Responses to Reviewers Comments: Noted with a ">", with the response following.

The authors have made substantial changes to the original manuscript, and it now reads much better. In particular, the presentation of the results has improved, which now greatly facilitates the interpretation of the results. Nevertheless, I believe some changes are still required before the manuscript can be accepted for publication.

1. The presentation of the results obtained at the so-called operational sites can be improved. Specifically, I would suggest that the authors present the results shown in Figure 6 in a format similar to Figure 4. This would make the comparison of the experimental sites with the operational sites much more easy.
> The plots of "point" measurements have been replaced by a time series of plots with the mean and basal values for the operational sites.

2. Although the discussion section has improved, it is rather long and somewhat unstructured. The authors could use sub-sections with headers to provide a better structure and rearrange the paragraphs accordingly. I would suggest to split the discussion into three sub-section, e.g. (i) limitations of the measurement setup (ii) observed changes to snowpack properties and (iii) significance/impact of changes.
> The discussion section has been significantly reorganized using the suggestions of the reviewer as a starting point and refining from there.

3. The authors now provide a simple model to predict densification due to snow mobile usage based on the number of passes, snow depth and bulk density. This is a nice addition to the paper as it shows that changes in snowpack density could be modelled. However, in the current model, if the number of passes is 0, there can still be a change in density. Perhaps a model of the form:
$\Delta\rho_{s\_bulk} = A \times passes(B \times d_s + C \times \rho_{s\_bulk} + D)$
would be better suited, as the change in density would go to zero when there were no passes.
> We used a non-linear version of the above model and were able to get a better fit. The fit to the operational sites was about the same.

Finally, the authors should mention the potential merits of a density change model in the context of land use management in the discussion section
> *Mentioned model in discussion section.*

and their density change model should also be mentioned in the conclusions.
> Completed.

4. The authors should discuss the role of spatial variability in their results in a more quantitative manner. Indeed, the authors mention that they had two control transects at FEF (lines 126-127) and that the first measurements at FEF were performed prior to any snowmobile treatment (lines 138-140). Furthermore, the deeper snow treatments at REP only started on 1 February (lines 247-

249). All these data can be used to assess the typical degree of spatial variability at the experimental sites in a more quantitative manner.
> We have added a figure illustrating the spatial variation in snowpack density, both mean and basal. This shows values at i) at REP deep snow (120 cm) compaction treatments (low and high use) on the first two sampling dates versus the control, ii) at FEF for the pre-treatment date (figure sampling date in Figures 5ii and 5iii) for the two sets of control snowpits at FEF. In the text we also mention a difference in hardness, but also acknowledge that the relative variation in hardness is larger than that of density since the non-treatment hardness values are so low (range of 0.4 to 5.8 kPa) versus the treatments (range of 30 to 1157 kPa).

Detailed comments:
line 22: change ‘where there was less snow accumulation’ to ‘for thinner snow accumulations’
> Modified statement.

line 48: on very shallow snow. Also, move the reference Keddy et al in line 50 to the end of line 48
> Added “very” and copied the Keddy reference to line 48 but also left at end of 51.

line 49: not clear how there can be an impact on the ‘underlying old snow’ if the snowpack is only 10 to 20 cm deep.
> Removed/modified this reference as line 56 references vegetation.

line 51: define what is meant by ‘deeper snow cover’.
> Added (>20 cm deep) to distinguish from the previous statement.

line 60: not sure what is meant by ‘greater heat loss from the snowpack and underlying soil’. Does this mean that there is more cooling in the snowpack and soil? This wouldn’t make sense to me.
> Modified sentence based on Fassnacht and Soulis, 2002 results to mean a delay in soil warming which can delay onset of vegetative growth.

lines 68-69: I don’t see how ‘and billions of dollars are spent each year on snowmobiling’ is relevant here and suggest removing it
> Refined the statement.

line 83: side of the pass …non-motorized users
> Corrected and made a few edits to following sentences to improve readability.

line 125: Two control transects: these are not shown in Fig. 2b.
> Figure and statement modified.

lines 154-155: remove this sentence
> Modified sentence for clarity.

line 167: not sure what the ‘point of zero amplitude’ is

> Clarified, with new citation added.

lines 172-173: remove ‘each stratified layer of’
> Modified sentence and removed.

line 179: rewrite as ‘It is due to’ does not make sense to me. Hardness is not due to something, it is a property related to something
> Reworded for clarity.

line 184-186: Did you perform multiple measurements in thicker layers and average those values, or did you only perform one hardness measurement?
> Clarified.

line 191: replace ‘tube’ with ‘rod’
> Replaced.

line 192: replace ‘of known weight’ with ‘of defined weight’
> Modified

line 197: here you mention ‘stratigraphic layers’. Are these the same as those identified in the manual snow profile? Usually, the layers identified in the ram profile do not correspond one-to-one to layers in the manual profile.
> Clarified sampling. Stratigraphic layers are not the same as the depths used in ram sampling.

line 204: The statement ‘This determines the statistical significance between two datasets’ is inaccurate. The Mann-Whitney test is used to compare two distributions and determine if these are statistically different from each other without assuming normal distributions.
> Modified for clarity.

lines 224-225: rewrite to: …REP had slightly below average snow depth compared to the 15 year mean based on the Columbine SNOTEL data…
>Modified.

line 226: rewrite to: …9 April was at 93% if the historical …
> Done.

line 229: rewrite to: …FEF was also below the 15 year …
> Clarified.

line 237: mention that this refers to the first data point in Figure 4ii
> Adjusted.

line 283: (Table 1c)
> Corrected and added section references to Table 1 sections for all properties.

line 296-297: remove sentence: ‘These results are also …’

> *Done.*

line 307: move (Table 1) to end of sentence
> *Completed.*

line 317: fragmented facetted crystals is not an official crystal type mentioned in Fierz et al. (2009)
> *Adjusted statement to better reflect observations.*

lines 322 to 324: rewrite to …and snow depth (Figure 6a), the amount of snow was comparable for the … sites, even though they were up to …
> *Adjusted.*

line 326: the statement ‘were similar’ cannot be concluded based on what is shown in Fig. 6. Suggest showing the results as in Fig. 4
> *Revised for clarity, see new figure.*

lines 334-336: The line of reasoning does not make sense to me. Just because data do not fit the expected trend, does not mean they should be excluded. It is better to argument that you want to focus on dry snow conditions, and therefore exclude the data from later in the season.
> *Modified statements for clarity.*

lines 338-339: it is not clear to me what ‘…were not cross-correlated’ means
> *Clarified statement.*

lines 345-349: Show the results which end up with a NSCE value of 0.71 in Fig. 7. Also, since you do not control the amount of snowmobile use at these sites, you can use the model to estimate it. It makes perfect sense that it varies throughout the season, as many factors influence the amount of use, including weather and time of year (holidays).
> *Revised section wording. Adjusted with new model.*

lines 354-357: Mention density changes in % to facilitate the comparison with literature values for grooming.
> *Calculated percentages for comparison.*

line 361: change ‘densification’ to ‘density’
> *Done.*

line 362: ‘compaction deformed fresh snow’ not sure what this means and on what observations this statement is based.
> *Modified for clarity.*

lines 378-379: Figure 3ai and 3aii
> *This likely refers to a previous version of the document, Figure 3 only has an a) and b) now and the text reference should be correct.*

line 382: ‘spatial variability between 40 to 200 kg/m3 for fresh snow’ I strongly doubt that such a variability would be observed in the experimental sites. Clearly, some quantification of the spatial variability observed at the experimental sites would be in place to provide some context.
> Clarified the statement, as a general observation based on previous studies and added more material based on new figure(s).

lines 386-388: this sentence seems misplaced and should be moved to the paragraph in lines 409-415
> Revised and moved.

line 387: based on Figure 4, the crystals at the end of the season were no rounded crystals, but rounded facets.
> Clarified.

line 395: rewrite to: …property changes we observed could therefore also be …
> Modified.

line 411: …, it could impact weak layers that cause avalanches (Saly et al., 2016), which are typically soft layers consisting of large facetted grains (e.g. Schweizer and Jamieson, 2003; van Herwijnen and Jamieson, 2007)
> Added and modified.

line 415: ‘Do not try …‘ rephrase this to say that the effects of snow mobile use on snow stability requires more investigation.
> Adjusted.

lines 428-430: also include Marty et al. (2017); Schmucki et al. (2015)
> Added references.

lines 432-440: move this paragraph to the start of the discussion
> Changed when reorganizing the discussion section.

>Recommended references added:

Fierz, C., Armstrong, R.L., Durand , Y., Etchevers, P., Greene, E., McClung, D.M., Nishimura, K., Satyawali, P.K. and Sokratov, S.A., 2009. The International Classification for Seasonal Snow on the Ground. HP-VII Technical Documents in Hydrology, 83. UNESCO-IHP, Paris, France, 90 pp.

Marty, C., Schlögl, S., Bavay, M. and Lehning, M., 2017. How much can we save? Impact of different emission scenarios on future snow cover in the Alps. The Cryosphere, 11(1): 517-529.

Schmucki, E., Marty, C., Fierz, C. and Lehning, M., 2015. Simulations of 21st century snow response to climate change in Switzerland from a set of RCMs. International Journal of Climatology, 35(11): 3262-3273.

Schweizer, J. and Jamieson, J.B., 2003. Snowpack properties for snow profile analysis. Cold Regions Science and Technology, 37(3): 233-241.

van Herwijnen, A. and Jamieson, J.B., 2007. Snowpack properties associated with fracture initiation and propagation resulting in skier-triggered dry snow slab avalanches. Cold Regions Science and Technology, 50(1-3): 13-22.

Snowmobile Impacts on Snowpack Physical and Mechanical Properties

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

Abstract

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

1. Introduction

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

There have been limited studies regarding the influence of snowmobile use on snowpack properties (Keddy et al., 1979; Thumlert et al., 2013; Thumlert and Jamieson, 2015). Studies have however, examined how the snowpack changes due to snow grooming at ski resorts (Fahay et al., 1999; Keller et al., 2004; Spandre et al., 2016a), or to traction and mobility of wheeled vehicles across a snowpack (Abele and Gow, 1990; Shoop et al., 2006; Pytka, 2010). One of the few studies on snowmobile use examined effects on very shallow snow (10 to 20 cm deep) (Keddy et al., 1979). The authors found a doubling of fresh snow density~~, little impact on the underlying old snow, but use was seen to significantly compress~~ and a compression of the natural vegetation below the snow (Keddy et al., 1979). Examining deeper snow cover~~,~~ (>20 cm deep), Thumlert et al. (2013) and Thumlert and Jamieson (2015) examined the distribution of stresses through the snowpack due to type of loading, depth and snowpack stratigraphy (Thumlert et al., 2013).

Changing snowpack conditions 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 densified snowpack and underlying soil, keeping soil temperatures colder longer (Fassnacht and Soulis, 2002; Rixen et al., 2003).

