*We want to thank the reviewers for good insight to help clarify many of the points that we were trying to make in this paper. We have changed the SWE time series to a more appropriate depth times series (as more data are now available), added a schematic of the control and treatment plots, and added a plot summarizing the data as a time series. The Introduction and Conclusions, as well as part of the Discussion have been rewritten to clarify the text. Below is how the reviewer comments were addressed.*

## REVIEWER 1

> The paper describes snow cover measurements to quantify the impact of snow mobile travel. Specifically, differences in density, hardness and temperature between an undisturbed snow cover and a snow cover subjected to various degrees of snowmobile usage are presented. The authors describe partly novel and thorough field experiments which were used to investigate these changes in detail. However, the results remain very qualitative and not very new.

*We disagree that the Results are qualitative – See Figures 4 through 9, and Tables 1 and 2. We also disagree that the Results are not new. As Review 2 states, there is only one similar paper in the literature (Thumlert and Jamieson, 2015).*

> Furthermore, since the goal of the study is not clearly defined in the introduction and the presentation and discussion of the results is rather poor, major revisions are required before the paper can be accepted for publication.

*We disagree. At the end of the Introduction, we clearly state the purpose and then the objectives of the paper: "We examined the effect of snowmobile use on the physical and material properties of the snowpack. The objectives of this research were: (1) quantify changes to physical snowpack properties due to compaction by snowmobiles; and (2) evaluate these changes based on the amount of use, depth of snow when snowmobile use begins, and the snowfall environment where snowmobiles operate."*

>Overall, there are three main issues with the paper:
1. After reading the introduction it does not become clear why this study is needed and why changes in snow properties due to snow mobile usage should be quantified. Indeed, the first paragraph deals with the economic importance of snowmobiling. It is completely unclear how this is at all relevant to the measurements presented in this paper. The second paragraph then lists several studies before stating the goals of this study. As such, there is no clear context, no knowledge gap is identified and it remains unclear why the authors performed these measurements.

*The first paragraph has been rewritten to be more succinct and use the economic and user data to set the stage for the work. Some of the specific details have been moved to an appendix. The second paragraph has also been rewritten to set the context and clearly state that no other papers have examined how snowmobiles influence the physical and material properties of the snowpack.*

>2. The presentation of the results is rather poor and the broader relevance remains unclear. In the results section the authors show vertical density, temperature, hardness and ramm hardness

profiles for all sampling dates. However, they mainly discuss mean (bulk) properties or the properties of the basal layer. As such, it would be better to show plots of the temporal evolution of the mean properties (e.g. mean density with time for the control, low use and high use) and the basal layer properties.

*We have added a set of figures summarizing the temporal evolution of the mean properties.*

>Furthermore, the authors essentially list the results and the writing is very dry. I would suggest that the authors use the figures and tables more actively in their writing and focus on the main results.
*Many parts of the text have been rewritten.*

>Finally, a more in-depth analysis is required to gain new insights into the effects of snow mobile travel on changes in snow cover properties and make the results more broadly relevant. Specifically, the authors could develop a simple model (e.g. linear regression) to predict snow densification after snow mobile usage.

*While this is an interesting idea, we feel that this would yield a qualitative model. As this is an interactive discussion, I am eager to hear what this could be.*

> and they should investigate how snow layering affects densification.
*This is beyond the scope of the paper.*

>3. The discussion and conclusion sections need to be rewritten. The lack of a clear objective in the introduction translates to a very scattered discussion. Vague and out of context statements are made which do not really relate to the work presented in this paper. For instance, the third paragraph of the discussion deals with snow metamorphism. Some very general statement on the influence of ground and air temperature are made and then related to very specific increases in density observed in the measurements (lines 332 to 334). The line of thought is very hard to follow. Similarly, there are vague statements about the transferability of the results to snow grooming (lines 306-316), minimum snow depth for skiing (lines 405-409) and snow making (lines 426-433) which seem completely out of context. The authors need to do a much better job at putting their results into context, discuss the limitations of their findings and highlight new insights.

*The vague statements have been removed or significantly rewritten, as per the specific comments. With changes to the Introduction, we feel the paper is put better into context.*

Specific comments:
>line 33: It is unclear to me why climate change will affect the amount of land available for snowmobiling.
*We think that this is self-evident.*

> line 36-39: How can there be old snow below a shallow snow cover? This sentence is very unclear and should be rewritten.
*We don't understand why this sentence is confusing. However, this sentence has been rewritten.*

> line 55: remove imperial units here and throughout the paper
*Removed here and through, except imperial units are left in the section that discusses the initiation of snowmobile use (12” and 48”) as those are the standard in the U.S.*

>line 58-61: it is not clear to me why this section on conflicts among different user groups is relevant to the paper.
*This is setting the context for the study site. A sentence has been added to clarify this.*

>line 67: The authors should describe what a SNOTEL station is and what they measure.
*A sentence and weblink have been added.*

