratigraphy, hardness, and ram resistance from snow pit profiles. Experiments~~properties, 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~~Differences between no use and varying degrees of snowmobile use (low, medium and high) ~~for different starts of snowmobile use, specifically on a~~on shallow (the operational standard of 30 cm) and deeper ~~snowpack~~snowpacks (120 cm~~). Significant changes in snowpack properties~~) were ~~measured due to snowmobile use beginning on a shallow snowpack. These snowpack~~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 ~~on a~~in deeper snow~~, in particular at 120cm~~ 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~~, where annually~~ 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 ~~is~~occurs on public land. The United States National Forest System ~~sees~~records about 6 million ~~annual~~ snowmobile visits annually, accessing about 327,000 km^2 of land (US Forest Service, 2010 and 2013a). ~~As~~With continued increases in the number of people participating in winter ~~recreeation is increasing~~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), ~~the presence of~~ activities like increased snowmobile use may influence snowpack properties in these seasonally snow-covered environments. ~~Further, as the~~Of additional concern, is that climate ~~changes, there~~change will ~~be~~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). ~~Various studies examine~~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 ~~these~~the few studies ~~has been for~~on snowmobile use examined effects on shallow snow (10 to 20 cm deep~~) that caused~~). The authors found a doubling of fresh snow density, little impact on the underlying old snow, but ~~had a highly significant effect upon~~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). ~~We~~

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 ~~of this research~~ were to: (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~~.~~; and (3) create a simple model to estimate the change in snowpack density due to snowmobile use. This work examines ~~both~~not only changes to the basal snowpack layer, but also to the entire snowpack ~~and the basal layer.~~. 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 ~~that are~~ , especially when the information may be used ~~by snowmobilers,~~ to reduce conflict among ~~others~~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 ~~NF~~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 ~~users~~uses and prohibits ~~the use of~~ motorized winter recreation ~~and,~~while 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~~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. ~~The~~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~~. Initially snow water equivalent and precipitation~~, and~~ were monitored, temperature and snow depth were added in the 1990s-2000s~~) for~~ to aid in 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 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 ~~treatment~~ 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 ~~Dumont Lakes and Muddy Creek~~ 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 ~~among~~surrounded by 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 FEF study plot allowed for replication and determination of variability. The location of control and treatment plots across each study site ~~was~~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 ~~in all study sites.~~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 ~~through~~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. ~~The repeatability in the~~

temperature measurement was better than ±1^{o}C, and temperatureTemperature 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) from thewith the distance (*d* in m) over which the change in temperature occurred. The snowpack depth where the temperature gradient was approximated as linear (from an upper boundary, that was 25-30 cm below the surface) and to the temperature at 0 cm (lower boundary) with the distance (*d* in m) over which the change in temperature occurred. 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 by characterizingthrough 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 freshprecipitation particles, rounded grains, faceted grains, and ice layers.

Hardness is the snowpack's compressive strengthpenetration resistance of the snowpack (Fierz et al., 2009), and is measuredreported 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 ~~known area~~ ~~(~~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 ~~weighing~~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 ~~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 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 ~~are comparable~~compared were density, temperature, hardness, and ram resistance profiles for the five different monthly measurements. A statistical significance was determined ~~to~~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 ~~an average~~ 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~~), while the~~). 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 ~~for Colorado was deemed to represent~~represents a deeper snow cover environment~~.~~ for Colorado. From the Middle Fork SNOTEL data, the 2009-2010 winter at FEF ~~was~~had less snow depth 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.

4.2 Snowpack Properties

4.2.1 Density

~~Bulk~~ 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 ~~at the~~ 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 ~~when low and high use compaction treatments began on 30 cm of snow (Figure 4a). As a result, low and~~ , 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 ~~between these treatments (low and high) and the control, and compared to both low and high use~~ than the control and compaction treatments beginning ~~on~~at 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~~ The density differences between the treatments ~~yielded an increase to 285 kg/m^3~~on the deep snow (120 cm) and ~~328 kg/m^3, respectively (Figure 4a). In contrast, compaction treatments (low and high) beginning on 120 cm of snow (Figure 4b) did~~the control were 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~~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 ~~observed on 12 December, respectively, compared to just over 200 kg/m^3 for the control (Figure 3ai). Snow compaction~~was not significant (Table 1). The density differences among treatments ~~had little impact on~~ are highlighted in the 10-cm individual density measurements (Figure 5a) and in the 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).~~(Figure 4bii).

~~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).~~

4.2.2 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°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°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°C m^{-1} by 17 April. Basal layer temperatures increased throughout the winter season until all uses exhibited a basal layer temperature of -1°C by 17 April.~~, and were isothermal at 0°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).

~~Low, medium~~

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 ~~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°C m^{-1}, 13°C m^{-1}, and 20°C m^{-1} on 27 December compared to 20°C m^{-1} measured at the control. Temperature gradients decreased throughout the winter season until all uses exhibited a temperature gradient near 0°C m^{-1} by 26 April (Figure 5b). The coldest~~started (06 Feb) on a deeper snowpack. However, basal layer ~~temperature was for medium use on 22 January (-6°C), with a basal layer temperature of -5°C on 27 December for all other~~hardness did decline at REP for both high and low use starting on 30 cm (Figure 4ei). With treatments~~. Basal layer temperatures increased for all uses throughout~~ at FEF, the ~~winter season until basal layer~~

~~temperatures reached -1°C by 26 April~~hardness was always much higher than the control (Figure ~~5b).~~

~~4.3~~ 4dii). Hardness

~~Mean snowpack 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 ~~6a), but only for high use starting on a deeper snowpack (Figure 6b).~~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). ~~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~~4ei).

Snow compaction treatments that began on 30 cm of snow increased basal layer hardness (Figure ~~5a~~4ei), 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.~~4ei). For both controls and all treatments that began on 120 cm of snow (Figure ~~6b~~4ei), the maximum basal layer hardness was about 6 kPa.

~~Low, medium, and high~~Increased hardness due to snowmobile use ~~compaction treatments resulted in a significant increase in mean~~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 ~~hardness following snow compaction treatments beginning on 30 cm of snow at~~ (Figures 5bi and 5bii). These results are also reflected in 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)~~ram resistance (Figures 5ci 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~~5cii).

4.2.4 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~~not significant for treatments that began on ~~30 cm of~~deep snow (120 cm; 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 (Table 1) 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 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).~~

~~***4.6***~~*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 ~~9d~~6d) and depth (Figure ~~9a~~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 ~~6km~~6 km apart (Figure 1). Also since these were operational sites, ~~i.e.,~~ the amount of treatment was not controlled and was based solely on permitted snowmobile use. Patterns of increased density (Figure ~~9a~~6a), hardness (Figure ~~9b~~6b) and ram resistance (Figure ~~9c~~6c) were similar to the ~~previous~~patterns seen in the previously presented experiments (Figures 4, ~~6,~~ and ~~7~~5) with the non-snowmobile impacted snowpits being less dense (Figure ~~9a~~6a) and having layers that were less hard (Figure ~~9b). For~~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 ~~9bii to 9biv)~~6b), but at times ~~was similar to~~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 ~~4a,~~4ai and ~~6a~~4di), and later into the snow season for the shallower snowpack (FEF in Figures ~~4c,~~4aii and ~~6c~~4dii). Similar differences were found ~~due to~~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 ~~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~~increased densification of the snowpack ~~due to snowmobile use~~which influences snow hardness (Figure ~~6) and ram resistance~~4) and ram resistance. Compaction deformed fresh snow (Figure 5), fragmented faceted grains (Figure 4fii), and reduced the growth of faceted grains (Figure ~~7~~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 ~~a deep~~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~~. A shallow snow environment is more susceptible to large changes in snow hardness due to varying snowmobile use.~~ (Figures 4dii and 4eii).

~~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°C m^{-1} at the beginning of the season, and approached 0°C m^{-1} as the snowpack became isotherm 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°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).

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 (assuming. 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). 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.

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, while low, medium, and high use resulted in average crystal sizes of 1.3 mm, 2.5 mm and 1.5 mm, respectively (Table 2). 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~~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 ~~snowpack~~snowpacks were found to not have ~~a~~ cooler soil ~~temperature~~temperatures under the snowpack (Keller et al., 2004), but ~~did melt~~melted out four weeks later than thinner snowpacks (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.

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.