In our research, we specifically examined the effect of snowmobile use on the physical and material properties of the snowpack. The objectives were to: (1) quantify changes to physical snowpack properties due to compaction by snowmobiles; (2) evaluate these changes based on the amount of use, depth of snow when snowmobile use begins, and the snowfall environment where snowmobiles operate; and (3) create a simple model to estimate the change in snowpack density due to snowmobile use. This work examines not only changes to the basal snowpack layer, but also to the entire snowpack. ~~Since there are many snowmobile users and billions~~The positive economic impact 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,~~ and increasing winter recreation use from non-motorized ~~recreation~~ activities (such as backcountry skiers, snowshoers, and those on fat bikes) ~~have access~~dictates a need to better understand impacts to ~~portions of~~snow and underlying natural resources in multi-use areas, especially when the information may be used by managers to reduce conflict among recreationists and protect the resource.

2. Study Sites

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

Two REP experimental snow compaction study plots were located adjacent to one another within an open meadow north of Colorado Highway 40 at an elevation of approximately 3,059 m (Figure 1). The snow compaction sites were established within an area that prohibits motorized use to protect the study sites from unintended impacts of snowmobilers. Data from the Columbine snow telemetry (SNOTEL) station, located at an elevation of 2,792 m, was used to show how the 2009-2010 winter compared to other winters at REP. The SNOTEL network was established in the late 1970s across the Western United States by the Natural Resources Conservation Service to monitor snowpack properties. Initially snow water equivalent and precipitation were monitored, temperature and snow depth were added in the 1990s-2000s to aid in operational runoff volume forecasting (see <wcc.nrcs.usda.gov>).

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

Another experimental snow compaction plot was established during the same winter snow season of 2009-2010 at the Fraser Experimental Forest (FEF) near the town of Fraser, Colorado in the Rocky Mountains of Central Colorado (Figure 1). The 93 km^2 experimental forest is a research unit of the United States Forest Service (USFS) Rocky Mountain Research Station (RMRS) located within the Arapaho NF. The FEF snow compaction site was located in a small meadow at an elevation of 2,851 m surrounded by lodgepole pine (*Pinus contorta*) forest. The Fraser Experimental Forest is closed to snowmobile use, but is used to access backcountry terrain by snowshoers, skiers, and snowboarders. The Middle Fork Camp SNOTEL station, located at an elevation of 2,725 m, was used to characterize the 2009-2010 winter at FEF.

3. Methods

3.1 Experimental snow compaction plots

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

Transects were treated by driving a Skidoo brand snowmobile weighing about 300 kg including the rider (Figure 2d) at 10 km/h over the length of each transect five, 25 (FEF only) or 50 times, representing low, medium (FEF only), and high snowmobile use, respectively. Treatments began (Figure 2c) when non-compacted snow depths were approximately 30 cm (12 inches) for both locations, and when unpacked snow depths equaled approximately 120 cm (48 inches) for REP only (Figure 2a). Treatments were implemented (Figure 2e) monthly thereafter, until peak accumulation (Figure 3). Snowpack sampling was performed usually within a week after each treatment (Figures 2 and 3). At FEF, snowpack sampling was performed prior to the first treatment to illustrate range of spatial variability across the plots (first set of points in Figure 4b).

3.2 Snow pit analyses and data collection

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

Density was measured at 10 cm intervals, from the surface of the snowpack to the ground, by extracting a 250 mL or 1000 mL snow sample using a stainless~~-~~-steel wedge cutter <snowmetrics.com> and measuring the mass on an electronic scale with a resolution of 1g. ~~The~~ With the 1000 mL wedge cutter, the density of the snow (ρ_s in kg/m^3) was ~~determined by dividing the mass of the snow sample by~~read directly from the scale as the volume of the ~~wedge cutter~~cutter is 1/1000 of a cubic meter and a gram is 1/1000 of a kilogram. For the 250 mL cutter, the mass measurement results were multiplied by 4 to obtain density. Snowpack density profiles were created from a continuous profile of discrete 10 cm measurements. The bulk snowpack density was determined by averaging the depth integrated density measurements over the entire depth of the snowpack. A mean of the density measurements for the bottom 10 cm of the snowpack were used to evaluate changes near the snow and ground interface (basal layer).

Temperature measurements were obtained at 5 cm intervals from the top to the bottom of the snowpack using a dial stem thermometer with ±1°C accuracy. Temperature gradients are well represented by this instrument, and the repeatability of temperature measurements are better than ±1°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 °C/m) was calculated as the ratio of the change in temperature (ΔT in °C) with the distance (d in m) over which the change in temperature occurred. The snowpack temperature gradient was approximated as linear from an upper boundary that was 25-30 cm below the surface to the lower boundary at 0 cm. For this study, the ~~point of zero amplitude~~depth below the snow surface where temperature did not fluctuate diurnally was used as the upper boundary to remove bias from diurnal fluctuations (Pomeroy and Brun, 2001). Basal layer temperatures taken at 0 cm were used to compare temperature changes near the snow and ground interface.

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

Hardness is the penetration resistance of the snowpack (Fierz et al., 2009), and is reported as the force per unit area required to penetrate the structure of the snowpack (McClung and Schaerer, 2006). It is ~~due to~~affected by snowpack microstructure and bonding characteristics of the snow grains (Shapiro et al., 1997). Hardness measurements were taken horizontally with a force gauge in each stratigraphic layer using a Wagner Instruments Force Dial gauge (<http://wagnerinstruments.com>) with maximum force measurements of 25 N and 100 N, and fabricated circular metal plate attachments of 20 cm^2 in area. ~~The~~For each measurement, the circular metal plate was pushed into the snow and the force required to penetrate the snow was recorded. The snow hardness (h_i in N/m^2) for each stratigraphic layer was calculated as the force required to penetrate the snow (F in N) per unit area of the circular metal plate (A in m^2). All layers thicker than 5 cm were identified using the 5-cm diameter of the plate. The bulk snowpack hardness (H_B in N/m^2) was determined by weighting each stratigraphic layer hardness measurement by the stratigraphic layer thickness. The hardness associated with the bottom stratigraphic layer for each transect was used to describe hardness changes in the basal layer of the snowpack.

The standard ram penetrometer is an instrument with a cone on the end of a ~~tube~~rod onto which a hammer of ~~known~~defined weight is dropped from a ~~known~~given height and the depth of penetration is recorded; it was used here to vertically measure the resistance of snow layers to assess the change in ram resistance due to compaction (American Avalanche Association, 2016). A ram profile measurement was taken 0.5 meters from the edge of the snow pit wall subsequent to snow pit profile measurements. The mean ram resistance (S_B in N) was determined by weighting each ~~stratigraphic layer's~~ ram resistance value obtained from the standard ram penetrometer measurement with the ~~layer thickness.~~depth sampled. 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 independent samples were selected from populations having the same distribution. ~~The~~For this work, the sets of samples compared were density, temperature, hardness, and ram resistance profiles for the five different monthly measurements~~.~~ and the controls (Table 1). A statistical significance was determined for the 95% (significant) and 99% (highly significant) confidence interval ($p<0.05$, and $p<0.01$) and noted with an asterisk in Table 1.

3.4 Bulk Snowpack Density Change Model

A multi-variate non-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,~~and the number of passes~~, and time between treatment and sampling.~~ (Figure 8). The cross-correlation between variables was considered to reduce model over-fitting. The model was calibrated with the experimental data from REP and FEF, and evaluated using data from the operational sites with Walton Creek as the control, Dumont Lakes as medium use, and Muddy Creek as high use. The Nash Sutcliffe Coefficient of Efficiency (NSCE, Nash and Sutcliffe, 1970) was used to evaluate the fit of the model.

4. Results

4.1 The Measurement Winter

The 2009-2010 winter at REP had slightly ~~less than the mean~~ below average snow depth ~~as~~ compared to the 15-year ~~average from 2003-2017~~mean, based on the Columbine SNOTEL data averaged from 2003-2017 (Figure 3a). A peak SWE value of 556 mm on 9 April was ~~less than~~93% of the historical average~~ peak SWE at 93%.~~. Maximum snow depth measured at the REP snow compaction study plot was approximately 1.5 m and represents a deeper snow cover environment for Colorado. From the Middle Fork SNOTEL data, the 2009-2010 winter ~~at FEF had less~~ snow depth ~~than~~at FEF was also below the 15-year historical average (Figure 3b). The measured snow depth at the FEF snow compaction study plot never exceeded 1 m, similar to the Middle Fork Camp, and therefore was used to represent a shallower snow cover environment.

4.2 Snowpack Properties

4.2.1 Density

Snowpack properties were very similar for all ~~FEF~~ plots, both prior to treatment~~,~~ at the start of the experiment and for the untreated control plots (Figure 4). The mean density values at the FEF plots were almost the same at the end of the sampling period in April (Figure ~~4ii~~5aii). The mean snowpack density increased over the snow season (Figure ~~4a~~5a), with the exception of the FEF control and at the high use site on 12 Feb 2010 due to fresh snow deposition. At the REP snow compaction study site, ~~bulk~~mean 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~~5ia, 6ai, and ~~5aii~~6aii), 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~~5ia). Density differences are more pronounced for the basal layer (Figure ~~4bi~~5ib); for compaction treatments starting at 30 cm, the lowest layers were much more dense (Figure ~~5a~~6a). 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~~5ia and ~~4bi~~5ib). After treatment, the high use treatment snowpack was more dense (Figures ~~4a~~5ia and ~~4b~~5ib). Densities for the compaction treatments starting at 30 cm were significantly different than the control and compaction treatments beginning at 120 cm of snow (Table ~~1~~1a). The density differences between the treatments on the deep snow (120 cm) and the control were not significantly different (Table ~~1~~1a).

Density increases due to snowmobile use were much greater at Fraser (Figures ~~4aii~~5iia and ~~4bii~~5iib) than Rabbit Ears. All treatments at FEF were significantly different than the control, but the difference among treatments was not significant (Table ~~1~~1a). The density differences among treatments are highlighted in the 10-cm individual density measurements (Figure ~~5a~~6a) and in the basal layer (Figure ~~4bii~~5iib).

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~~5c) as 18, 28, and 25°C/m for the control, low use, and high use compaction treatments that began on a shallow snowpack, while they were almost the same (23, 23, and 25°C/m) for the control, low use, and high use compaction treatments that began on a deep snowpack. Temperature gradients for all treatments decreased throughout the winter season, and were isothermal at 0°C/m by mid to late April (Figures ~~4ci~~5ic and ~~4cii~~5iic), since the snow had stared to melt (Figure 3). Overall, temperature gradients were not very different (Figure ~~4c~~5c) and were not found to be significant (Table 1b).

4.2.3 Hardness

The snowpack was harder for snowmobile use starting on 30cm than the control (no use) for both sites (Figures ~~4d~~5d and ~~4e~~5e). Mean snowpack hardness did not change much over time (Figure ~~4d~~5d), except once high use treatments started (06 Feb) on a deeper snowpack. However, basal layer hardness did decline at REP for both high and low use starting on 30 cm (Figure ~~4ei~~5ie). With treatments at FEF, the hardness was always much higher than the control (Figure ~~4dii~~5iid). Hardness initially increased at the REP snow compaction study site following low and high use compaction treatments that began on 30 cm of snow (Figure ~~4di~~5id), 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~~1c). In contrast, mean snowpack hardness was not significantly impacted by snow compaction treatments that began on 120 cm of snow (Table ~~1~~1c). Mean snowpack hardness increased following the initial snow compaction treatments for low and high use, but subsequent compaction treatments did not appear to have a large effect (Table ~~1~~1c). Mean snowpack hardness for low and high use was greater than the control following the initial snow compaction treatment for both initiation depths (30 cm and 120 cm), but there were minimal differences by the last sampling date (Figure ~~4ei~~5ie).