>line 68: “: : : was used to characterize the 2009-2010 winter on REP”. Characterize is not very specific.
*This sentence has been changed. The point is to show “how the 2009-2010 winter compared to other winters.”*

>line 69: it is unclear what is meant by operational sites. This only became clear after reading the results.
*These are “not experimentally controlled.” This has been added to the sentence.*

>line 92-100: a sketch of the experimental setup would make this description more easy to follow.
*A figure has been added.*

>line 107: remove “and continued through the duration of the winter season”.
*Removed.*

>line 110-113: rewrite to “Vertical snow profiles were observed to record snowpack properties including snow density, temperature, stratigraphy hardness and ramm resistance.”
*We use the word “ram”, rather than “ramm” throughout. This sentence has been rewritten as two sentences.*

>line 118: mL should be ml
*Either of these version are SI, so mL is maintained.*

>line 118: mention the thickness of the density cutters
*I am not sure what the reviewer is asking for here. We measured snow density as a continuous profile of discrete 10cm measurements.*

>line 119-121: remove the sentences “The density of snow : : :. and bulk snowpack density were compared.”
*The later part of this sentence was removed and the former part was rewritten.*

>line 123-125: Unclear how a mean over 10 cm can be taken if the measurements are done every 10 cm.

*Yes, see line 118 above.*

>line 127-129: “However, repeatability for any : : :” it is unclear what the authors want to say here.
*This sentence was rewritten.*

>line 131: unclear what is meant by “point of zero”. Do you mean the minimum temperature?
*This is rewritten as “the snowpack depth where the temperature gradient was linear”*

>line 141-142: remove sentence “The main crystal forms: : :.”
*This sentence has been rewritten.*

>line 148: mention the area of the metal plate attachment.
*Added.*

>line 156-160: ramm and not ram.
*We disagree. To be consistent we used “ram” throughout.*

>Also, better describe how ramm measurements are made. Right now it is not clear that this is a cone penetration test. Provide a reference, e.g. Gubler (1975).
*Text has been added based on the following citation:*
*American Avalanche Association: Snow, Weather and Avalanches: Observation Guidelines for Avalanche Programs in the United States (3rd ed.). Victor, ID, 104pp, 2016.*

>line 162-163: “bottom stratigraphic layer” is not defined. Do you mean basal layer as defined I layer 125? If so, consistently use basal layer.
*Not necessarily. The bottom layer can be greater than the basal layer, which we define as the bottom 10 cm from the density and temperature measurements.*

>line 171: typo “sets samples of samples”
*changed.*

>line 173-174: clearly state what you define as significant and highly significant.
*Added.*

>line 177-185: The definition of a deep and shallow snowpack seems rather arbitrary since the difference in snow depth is not very large. Furthermore, I would not qualify a snow cover of 150 cm as deep.
*We have changed Figure 2 to a plot of snow depth and chosen a different SNOTEL station that is more representative of the snowpack conditions at FEF. In Colorado a snowpack deeper than 1.5 meters is considered a deeper snowpack, and this was the assumption used in this paper. We changed the text accordingly.*

>line 223 changes in temperature gradient
*changed*

>line 228-229: remove “favoring sintering and bonding of snow crystals” as it is not relevant here.
*Removed.*

>line 229-231: rewrite this sentence
*deleted*

>line 245: unclear what is meant by “the deeper snowack”
*This is when use starts on a deep snowpack.*

>line 266: unclear what “These” refers to.
*Changed to “hardness.”*

>line 267-268: unclear what is meant by “treated transects were approaching control values by the last sampling date” since the colored hardness profiles in bottom of figure 5c were not close to the control profile.
*By 17 April, hardness values were similar.*

>line 269: change “orders” to “one to two orders”.
*Changed*

>line 309-311: rewrite to clarify
*rewritten*

>line 312: change to “on the underlying snowpack”
*changed*

>line 322: change “also gets more dense” to “increases in density”
*changed*

>line 325: this statement does not fit well with the temperature measurements shown in Figure 4. In particular the measurements in Figure 4b show a temperature of -4 at the base of the snow cover. It is not clear what the authors want to discuss here and this entire paragraph seems out of place.
*Much of this paragraph has been deleted as it is not necessary.*

>line 330-331: not clear what the authors mean by “easily sinter”. Rounded grain do not sinter more readily than facetted grains, as was shown in van Herwijnen and Miller (2013).
*This has been deleted as it is not necessary.*

>line 331-332: “Rounding increases density and snowpack strength” it is not clear what the point of this statement is.
*This has been deleted as it is not necessary.*

>line 340: typo “snowthrough”
*changed*

>line 360: this is speculation since the authors did not make any observations of grain arrangements.
*This has been deleted*

>line 362: not clear what is meant by “avalanche evaluation”
*This is meant to imply a simpler method. The text has been changed.*