~~Without wind, snow depth will be less~~ 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. ~~The local~~Local terrain features and position and extent of canopy cover influence how the wind interacts with the snowpack (Pomeroy and Brun, 2001). In an ~~Australia~~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 ~~9d~~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

~~This study examined the effect of compaction from~~ 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. ~~It showed that snowpack properties change with varying use of~~ We examined the effect of snowmobile use~~, annual snowfall (REP versus FEF), and the depth at which snowmobile use was initiation. Snowmobile use creates compaction that influences~~ on the physical and ~~mechanical~~material properties of the snowpack~~. In particular, this increases~~ 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 ~~density, hardness, and ram resistance when winter recreational use occurs.~~properties observed at undisturbed control sites and at operational sites with varying levels of use. The largest differences in snowpack properties ~~are~~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 ~~as seen by~~of density, temperature, hardness, and ram resistance ~~measurements comparable~~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 ~~experiment~~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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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.

Fassnacht, S.R., and Hultstrand, M.: Snowpack Variability and Trends at Long-term Stations in Northern Colorado, USA, Proceedings of the International Association of Hydrological Sciences (Hydrologic Non-Stationarity and Extrapolating Models to Predict the Future), 371, 131-136, [doi:10.5194/piahs-92-1-2015], 2015.

Fassnacht, S.R., and Records, R.M.: Large snowmelt versus rainfall events in the mountains, Journal of Geophysical Research - Atmospheres, 120(6), 2375-2381 [doi:10.1002/2014JD022753], 2015.

Fassnacht, S.R., López-Moreno, J.I., Ma, C., Weber, A.N., Pfohl, A.K.D., Kampf, S.K., and Kappas, M.: Spatio-temporal Snowmelt Variability across the Headwaters of the Southern Rocky Mountains, Frontiers of Earth Science, 11(3), 505-514, [doi: 10.1007/s11707-017-0641-4], 2017.

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.

Moriasi, D. N., Arnold, J. G., Liew, M. W., Bingner, R. L., Harmel, R. D., and Veith, T. L.: Model Evaluation Guidelines for Systematic Quantification of Accuracy in Watershed Simulations, Transactions of the ASABE, 50(3), 885-900, doi:10.13031/2013.23153, 2007.

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.

Rixen, C., Stoeckli, V., and Ammann, W.: Does artificial snow production affect soil and vegetation of ski pistes? A review, Perspectives in Plant Ecology, Evolution and Systematics, 5(4), 219-230, 2003.
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.
Saly, D., Hendrikx, J., Birkeland, K., Challender, S., and Leonard, T.: The Effects of Compaction Methods on Snowpack Stability, Proceedings of the 2016 International Snow Science Workshop, Breckenridge, Colorado, 716-720, 2016.
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

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

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 ~~Berthoud Summit~~ Middle Fork Camp SNOTEL near Fraser Experimental Forest (FEF~~).~~), Colorado, illustrating the dates of treatment and dates of sampling. Data were obtained online from the Natural Resource Conservation Service (NRCS) National Water and Climate Center (http://www.wcc.nrcs.usda.gov/).

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.

~~4.~~ a) Density**, b) hardness, and c) ram resistance** profiles for ~~five~~**the February sampling** dates (~~i to v~~**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 ~~a~~**i**) 30 cm and ~~b~~**ii**) 120 cm of snow, and ~~c~~**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.~~

~~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.~~

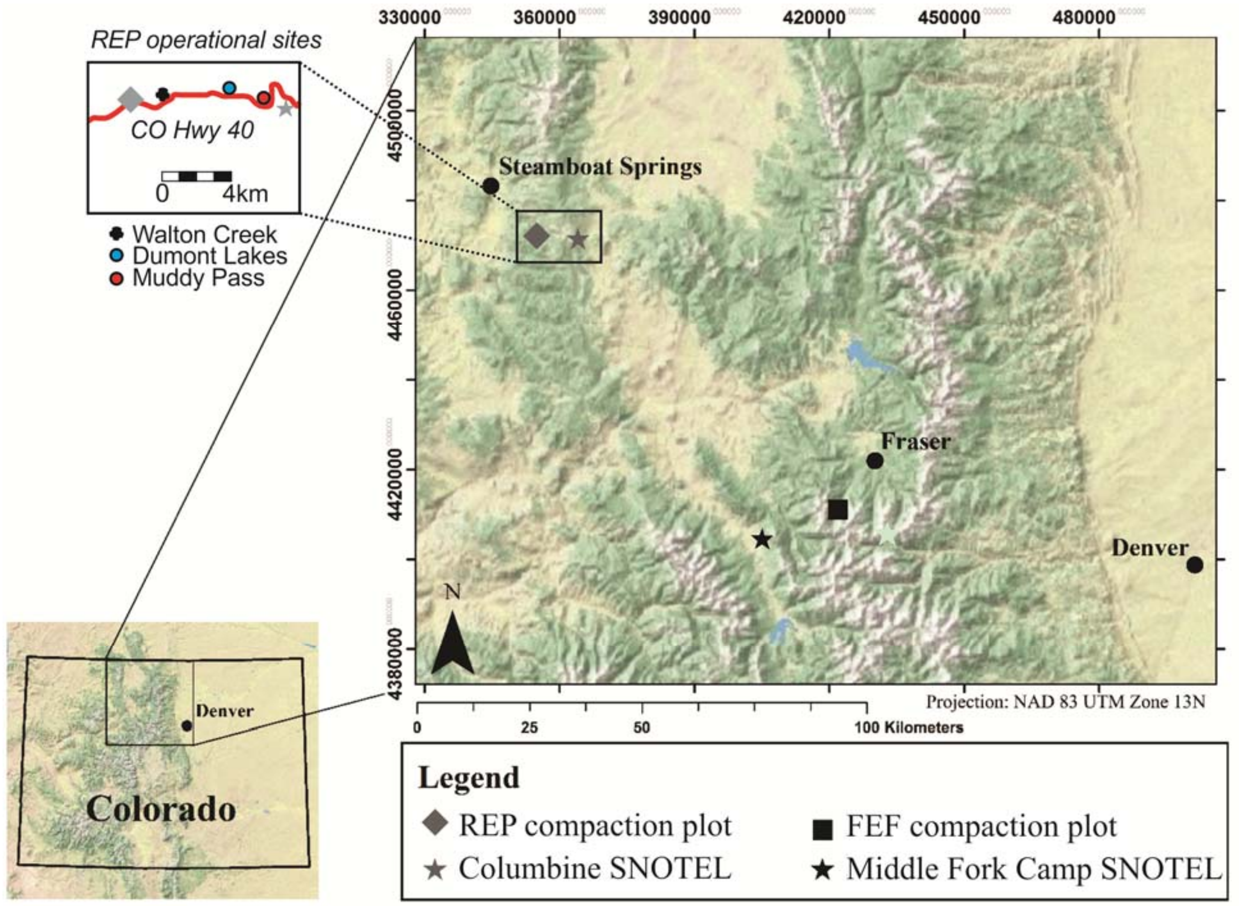
~~6. Hardness profiles for five dates (i to v) measured at the REP snow compaction study plot for no, low, and high use treatments beginning on a) 30 cm and b) 120 cm of snow, and c) the FEF snow compaction study plot for no, low, medium, and high use treatments beginning on 30 cm of snow.~~

~~7.~~5. ~~Ram resistance profiles for five dates (i to v) measured at a) the REP snow compaction study plot for no, low, and high use treatments beginning on 30 cm and 120 cm of snow and b) the FEF snow compaction study plot for no, 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.