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

There was more spatial variability in snowpack hardness (NCSE of 0.50; results not shown graphically) than differences in density (NCSE of 0.93 in Figure 4) for low and high use compaction treatments versus the control on the first two sampling dates at REP and for the control snowpits at FEF on the pre-treatment date. These larger differences are attributed both to spatial variability, but most to the low range of non-treatment hardness values from 0.4 to 5.8 kPa compared to the range of treatment hardness values from 30 to 1157 kPa (Figure 5d and 5e).

4.2.4 Ram resistance

Low and high use compaction treatments at REP caused an increase in mean snowpack ram resistance, but the difference was not significant for treatments that began on deep snow (120 cm; Table ~~1~~1d). After the initial snow compaction treatments mean snowpack ram resistance for low and high use was greater than the control for the entire study period, but by the end of the study period minimal differences were observed between treatments. Basal layer ram resistance increased as a result of low and high use compaction treatments that began on both 30 cm and 120 cm of snow. Snow compaction treatments at the FEF snow compaction study site caused a significant increase ~~(Table 1)~~ in mean snowpack ram resistance~~.~~ (Table 1d, e.g. Figure 6ciii for the February sampling dates). Basal layer ram resistance increased following the initial snow compaction treatments and continued to increase throughout the duration of the winter season.

4.2.5 Grain Size

Smaller crystals were observed for snowmobile use starting on a shallow snowpack compared to the control or starting on a deeper snowpack (Figure ~~4f~~5f). 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~~5if). 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; fragmentation was noted in the faceted crystals ~~were fragmented~~found in the basal layer of the treated plots~~ until they~~, which began rounding by the last sampling date (Figure ~~4fii~~5iif). The shallower snow at FEF enabled large faceted crystals to grow in the basal layer, up to 9 mm in size (Figure ~~4fii~~5iif).

4.3 Operational Sites

As illustrated by SWE (Figure ~~6d~~7d) and snow depth (Figure ~~6a~~7e), the amount of snow was ~~similar~~comparable for the snowpits dug at the three operational sites, ~~but not exactly the same since~~even though they were located up to 6 km apart (Figure 1). Also since these were operational sites, the amount of treatment was not controlled and was based solely on permitted snowmobile use. ~~Patterns~~ Generally, patterns of increased density (Figure ~~6a~~7a), hardness (Figure ~~6b~~7b) and ram resistance (Figure ~~6c)~~7c) seen at the REP operational sites were similar to the overall patterns seen in the previously presented experiments from REP and FEF (Figures ~~4, and~~ 5, and 6) with the non-snowmobile impacted snowpits being less dense (Figure ~~6a~~7a) and having layers that were less hard (Figure ~~6b~~7b). From visual inspection of the sites and the measurement results, Muddy Creek had the most snowmobile use and thus ~~had~~exhibited the highest density throughout the winter, and the hardest snowpack for mid-winter (Figure ~~6b~~7b), but at times the results for Dumont Lakes were similar.

4.4 Bulk Snowpack Density Change Model

~~The snowpack started~~A non-linear bulk snowpack density change model was created using data from the experiments prior to onset of melt ~~by~~conditions (Fassnacht et al., 2010); before the last sampling date (Figure 3) and prior to when 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~~5a). Additionally, treatments starting on a deep snowpack at REP were not significantly different than the control (Figure ~~4a~~5a, Table 1) ~~so these data~~and were ~~also excluded.~~not used in fitting the model. The variables of number of passes per treatment, depth, and bulk density were ~~not cross-correlated~~tested for correlation that might result in model over-fitting. Cross-correlation results were small (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~~8a). The optimal model had a NSCE of 0.~~69~~81 (Figure ~~7a~~8a), which is considered ~~reasonable (Morasi~~very good (Moriasi et al., 2007). The model ~~fit~~ was calibrated on the ~~FEF data better than the REP~~experimental data (Figure ~~7a). When~~8a) and applied to the operational sites~~,~~ (Figure 8b), with no passes occurring equivalent to a density change of 0 kg/m^3. The evaluation results were less optimal, with a NSCE of -0.79 for the four dates tested in December through March (Figure 8b). The poorer performance of the model ~~results appear reasonable (Figure 7b), with the exception of the first sampling day (11 Dec). It~~at the operational sites is ~~likely that~~ due to an unknown number of snowmobile passes at each site and from limited snowmobile use ~~was limited this~~ early in the season~~,~~ (December), resulting in minimal differences between compaction levels at that time (Figures ~~7b). The NSCE for the last 4 dates is 0.39 (Figure 7b), which can be~~7 and 8b). Removal of the December data points and using only the January through March dates 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.~~model fit to a NSCE of 0.34 (Figure 8b).

5. Discussion

5.1 Observed Changes to Snowpack Properties

Snowpack changes were observed for varying snowmobile use beginning with two different snow depths (REP only in Figure ~~4~~5 or ~~5i~~6i and ~~5ii~~6ii) and for two different snow-covered environments (Figures ~~4~~5 and 6). A total of 101 snowpits (50 at REP, 15 at the operational sites, and 36 at FEF) were dug and sampled for this work.~~5).~~ The increase in density and hardness from snowmobile use is greatest compared to an untreated snowpack in early to mid-season (January) for a deeper snowpack ~~(~~at REP~~ in Figures 4ai~~, with density increases of 7-33% and ~~4di),~~hardness 4 to 13 times greater than the control (Figures 5ia and ~~later into the snow season for the~~ 5id). For a shallower snowpack ~~(~~at FEF~~ in~~, density increased by 64-76% and hardness was 500-2000 times greater than the control (Figures ~~4aii~~5iia and ~~4dii).~~ 5iid).

Similar differences were found from ski run grooming in an Australia snowpack with a 400% increase in hardness early in the snow season but only about a 40% increase later in the winter (Fahey et al., 1999). Snow grooming increased the average density by up to 36% compared to non-groomed ski slopes (Fahey et al., 1999, Rixen et al., 2001).

~~Compaction due to snowmobile use increased densification of the snowpack which influences snow hardness (Figure 4) and ram resistance. Compaction deformed fresh snow (Figure 5), fragmented faceted grains (Figure 4fii), and reduced the growth of faceted grains (Figure 4f). In this study, snow-hardness gauges and circular metal plates of known area were used for hardness testing (McClung and Schaerer, 2006), rather than the more simplistic in situ hand hardness test (American Avalanche Association, 2016). However, the hardness of thin layers could not be measured as the circular metal plate used for measurements had a diameter of 5 cm, omitting the possible measurement of thin ice layers. Snowmobile use beginning on a shallow snowpack (30 cm) for an overall deeper snowpack (REP) resulted in a 2- and 6-fold increase in maximum snow hardness for low and high use compared to no use (Figures 4di and 4ei), whereas at a shallow snow study site (FEF), a 15-, 30- and nearly 200-fold increase in maximum snow hardness for low, medium, and high use was observed (Figures 4dii and 4eii).~~

~~The impact of snowmobile use on snowpack ram resistance has only been observed by Pruitt (2005), who stated that the ram resistance of fresh snow and layers with limited metamorphism was less than 1N and could increase by 70N due to two passes of a snowmobile. The change in ram resistance mirrored what was observed with changes in hardness (Figures 5c and 6c). The snowpack properties of a shallow snow environment can be more greatly affected by snowmobile use than those for an area that receives more snow (e.g., Figure 3b versus Figure 3a). Density differences were greatest for a shallow snow cover environment (FEF), while no~~

~~significant differences in density were observed when snowmobile use began on a deep snowpack (120 cm) (Figure 4a, Table 1). Snowpack density does vary spatial and temporally, between 40 to 200 kg/m^3 for fresh snow (Fassnacht and Soulis, 2002), but this can double with just one pass of a snowmobile on a very shallow snowpack (Keddy et al., 1979). With more accumulation, density will also increase, but high levels of snowmobile use will tend to increase the density above what is observed with non-snowmobile impacted snow (Figures 4 and 6). Densification of the snowpack at the start of testing from snowmobile impacts led to a decrease in grain size throughout the season, until rounded crystals were observed with the last observations (Figure 4f).~~

At rest, a snowmobile and its rider exert 4 to 10 kPa of pressure to the underlying snowpack. This assumes a track length from 0.9 to 1.4 m, width of 0.50 m, a snowmobile weight of 200 to 350 kg, and a rider weight of about 100 kg (data from <polarisindustries.com>). There is an increase of less than an order of magnitude due to snowmobile movement. Thumlert et al. (2013), measured stresses of about 10 to 20 kPa at a depth of 30 cm below the surface of a deep snowpack. At 20 cm below the snow surface, the induced stress from a snowmobile is already much less than 10 cm below the surface (Thumlert et al., 2013). Grooming vehicles add a force similar to snowmobiles (Pytka, 2010) based on mass and track size~~; the~~. The snowpack property changes we observed ~~herein~~ could therefore also be ~~translated to such~~representative of impacts from both types of 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).

Compaction due to snowmobile use increased density of the snowpack which influences snow hardness (Figure 5d and 5e) and ram resistance (Figure 6c). Compaction altered snow characteristics (Figures 5, 6, and 7), fragmented faceted grains (Figure 5iif), and reduced the growth of faceted grains (Figure 5f). While density measurements for fresh and/or uncompacted snow vary spatially and temporally (Figure 4) and can range from 40 to 200 kg/m^3 depending on the environment (Fassnacht and Soulis, 2002), these values can double with just one pass of a snowmobile on a very shallow snowpack (Keddy et al., 1979). The snowpack properties of a shallow snow environment can be more greatly affected by compaction from snowmobile use than those for an area that receives more snow (e.g., Figure 3b versus Figure 3a). –With more snow accumulation, density also increases, but high levels of snowmobile use will tend to increase the density above what is observed with non-snowmobile impacted snow (Figures 5, 6, and 7).

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 5a, Table 1). Snowmobile use beginning on a shallow snowpack (30 cm) for an overall deeper snowpack (REP) resulted in a 2- and 6-fold increase in maximum snow hardness for low and high use compared to no use (Figures 5id and 5ie), whereas at a shallow snow study site (FEF), a 15-, 30- and nearly 200-fold increase in maximum snow hardness for low, medium, and high use was observed (Figures 5iid and 5iie). The impact of snowmobile use on snowpack ram resistance has only previously 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 seen at

REP and FEF mirrored what was observed with changes in hardness (Figures 6b and 6c, 7b and 7c).

5.2 Limitations of the Measurements

Variability in snow conditions were observed from site to site (Figure 4) and through time, with the mean snowpack density being less in February (Figure 6) than January at FEF (Figure 5ii). 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 7; and observed in the experimental treatments- not shown graphically). 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. Future investigations could focus on specific aspects of this study, such as using a finer temporal resolution, but with fewer treatments.

Another source of variability or bias is the type of equipment used for sampling. Density and temperature were measured at 10-cm intervals using the Snowmetrics wedge cutter and dial gauge thermometers. A different sampler could be used to measure the density over each layer and other types of thermometers could be used. 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 these thin layers. Thus, bulk hardness was possibly under-estimated. 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 5id). Different equipment may resolve this issue.