~~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.~~

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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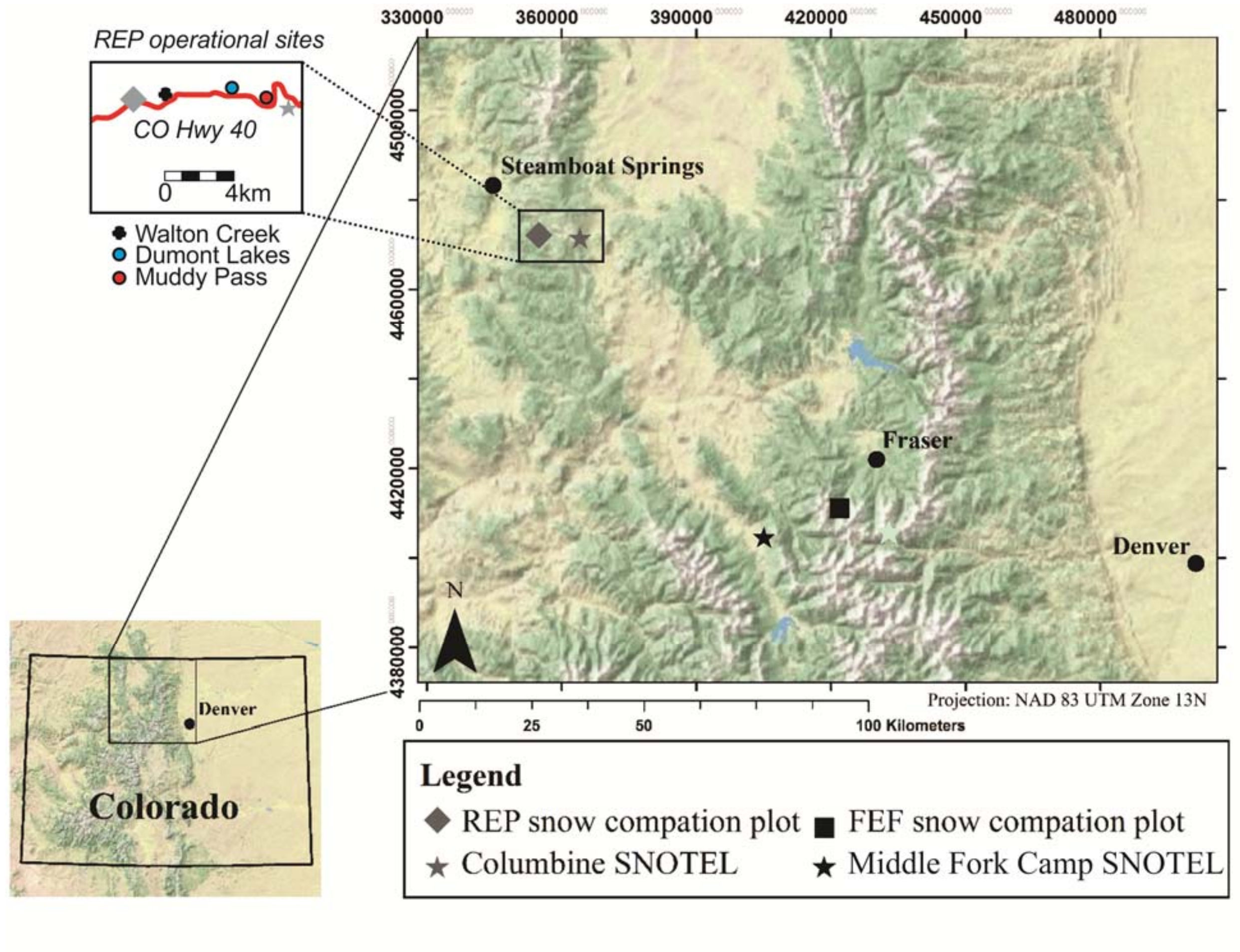

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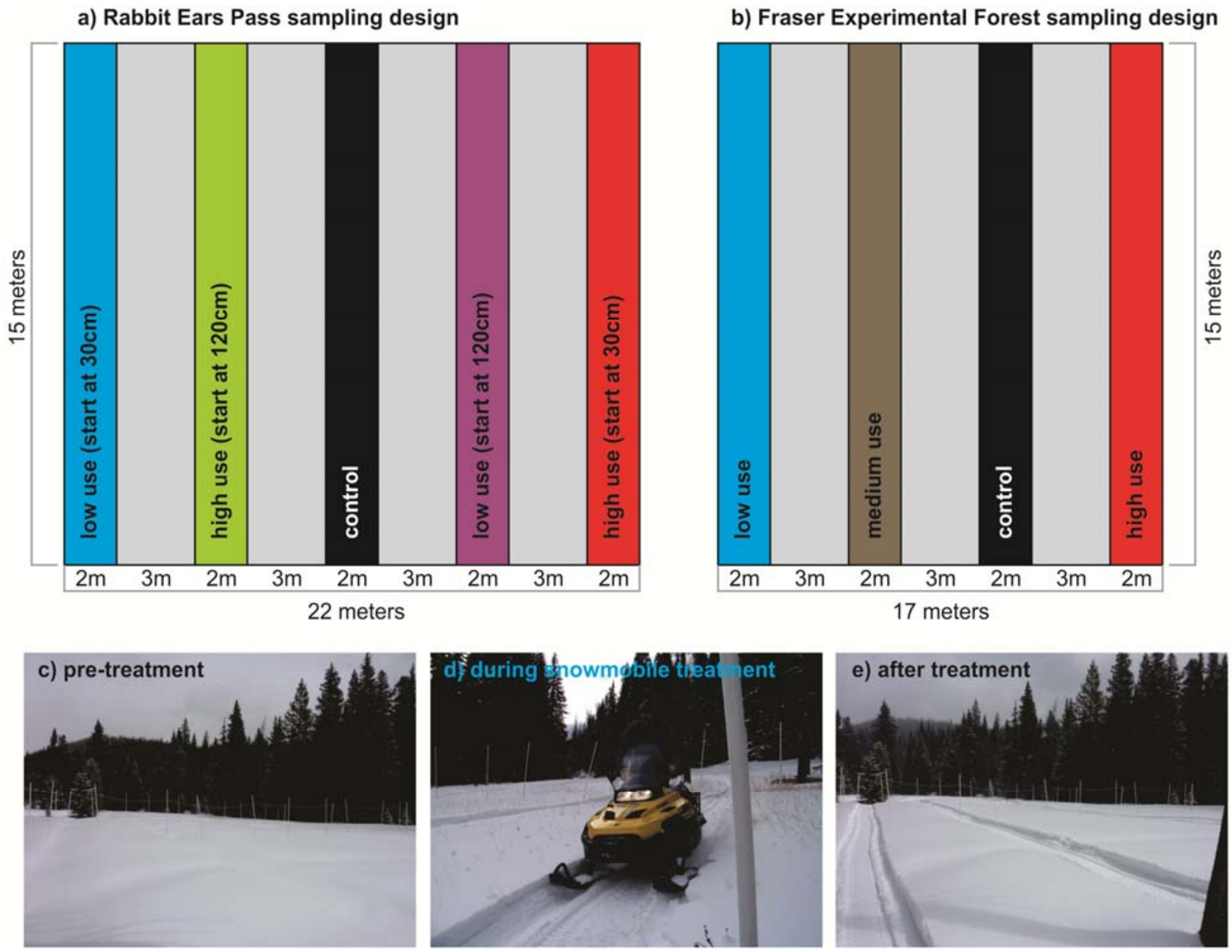
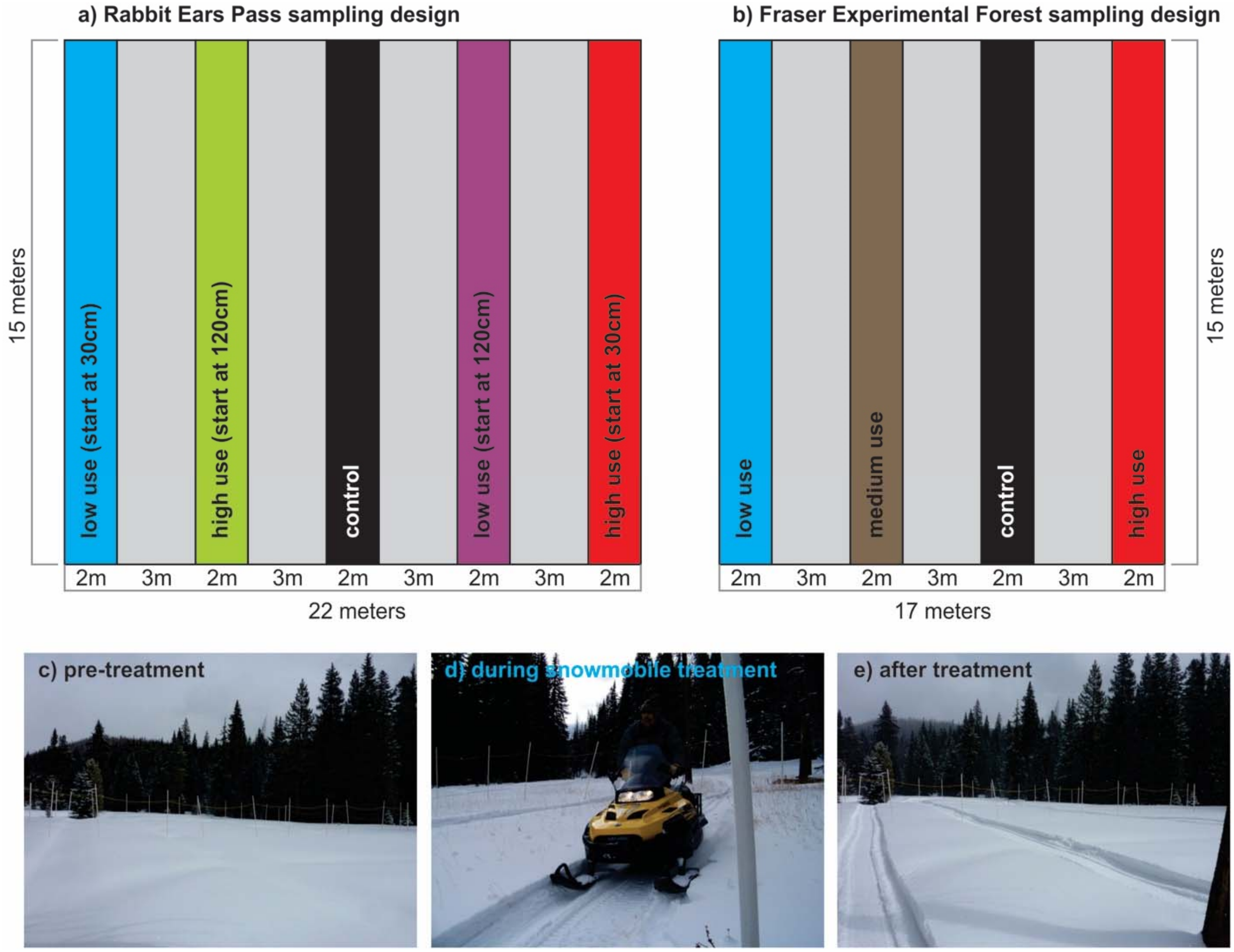