5.3 Significance of the Changes to Snowpack Properties from Snowmobile Use

Snowmobile use was found to have a highly significant effect upon natural vegetation below the snow (Keddy et al., 1979), and by extension ~~through~~from snowmaking as well (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 temperatures (Fassnacht and Soulis, 2002). Deeper snowpacks were found to not have cooler soil temperatures under the snowpack (Keller et al., 2004), but melted out four weeks later than thinner snowpacks (Keller et al., 2004). Since the changes due to snowmobile traffic on a shallow snowpack were significant (Table 1), the effects of snowmobile use on the soil and vegetation underlying a shallow snowpack should be further investigated.

Snowmobile use, starting with a shallow or thin (30 cm) snowpack, resulted in a denser and harder snowpack with ~~smaller basal grains (~~a decrease in grain size throughout the season, and rounded crystals or facets observed with the last measurements (Figure ~~4~~5f). If compaction penetrates deep enough into the snowpack, it could ~~impact~~affect weak layers that cause avalanches (Saly et al., 2016), which are typically composed of soft layers consisting of large facetted grains (e.g. Schweizer and Jamieson, 2003; van Herwijnen and Jamieson, 2007). 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~~The effects of snowmobile use ~~in the backcountry to reduce~~for avalanche hazard~~.~~ reduction through changing snow stability properties requires more investigation.

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~~7; Rixen et al., 2001; Spandre et al., 2016a). However, wind is often present in open areas where snowmobiling occurs. Local terrain features and position and extent of canopy cover influence how the wind interacts with the snowpack (Pomeroy and Brun, 2001). In an Australian case study, SWE increased by 45% in groomed areas (Fahey et al., 1999); at the Rabbit Ears Pass recreational use areas, SWE also increased (Figure ~~6d~~7d) 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~~Lazar and Williams, 2008; Steiger, 2010; Dawson and Scott, 2013; Marke et al., 2015; Schmucki et al., 2015; Tercek and Rodman, 2016~~).~~ ; Marty et al., 2017). In addition~~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~~possible effects 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~~a changing climate, 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).~~2017). The effects of this variability should be included in long term motorized use land management considerations.

The significant change to snowpack properties by snowmobiles, except when treatments/use ~~was~~were 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 ~~(~~according to work done by Thumlert et al~~.,~~. (2013~~). At 20~~), but additional work could test starting depths such as 30, 60 and 90 cm ~~below~~in differing snow conditions to identify the ~~snow~~

~~surface, the induced stress is already much less than 10 cm below the surface from a~~depth when snowmobile ~~(Thumlert et al., 2013) or a grooming machine (Pytka, 2010).~~use has no significant impact. 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). Additionally, the non-linear bulk density change model developed here and applied to operational sites could be used predictively for management needs. This model may be useful in terms of estimating when to limit snowmobile use given changes in specific snow depth and density conditions.

Where the experiments for this study were undertaken, on public lands in Colorado, there are 1.1 to 1.6 million annual snowmobile visits, with an increase from 580 thousand to 690 thousand between 2010 to 2013 in northern Colorado (Routt NF and Arapaho-Roosevelt NF) and southern Wyoming (Medicine Bow NF) (US Forest Service, 2010 and 2013a) alone. The ~~an~~ annual economic impact of snowmobile use is more than $125 million to each state (Nagler et al., 2012; Colorado Off-Highway Vehicle Coalition, 2016). Snowmobile use is likely to continue to increase, and economic gains need to be balanced with potential impacts to the landscape, particularly in those times and places where snowpacks are shallow.

6. Conclusion

Snowmobiling is a multimillion dollar industry that impacts local and regional economies and public recreation lands. There have been limited studies regarding the influence of snowmobile use on snowpack properties. We examined the effect of snowmobile use on the physical and material properties of the snowpack at sites with varying snowmobile use and seasonal snow conditions. Low, medium, and high snowmobile use was simulated on experimental transects and snowpack sampling results from the treated sites were compared to the snowpack properties observed at undisturbed control sites, and at operational sites with varying levels of use. A non-linear bulk snowpack density change model was developed relating changes in bulk density to snowmobile use as a function of the number of passes, snow depth (inverse relation) and bulk density. The largest differences in snowpack properties occur with snowmobile use beginning on a shallow snowpack (30 cm) compared to no use, which increases snowpack density, hardness, and ram resistance. These increases are directly related to increasing snowmobile use (from low to medium to high). Conversely, snowmobile use that begins on a deep snowpack (120 cm) has a limited effect on the snowpack properties of density, temperature, hardness, and ram resistance as compared to an undisturbed snowpack. These results suggest that from a management standpoint, it may be desirable to limit snowmobile use in shallower snow conditions to avoid increases in density, hardness, and ram resistance that could possibly impact land resources below the snowpack.

Author contribution

The experiments were designed by J.T. Heath and S.R. Fassnacht with input from K.J. Elder. J.T. Heath performed the experiments with assistance from K.J. Elder at the Fraser site. ~~All authors contributed to the writing~~The initial manuscript was written by J.T. Heath, S.R. Fassnacht, and K.J. Elder. The final version of the manuscript~~, with~~ was written by 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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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*	

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, as are the three operational (non-experimentally manipulated) sites (Walton Creek with no use, Dumont Lakes with low to medium use, and Muddy Pass with high use based on field observations). The Columbine snow telemetry (SNOTEL) station was used to identify the amount of annual snowfall in 2009-2010 compared to the long-term average. The Fraser Experimental Forest (FEF) site is within the Arapaho-Roosevelt National Forest near the town of Fraser. The Middle Fork Camp SNOTEL site was used to represent the year's snowfall.

2. The sampling design for the snow compaction plots at a) Rabbit Ears Pass, b) Fraser Experimental Forest, and photographs of the study plots c) pre-treatment, d) during treatment, and e) after treatment. The colors used for the control and treatment plots are used in Figures ~~4~~5 through ~~7~~8.

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/).~~(http://www.wcc.nrcs.usda.gov/).

4. Spatial variability of mean (yellow) and basal (blue) snowpack density by comparison of values at the Rabbit Ears Pass (REP shown with circles) deep snow (120 cm) compaction treatments (low and high use) and the control on the first two sampling dates, and at the Fraser Experiment Forest (FEF shown with triangles) for the two sets of control snowpits on the pre-treatment sampling date (see Figures 5i and 5ii, parts a) and b), respectively).

~~4.~~5. Time series for i. Rabbit Ear Pass (REP) and ii. Fraser Experimental Forest (FEF) 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 that were fragmented. 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.

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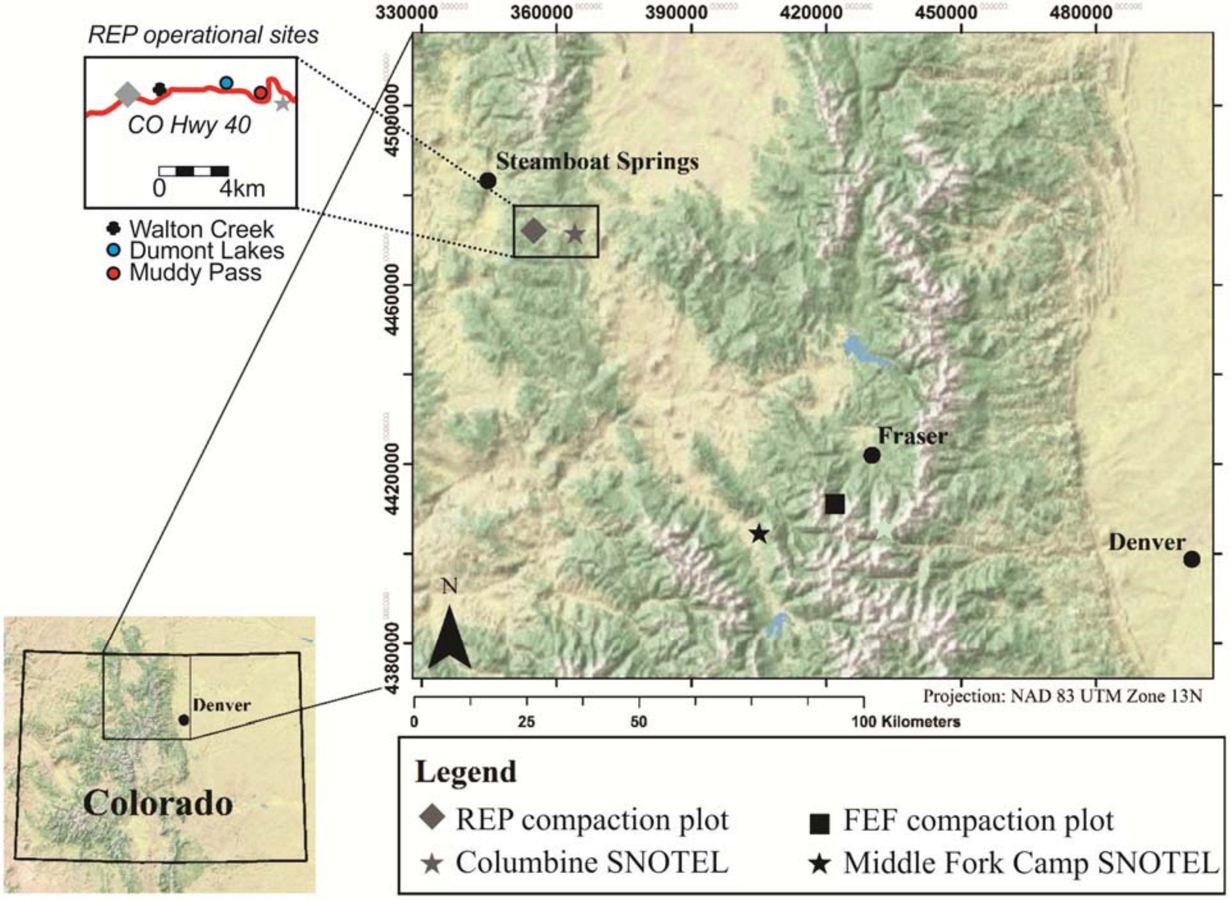
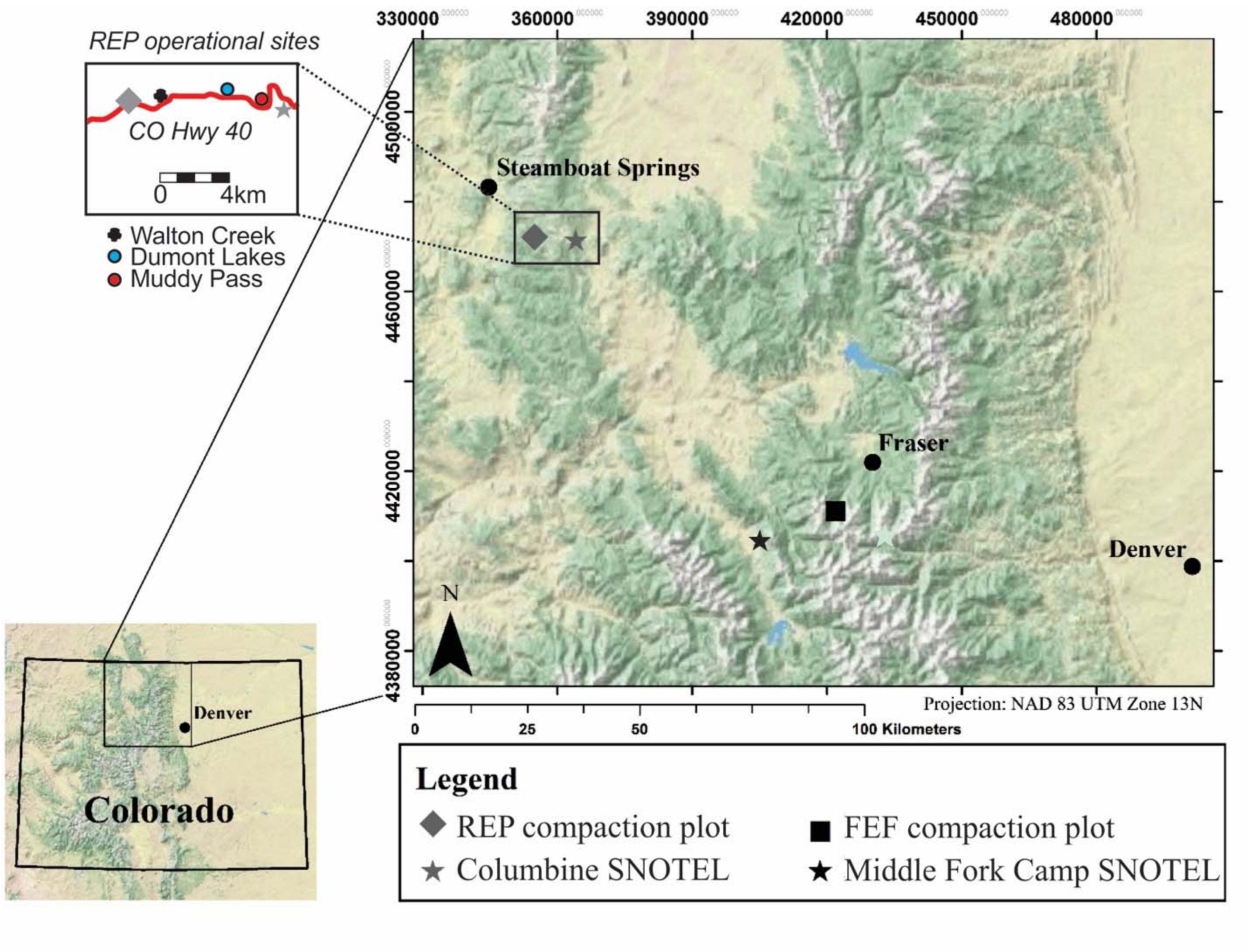
~~7.~~8. Bulk snowpack density change model for different amounts of use compared to the control of no use a) calibrated for the two experiment sites (Rabbit Ears Pass, REP and Fraser Experimental Forest, FEF), and b) applied to the operational sites (Dumont Lakes and Muddy Creek), compared to the no 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~~.~~: the four pre-melt dates (December through March- 4 dates) and the later three pre-melt dates (January through March- JFM).


REP operational sites
CO Hwy 40
0
4km
Walton Creek
Dumont Lakes
Muddy Pass
330000
360000
390000
420000
450000
480000
4500000
4460000
4420000
4380000
Steamboat Springs
Fraser
Denver
N
Colorado
Denver
Projection: NAD 83 UTM Zone 13N
0
25
50
100 Kilometers
Legend
REP compaction plot
Columbine SNOTEL
FEF compaction plot
Middle Fork Camp SNOTEL



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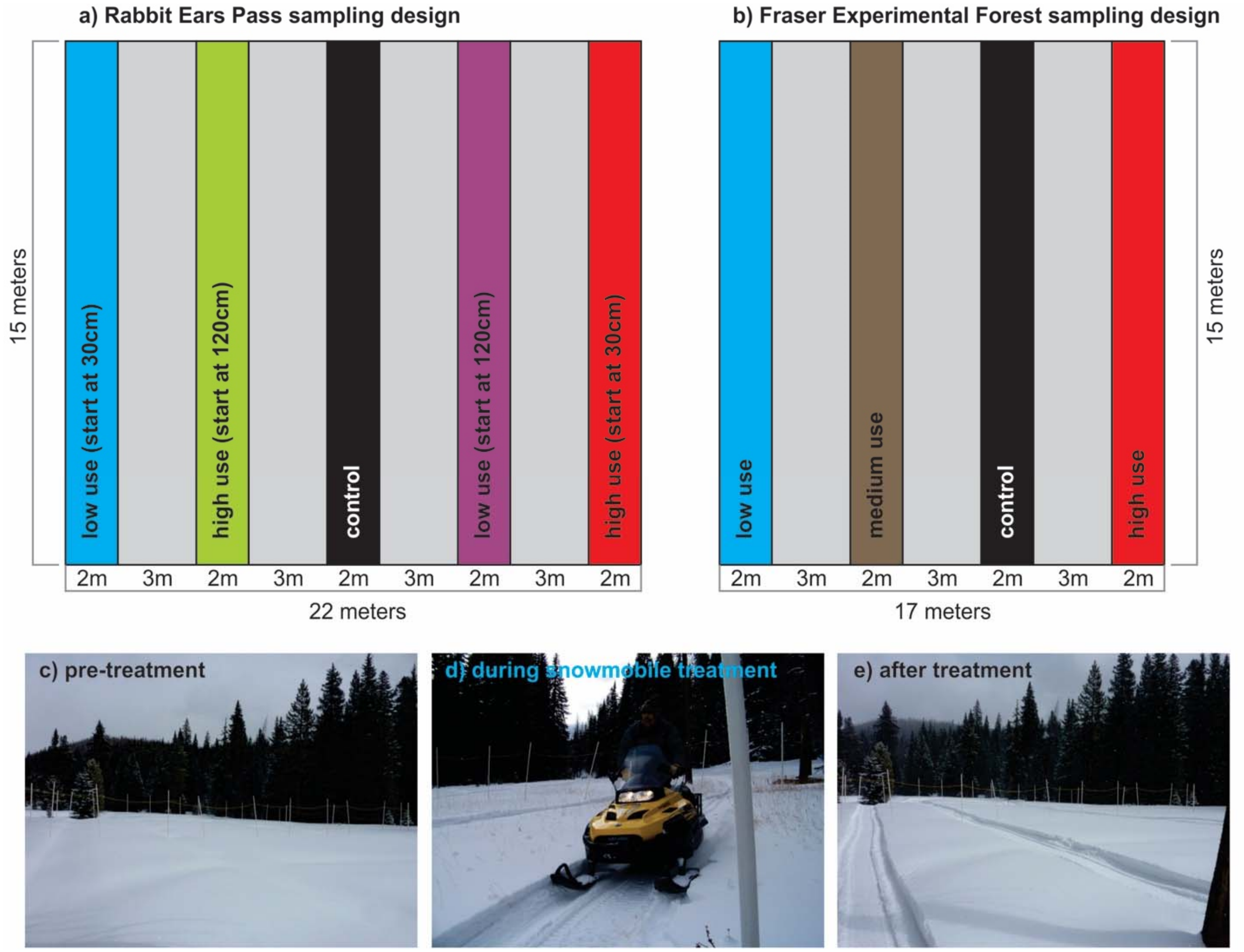
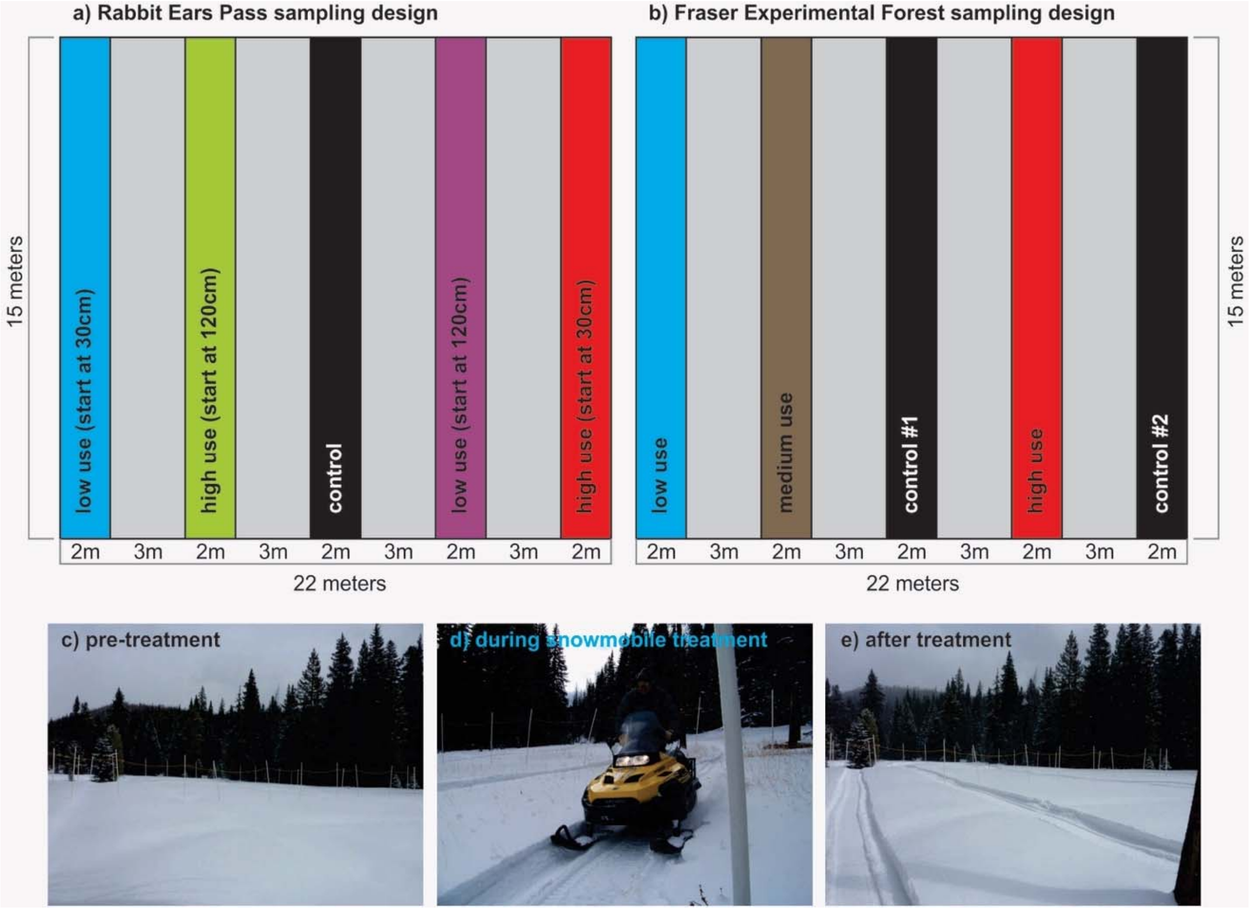

a) Rabbit Ears Pass sampling design
15 meters
low use (start at 30cm)
high use (start at 120cm)
control
low use (start at 120cm)
high use (start at 30cm)
2m
3m
2m
3m
2m
3m
2m
3m
2m
22 meters
b) Fraser Experimental Forest sampling design
low use
medium use
control
high use
15 meters
2m
3m
2m
3m
2m
3m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