a) Rabbit Ears Pass sampling design
b) Fraser Experimental Forest sampling design
15 meters
low use (start at 30cm)
high use (start at 120cm)
control
low use (start at 120cm)
high use (start at 30cm)
2m 3m 2m 3m 2m 3m 2m 3m 2m
22 meters
low use
medium use
control
high use
2m 3m 2m 3m 2m 3m 2m
17 meters
15 meters
c) pre-treatment
d) during snowmobile treatment
e) after treatment



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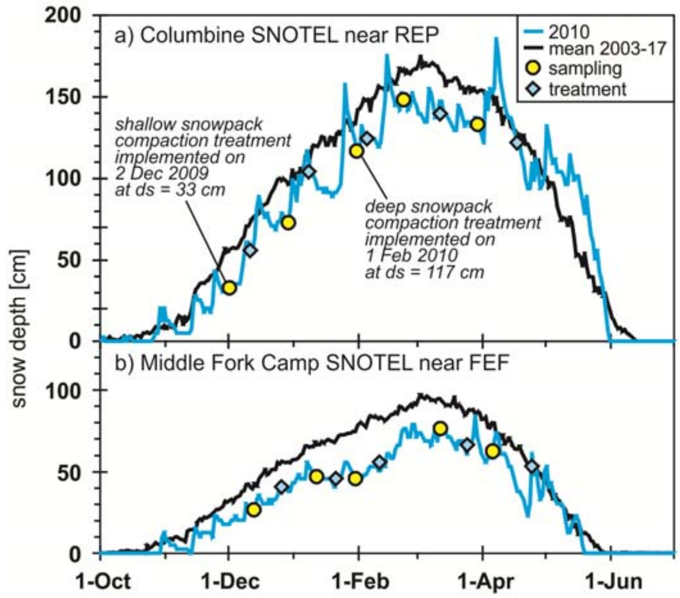


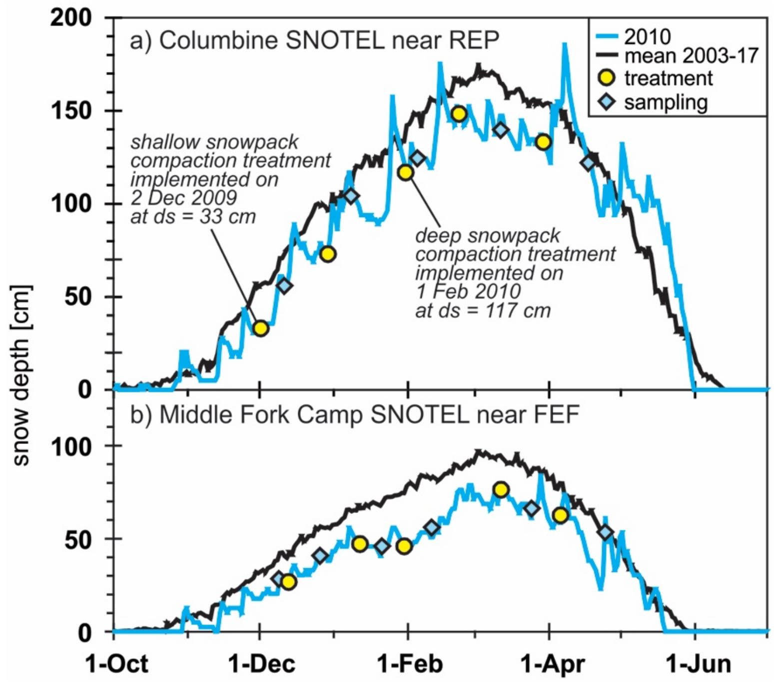
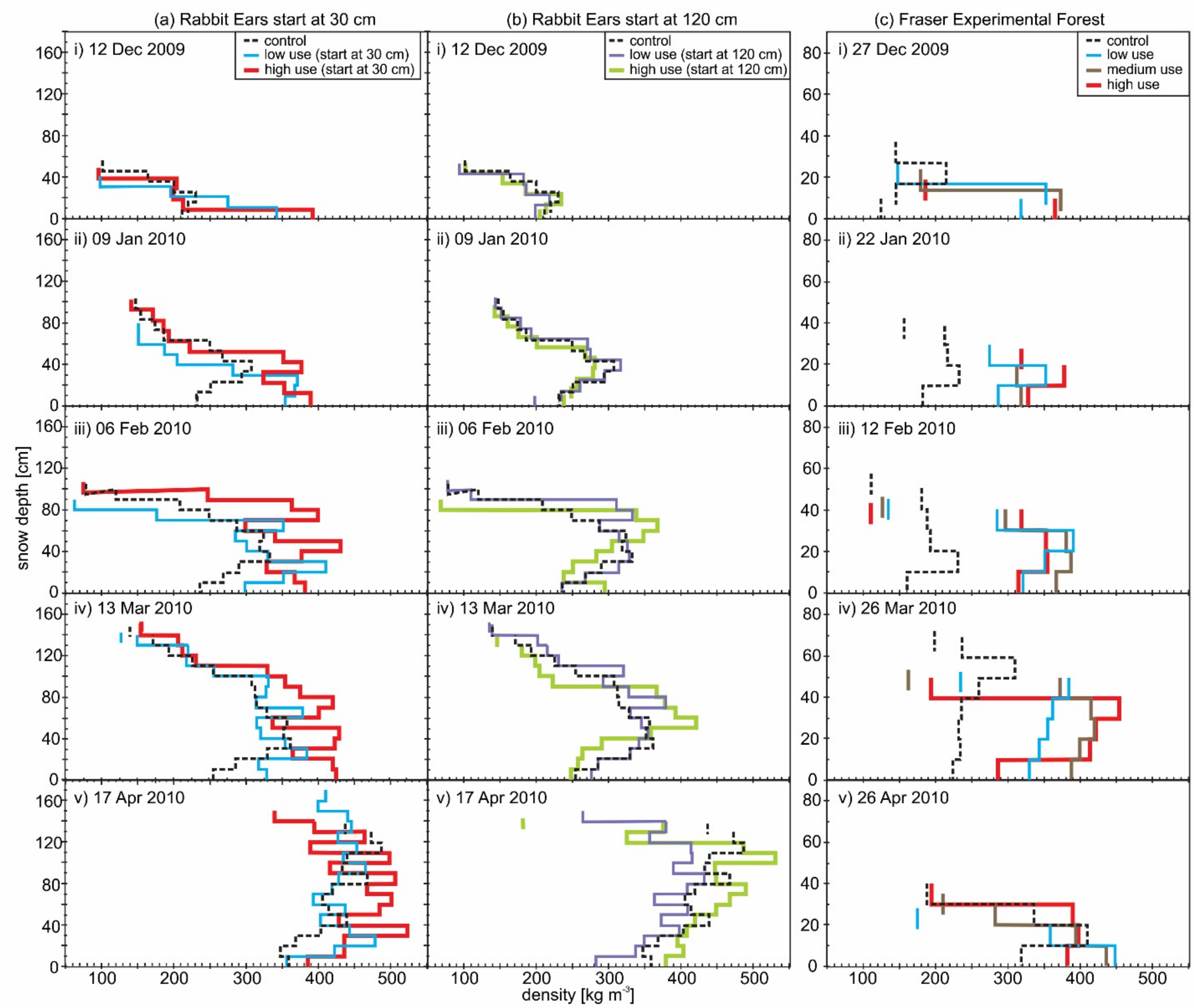
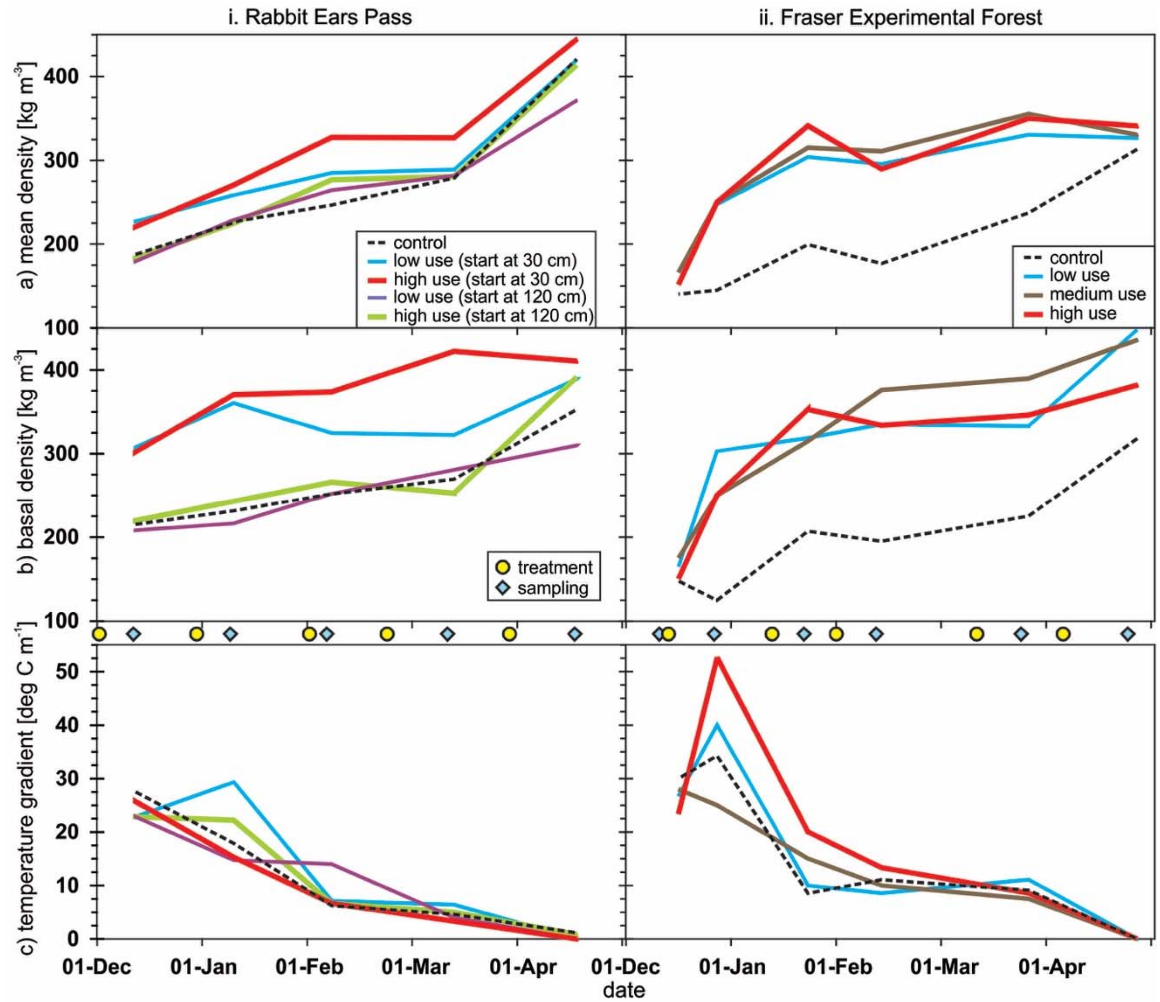


Figure 3. Mean snow depth from 2003-2017, and for the 2010 water year (WY2010) measured at a) the Columbine SNOTEL site near Rabbit Ears Pass (REP), Colorado and b) the Middle Fork Camp SNOTEL near Fraser Experimental Forest (FEF~~).~~), Colorado, illustrating the dates of treatment and dates of sampling.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


(a) Rabbit Ears start at 30 cm
(b) Rabbit Ears start at 120 cm
(c) Fraser Experimental Forest
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)
low use
medium use
high use
i) 12 Dec 2009
ii) 09 Jan 2010
iii) 06 Feb 2010
iv) 13 Mar 2010
v) 17 Apr 2010
i) 27 Dec 2009
ii) 22 Jan 2010
iii) 12 Feb 2010
iv) 26 Mar 2010
v) 26 Apr 2010
snow depth [cm]
density [kg m⁻³]



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]
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

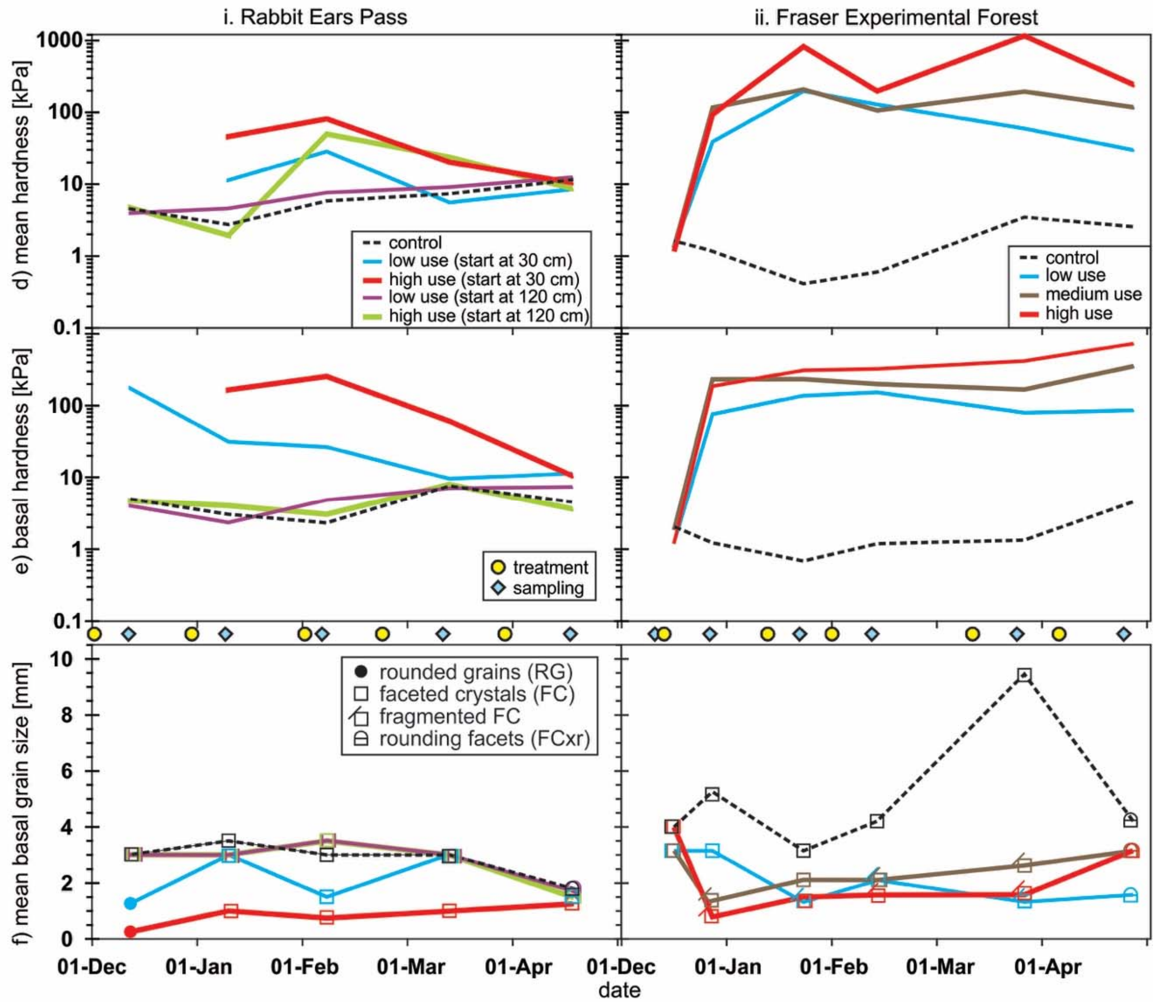
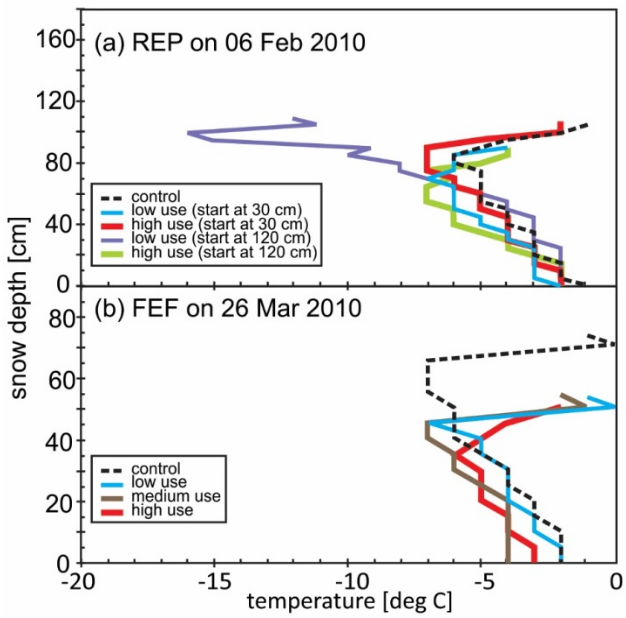
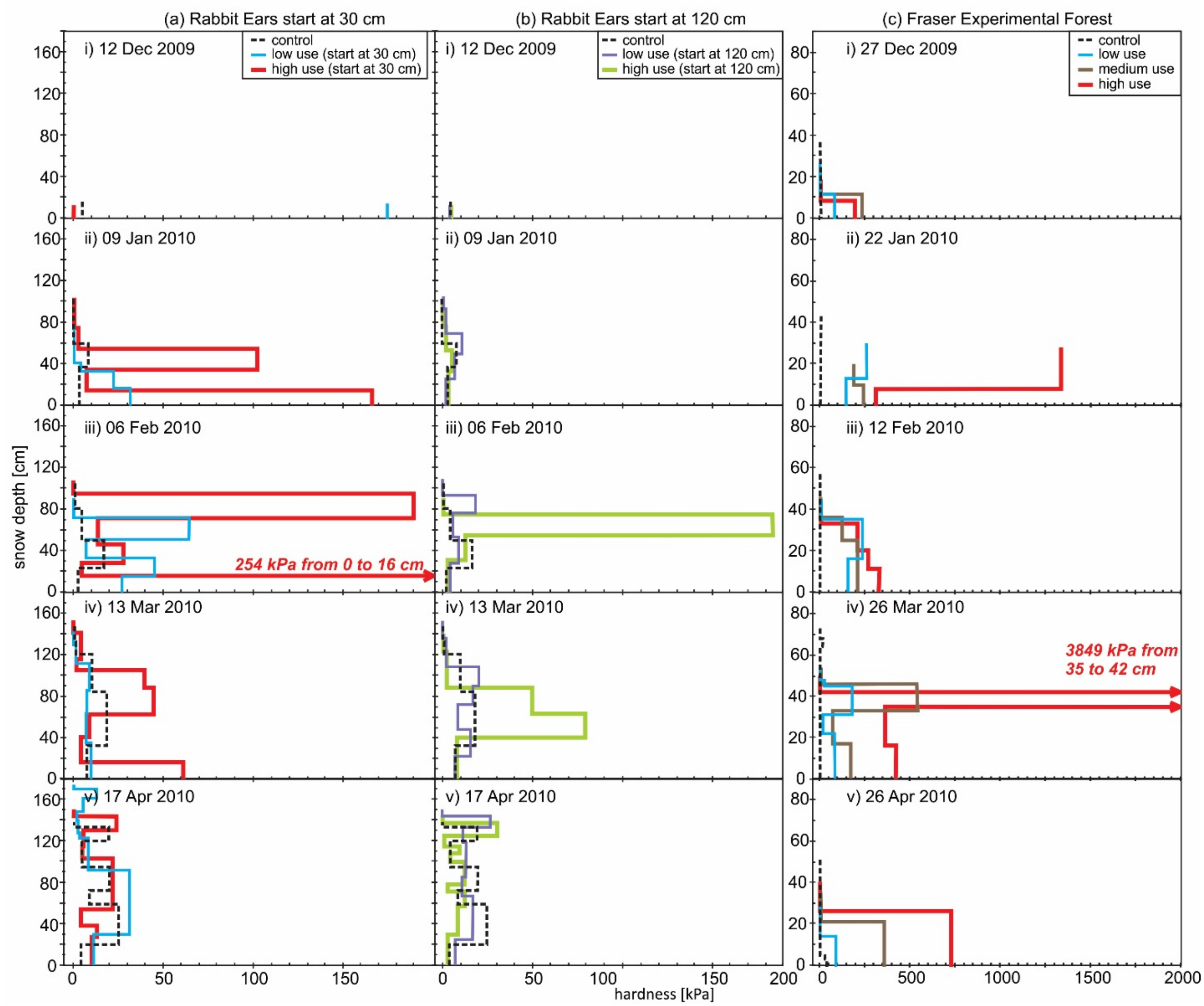


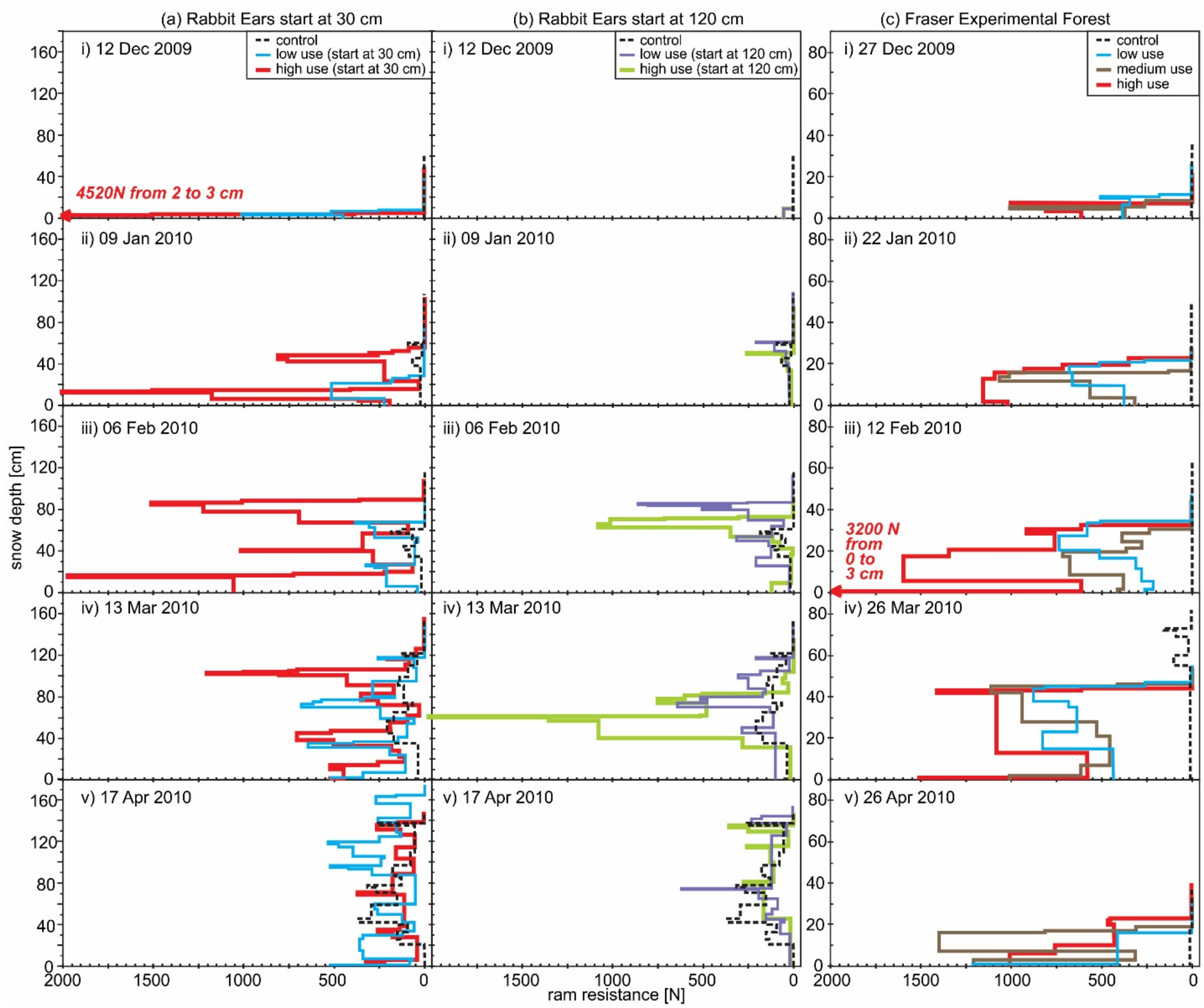
Figure 4. ~~Density profiles for five dates (i to v) measured at the REP snow compaction study plot for no (control), low, and high use treatments beginning on a) 30 cm and b) 120 cm of snow, and c) the FEF snow compaction study plot for no (control), low, medium, and high use treatments beginning on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