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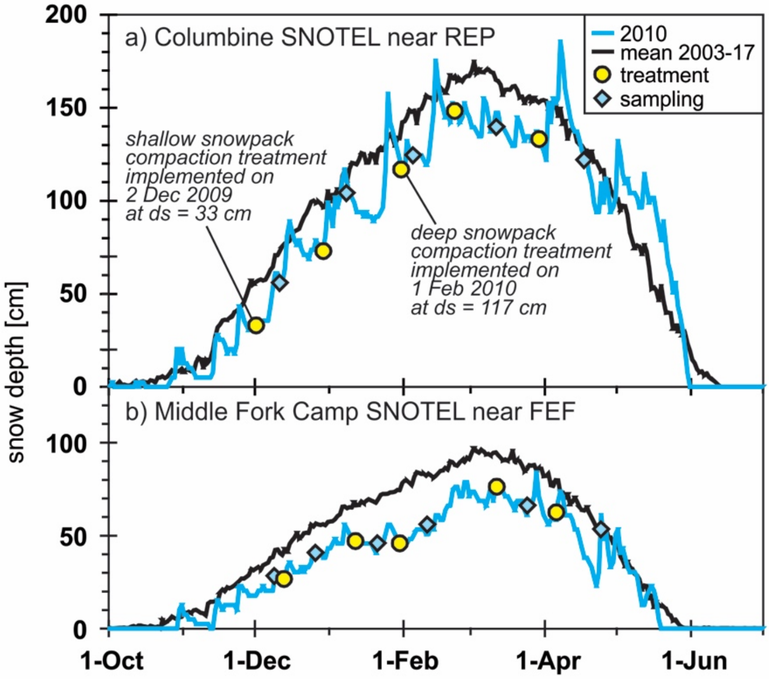
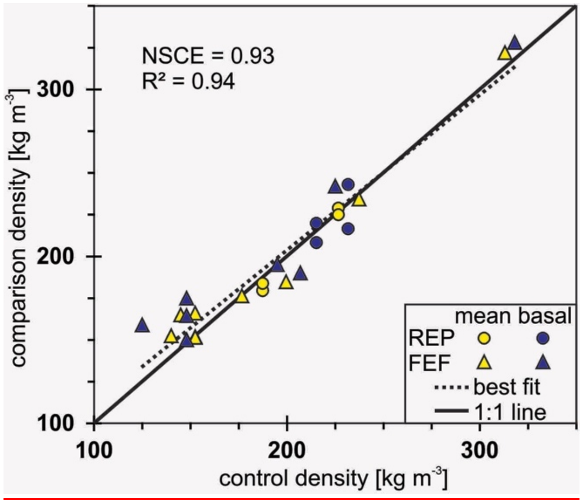
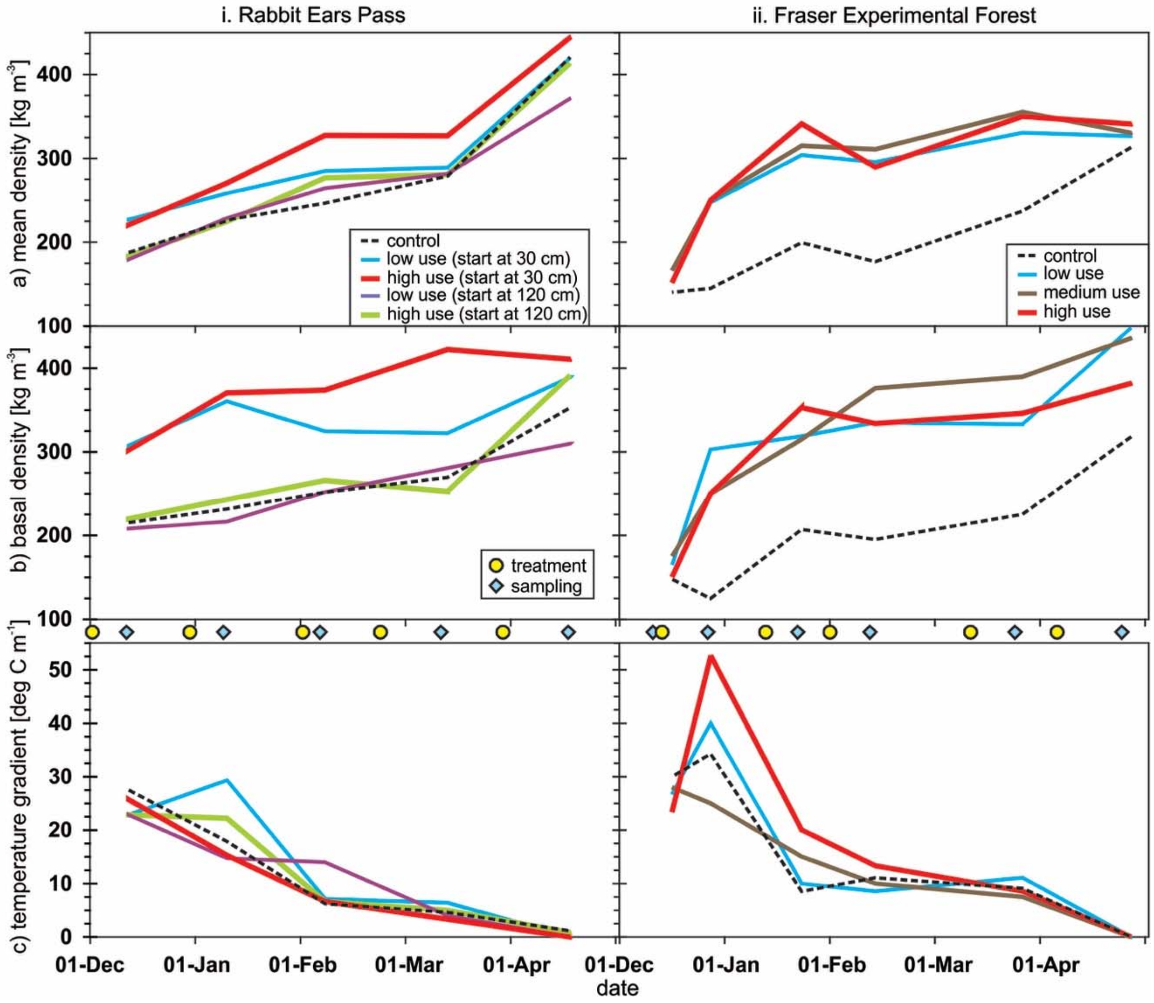
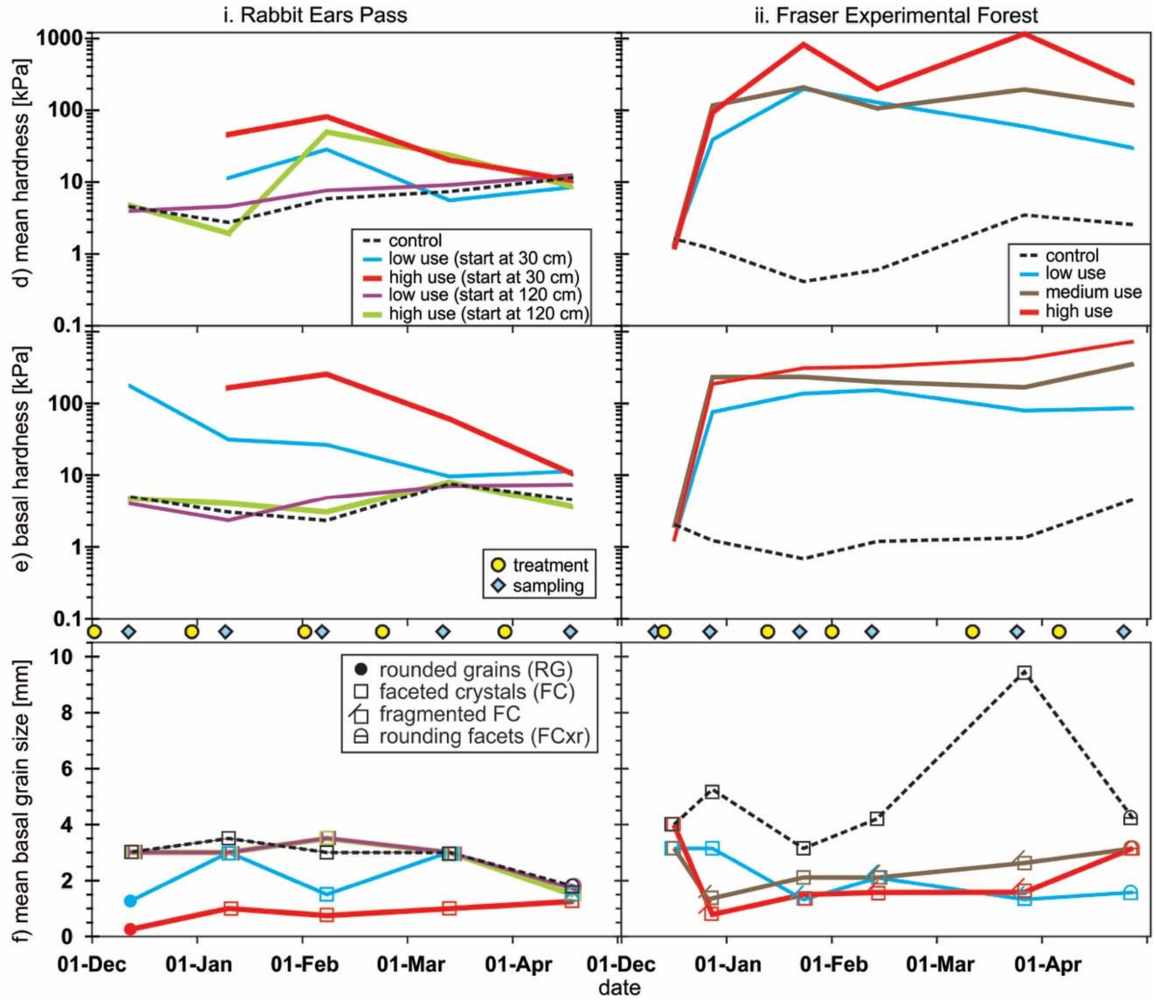


Figure 3. Mean snow depth from 2003-2017, and for the 2010 water year (WY2010) measured at a) the Columbine SNOTEL site near Rabbit Ears Pass (REP), Colorado and b) the Middle Fork Camp SNOTEL near Fraser Experimental Forest (FEF), Colorado, illustrating the dates of treatment and dates of sampling.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


NSCE = 0.93
R² = 0.94
comparison density [kg m-3]
control density [kg m-3]
100
200
300
100
200
300
mean basal
REP
FEF
best fit
1:1 line


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
100
200
300
400
0
10
20
30
40
50
01-Dec
01-Jan
01-Feb
01-Mar
01-Apr
01-Dec
01-Jan
01-Feb
01-Mar
01-Apr
date