~~**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.~~

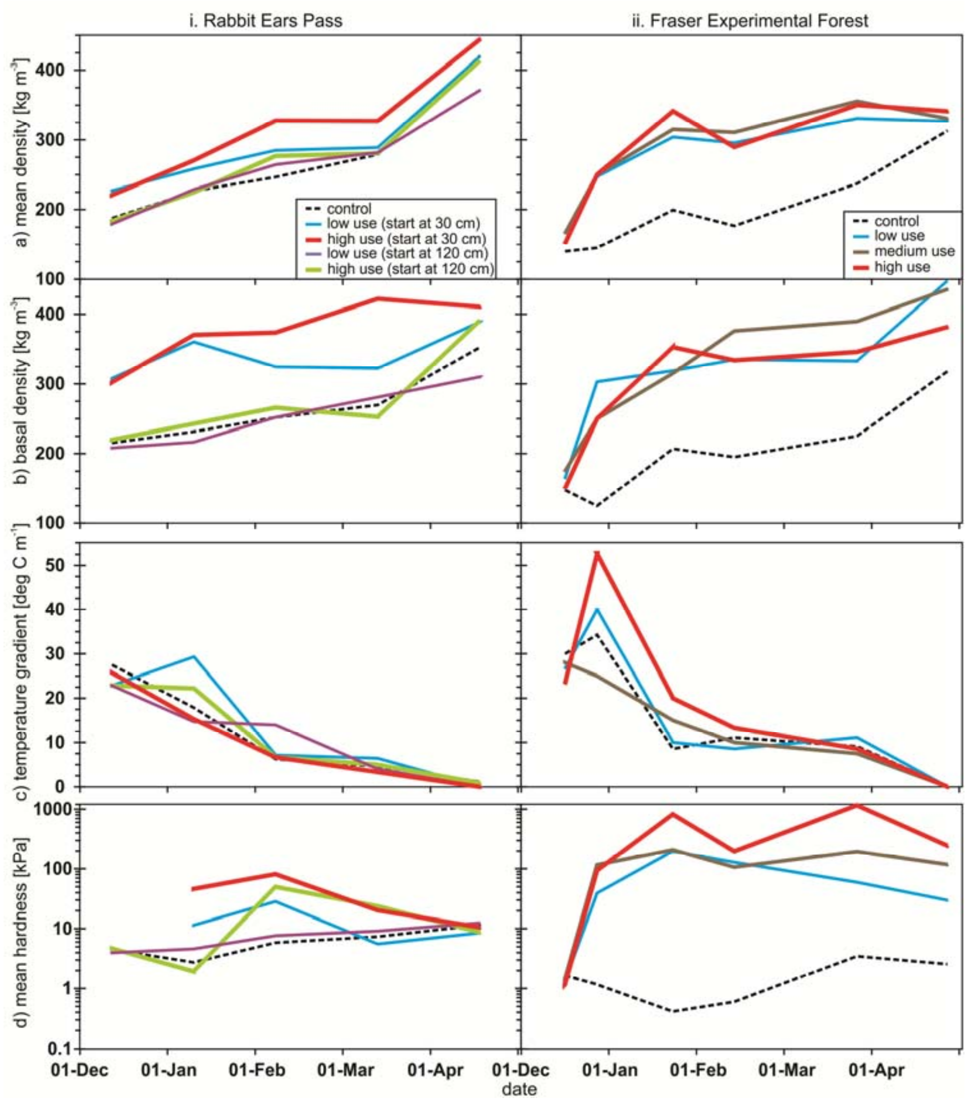


Figure 8. Time series for i. Rabbit Ear Pass (REP) and ii. Fraser Experimental Forest at the different sampling dates of a) mean snowpack density, b) basal snowpack density, c) snowpack temperature gradient, and d) mean snowpack hardness for i., e) basal layer hardness, and f) mean basal crystal size 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 Rabbit Ear Pass (REP) 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.

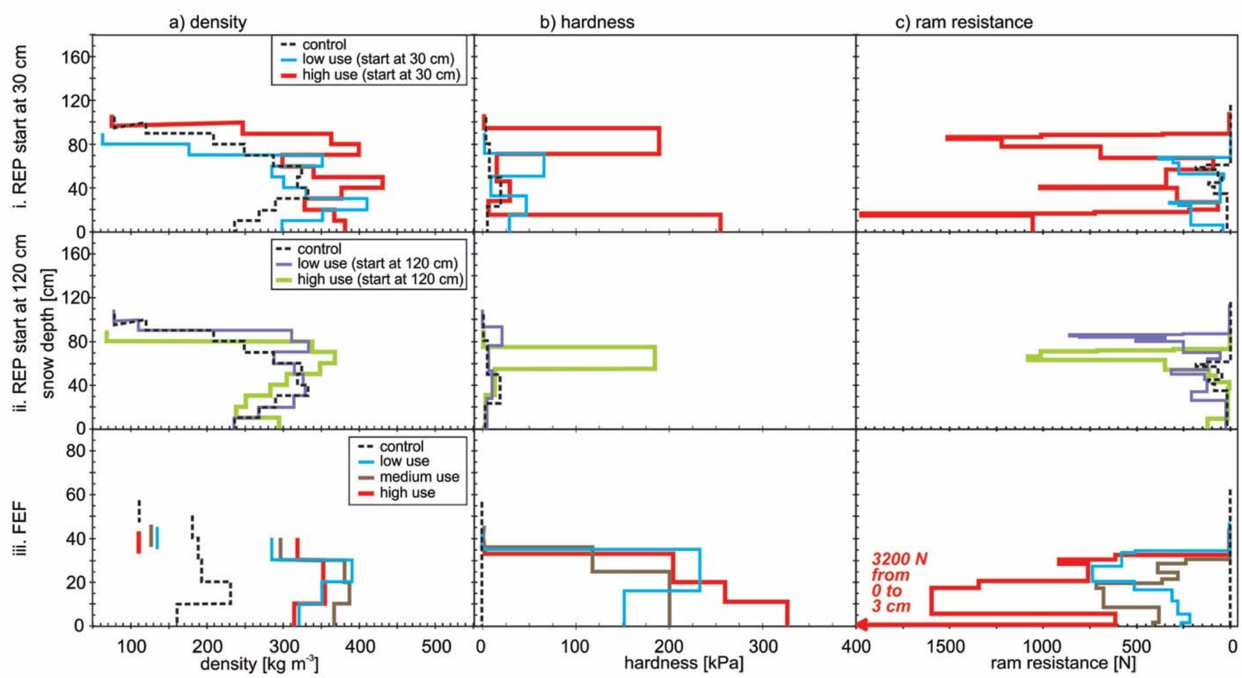


Figure 5. a) Density, b) hardness, and c) ram resistance profiles for the February sampling dates (06 Feb at REP and 12 Feb at FEF) measured at the REP snow compaction study plot for no (control), low, and high use treatments beginning on i) 30 cm and ii) 120 cm of snow, and iii) the FEF snow compaction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