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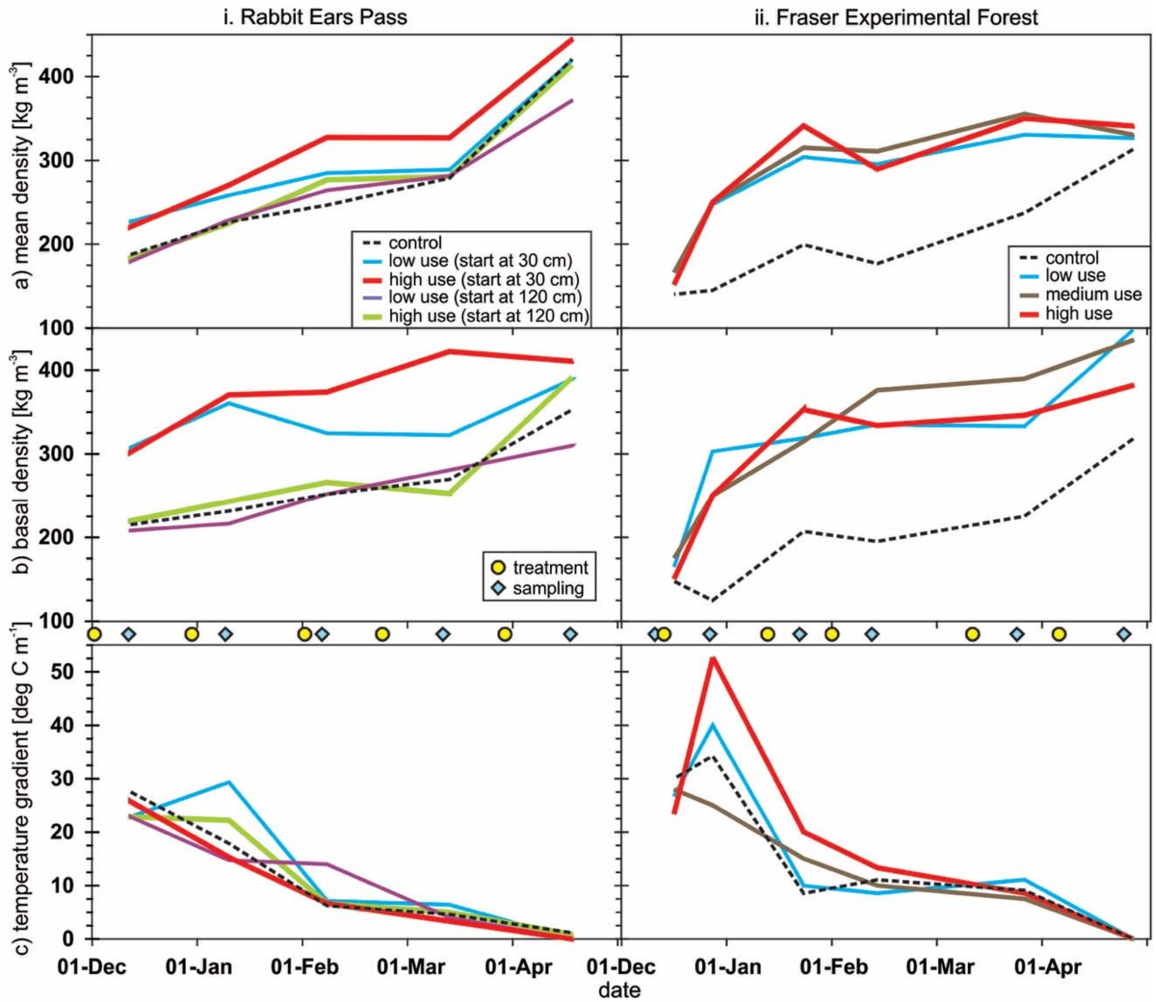
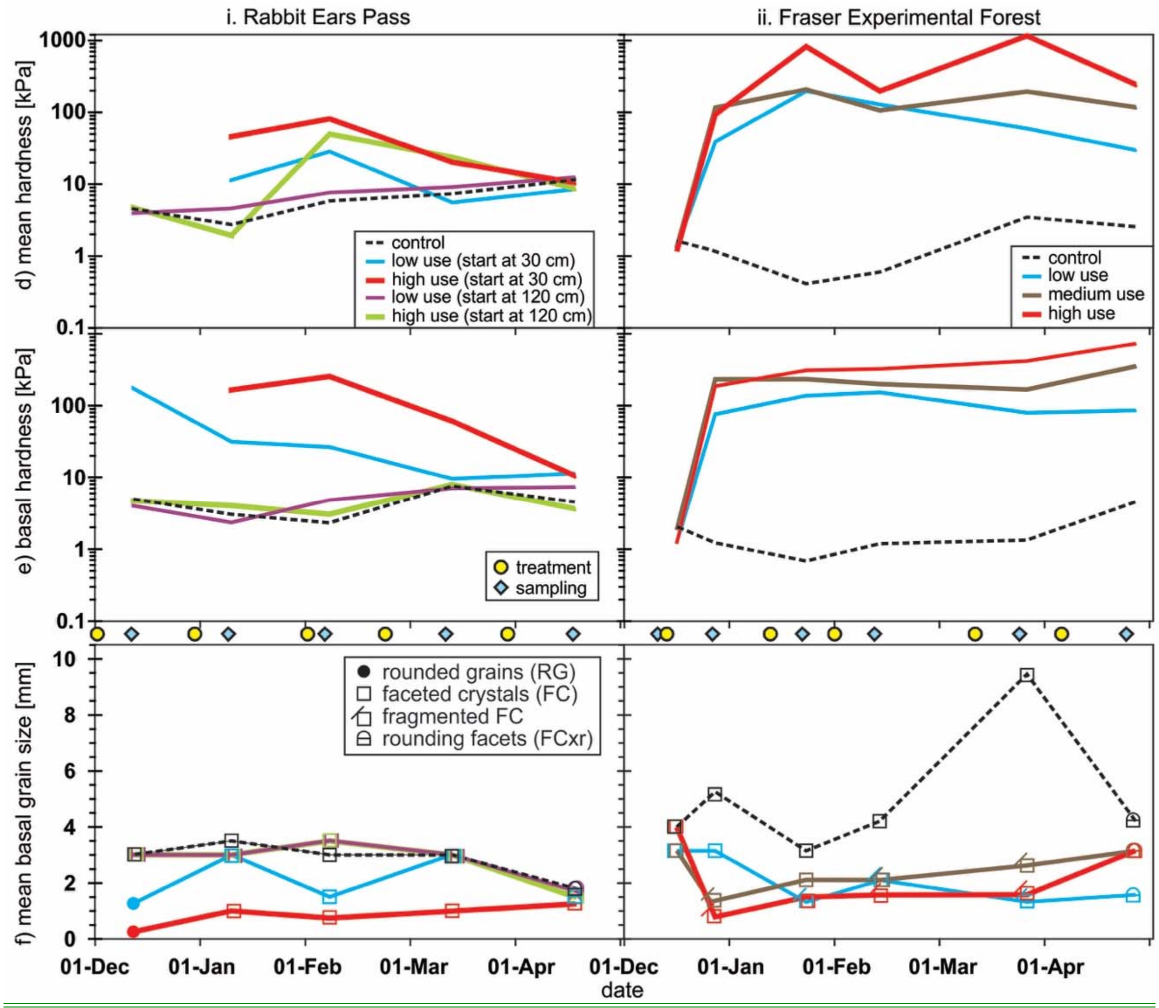

i. Rabbit Ears Pass
ii. Fraser Experimental Forest
a) mean density [kg m^{-3}]
b) basal density [kg m^{-3}]
c) temperature gradient [deg C m^{-1}]
100
200
300
400
0
10
20
30
40
50
control
low use (start at 30 cm)
high use (start at 30 cm)
low use (start at 120 cm)
high use (start at 120 cm)
control
low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



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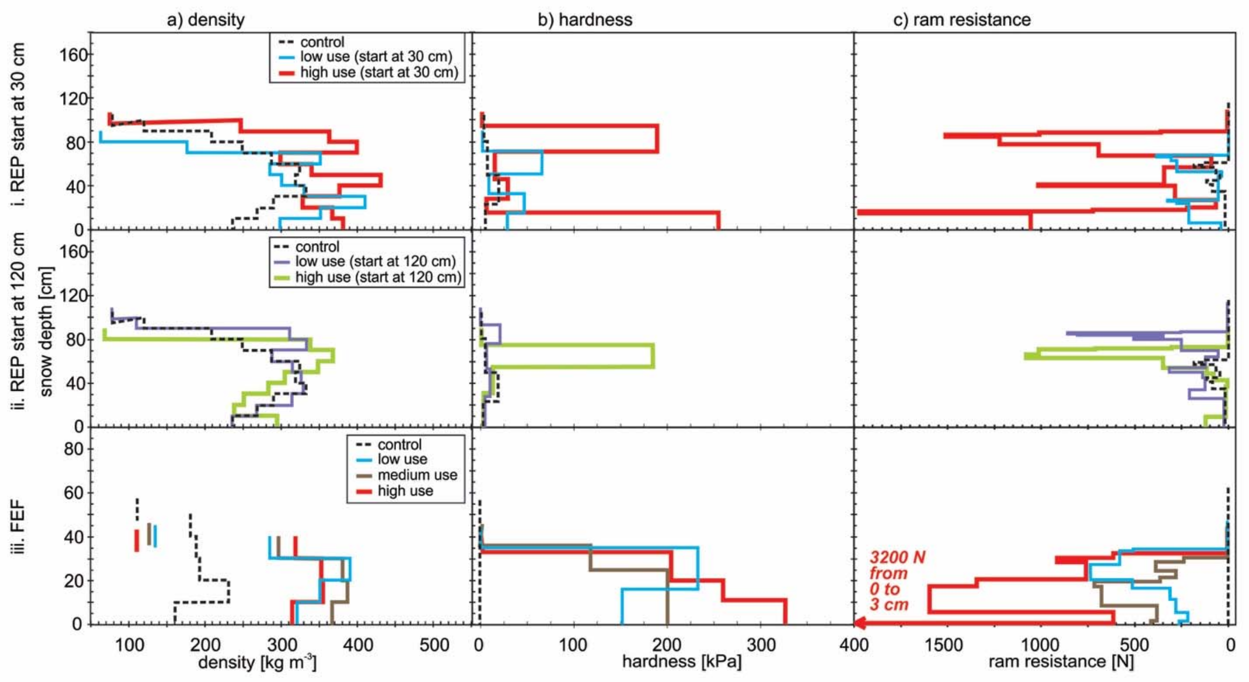