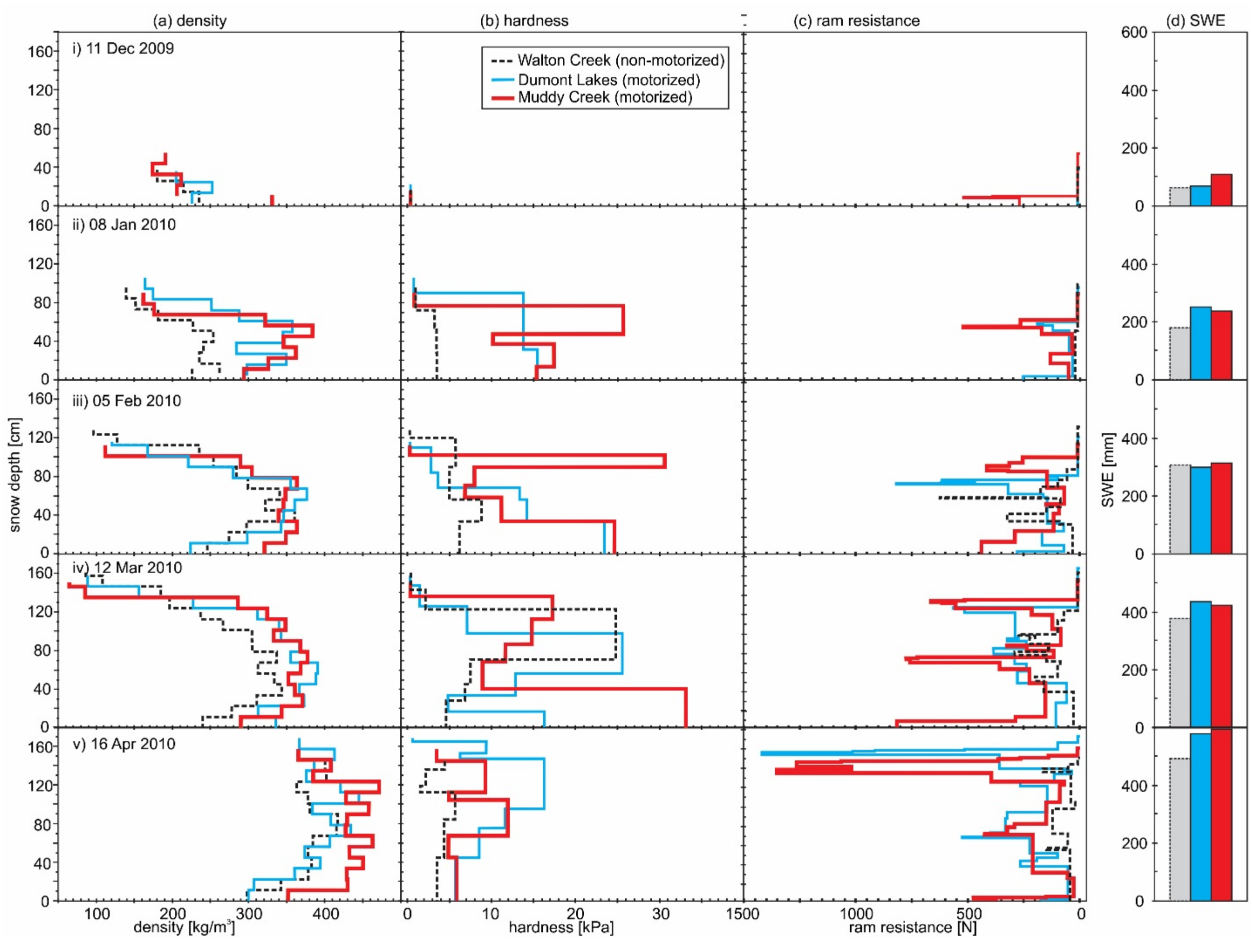


Figure 9. The ground is at zero snow depth.

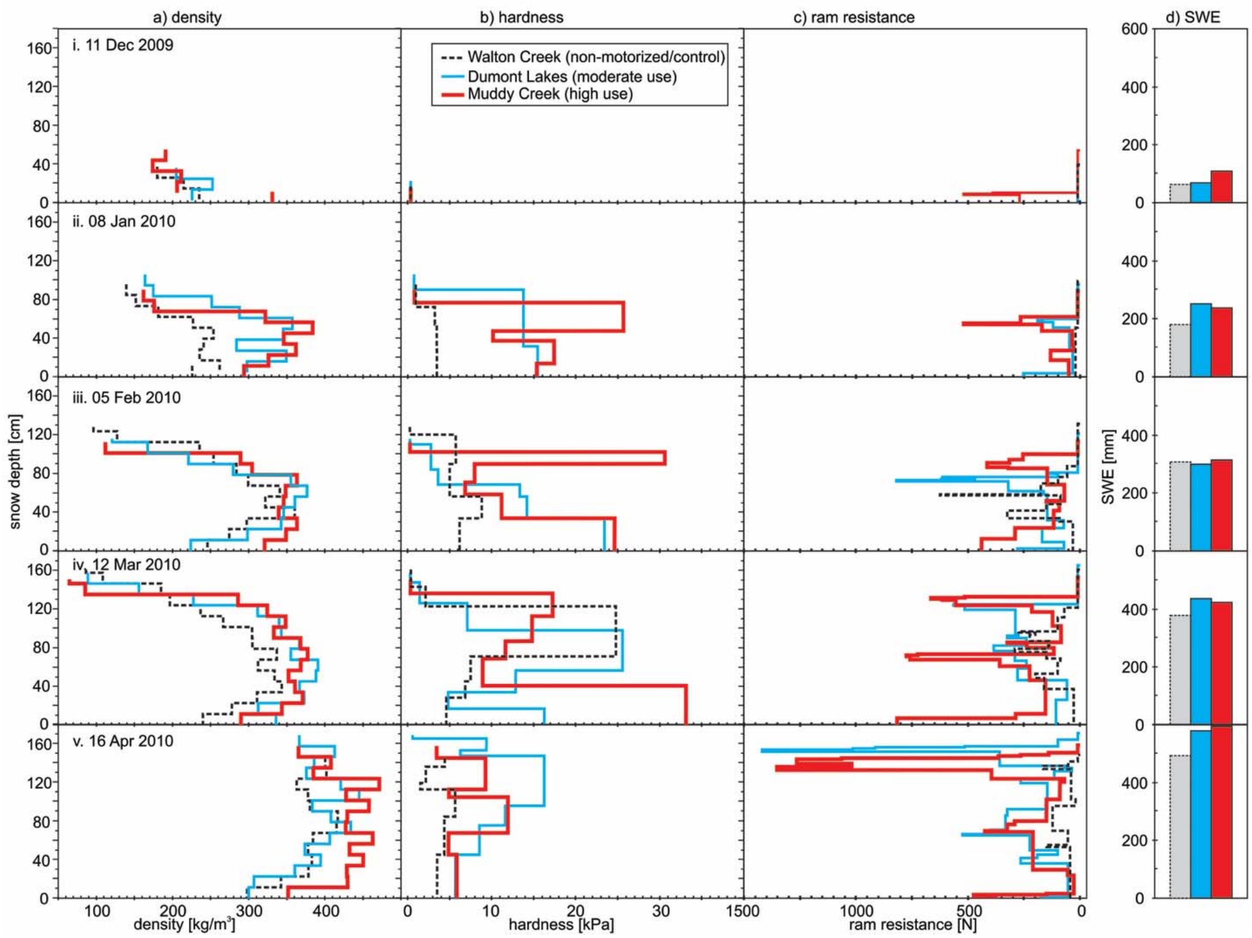


Figure 6. Snowpit data for Walton Creek (no snowmobile use), Dumont Lakes (moderate snowmobile use) and Muddy Creek (high snowmobile use) in the Rabbit Ears Pass recreational use areas illustrating a) density, b) hardness, c) ram resistance, and d) SWE.

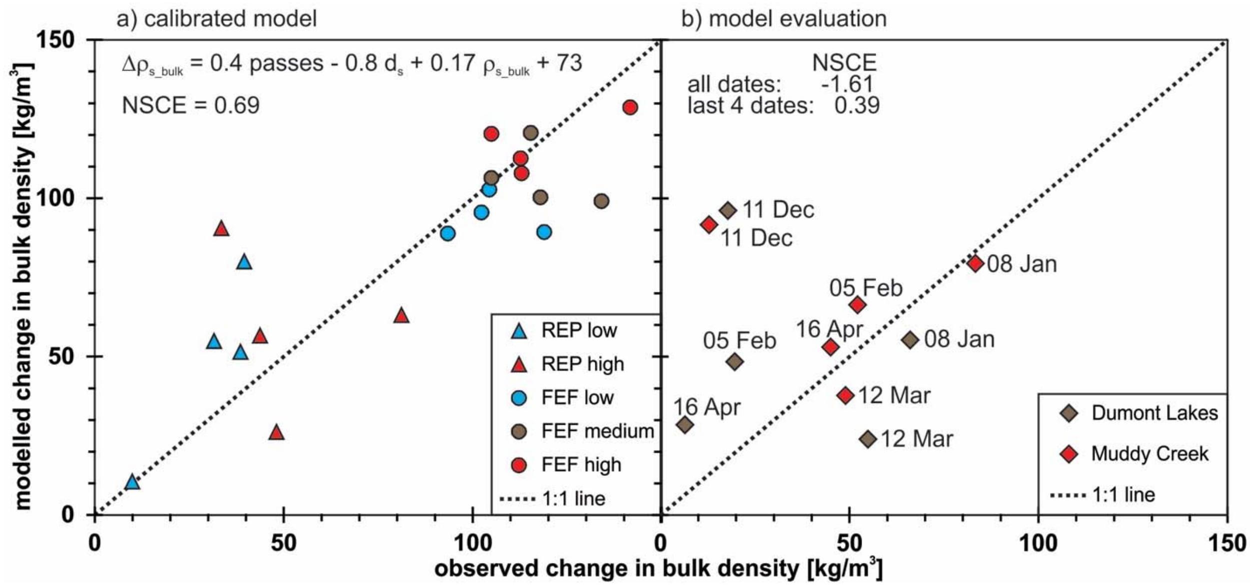


Figure 7. Bulk snowpack density change model for different amounts of use compared to the control of no use a) calibrated for the two experiment sites (Rabbit Ears Pass, REP and Fraser Experimental Forest, FEF), and b) applied to the operational sites (Dumont Lakes and Muddy Creek), compared to the no 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.