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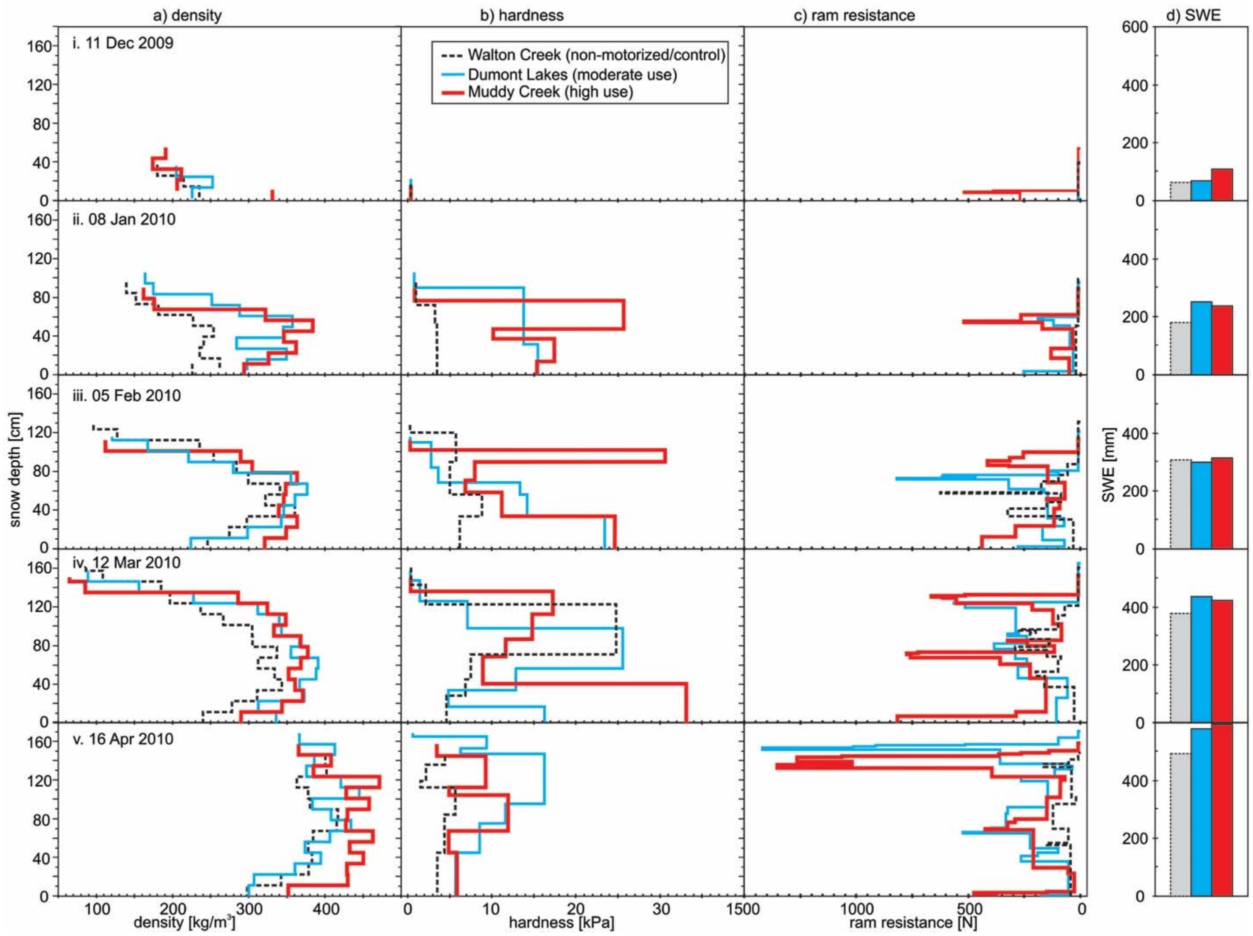
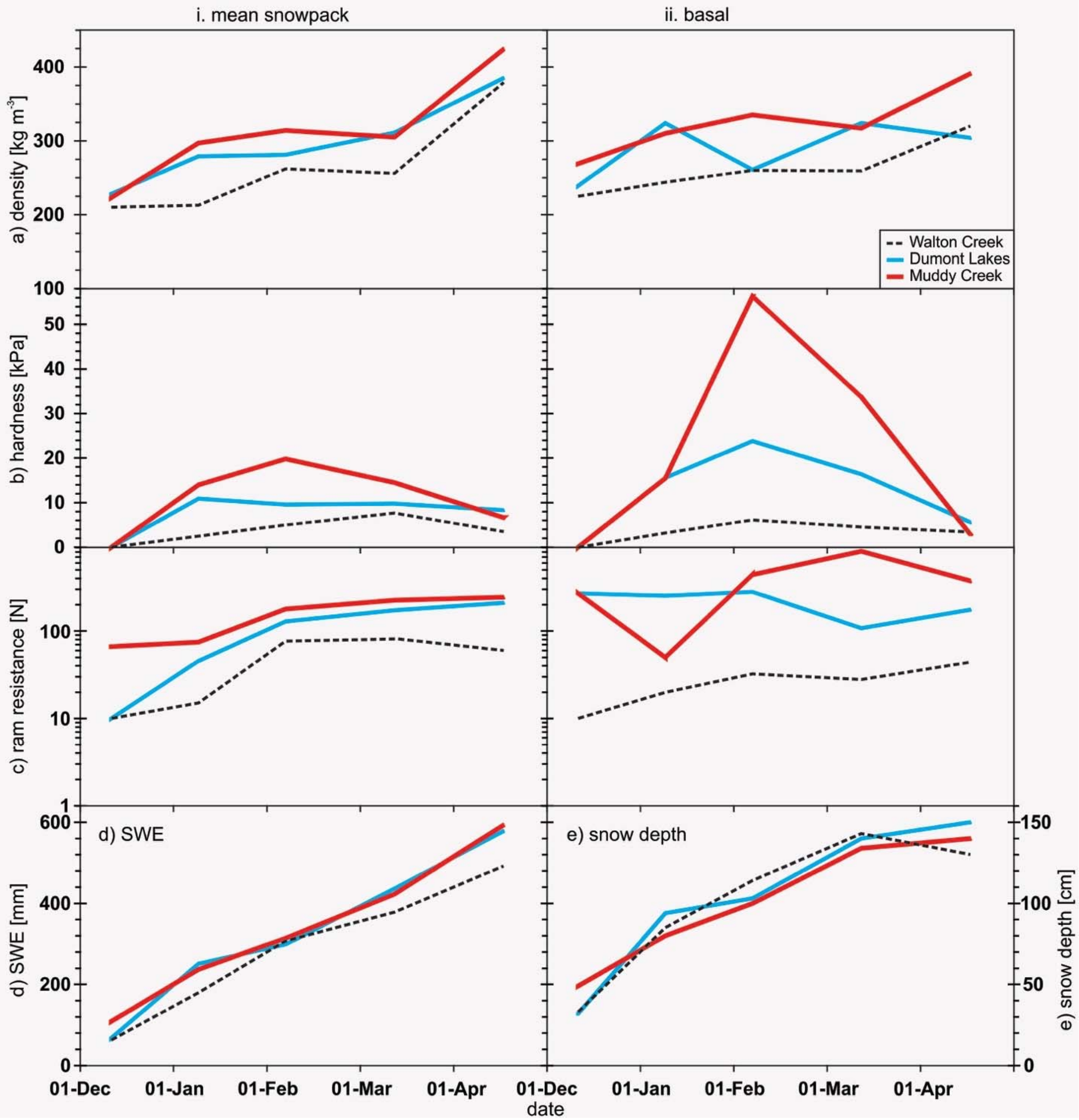

a) density
b) hardness
c) ram resistance
d) SWE
i. 11 Dec 2009
ii. 08 Jan 2010
iii. 05 Feb 2010
iv. 12 Mar 2010
v. 16 Apr 2010
Walton Creek (non-motorized/control)
Dumont Lakes (moderate use)
Muddy Creek (high use)
snow depth [cm]
0
40
80
120
160
density [kg/m³]
100
200
300
400
hardness [kPa]
0
10
20
30
ram resistance [N]
1500
1000
500
0
SWE [mm]
0
200
400
600



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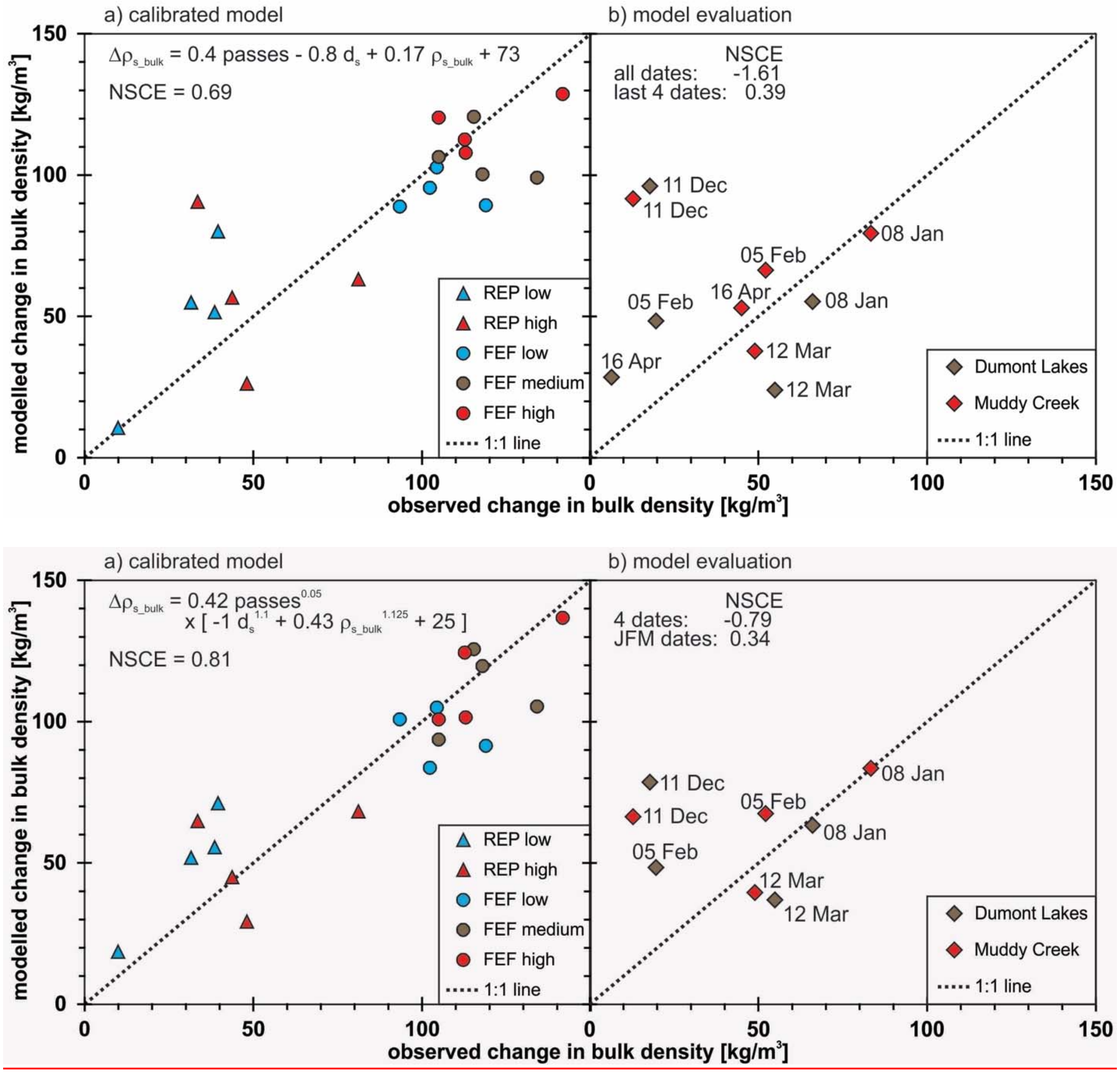

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