>line 370: how can the precision of the ramm penetrometer be determined??
*This is based on measurements and calculated forces.*

>line 371: not clear what the authors mean by “undisturbed snowpack” since the ramm penetrometer is widely used to characterize the hardness of undisturbed snowpacks throughout the world.
*This sentence has been rewritten.*

>line 382-383: unclear how the reference to de Quervain is relevant here.
*This has been removed.*

>line 384-387: remove this since the explanation in terms of edge effect and heat transfer from the buffer areas is very speculative and not convincing.
*This sentence was deleted.*

>line 396: “temperature gradients and thus vapour pressure gradients were less” unclear what this statement is based on since there was no significant difference in temperature gradients and vapour pressure gradients were not measured.
*We can infer vapour pressure gradients from temperature gradients. While there is no significant difference, they were still less and a difference hoar crystal size was seen.*

>line 397-399: this sentence is contradictory, is it similar or different?
*This sentence was reworded.*

>line 405-409: unclear how these minimum snow depth guidelines fit in the discussion here.
*The last sentence has been changed. This is an implication of the findings of this work.*

>line 414-415: cooler snowpack at the end of the summer?
*This is deleted.*

>line 418: snow depth was not less for the disturbed sites in Figure 3!
*This has been reworded.*

>line 431: typo “create surface different conditions”
*This has been rewritten.*

>line 432-433: It is unclear how to consider artificial snow with the present results.
*This paragraph has been deleted.*

>line 442-444: I do not understand how the results presented in this paper can help when modelling the impact of snow grooming or snow making.
*This paragraph has been deleted, and replaced with one sentence mentioning snowmaking, as there could be cross-over implication. This is not explored herein.*

>line 448-449: the authors did not show that the amount of snowfall influenced their results!
*The point is the difference between the two sites. The sentence has been reworded.*

>line 453-454: this statement is incorrect since there were no significant differences between low and high snow mobile usage.
*This is compared to no use, as shown in Table 1.*

>Figure 1: improve the caption and describe what is shown in the figure.
*More detail is provided.*

>Figure 2: It would be better to show snow depth rather than SWE to be consistent with the other figures. Also, there is no need to show data from July to September. Finally, please show the first of each month on the x axis.
*This figure has been changed.*

>Figure 3: it would be better to show the mean snow density with time. Also, the snow depth is sometimes larger for the disturbed sites than for the undisturbed site, which seems counterintuitive.
*A plot has been added.*

>Figure 4: why are there vertical jumps in the temperature profiles?
*This is not known.*

>Also, it would be better to show the mean temperature gradient with time.
*A plot has been added.*

>Figure 5: The results shown in this figure are odd. It is not clear to me how and why the hardness of certain layers would decrease in the second half of the season. This is also not in line with the density measurements which show an overall increase over the course of the season. And again, it would be better to show mean hardness with time.
*A plot has been added.*

>Figure 6: better to use a logarithmic x axis. Also, show mean ramm hardness with time.
*Our intention is show the differences at multiple scales. Some of this may be lost using a logarithmic axis.*

Gubler, H., 1975. On the rammsonde hardness equation. IAHS Publication, 114: 110-121.
van Herwijnen, A. and Miller, D.A., 2013. Experimental and numerical investigation of the sintering rate of snow. Journal of Glaciology, 59(214): 269-274.

**REVIEWER 2 (Edward Bair)**

This is a field-based study on the impacts of snowmobiles on the snowpack in several areas in Colorado USA. I’ve carefully read the manuscript as well as the first referees comments, which I mostly agree with. My overall is assessment is that the study may be publishable after revision based on corrections that I’ve included in an annotated PDF. As the authors discuss, snowmobile use in the US is sizable yet there are very few studies on how snowmobiles affect the snowpack. In fact, I also reviewed one of the only two studies cited in the manuscript [Thumlert and Jamieson, 2015] where the impacts of snowmobiles were quantitatively measured on a backcountry snowpack. Thus, there is a significant gap in the research, but the authors do not present convincing evidence that this gap is worth addressing. The authors need to motivate the study.

*>>The introduction has been rewritten to highlight the lack of research in this area, as well as the number of recreational users that this could impact.*

Why study changes in stratigraphy related to snowmobiles? Who will this research benefit?

*>>This work will benefit managers who need to make decisions about multi-use areas that are used by snowmobilers. As there has been limited related work, this also provides more quantitative information on how snowmobile use changes the snowpack. The text has been changed accordingly.*

The main conclusion that I came away with from this study is that regular snowmobile use, starting with a thin (30 cm) snowpack, results in a denser and harder snowpack with smaller basal grains. That conclusion is unsurprising, in that it could likely be predicted based on a basic understanding of snow mechanics, but given the lack of study on snowmobile effects, I still suggest the results are worth publishing. However, I worry that a reader might be tempted to conclude 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 true for isolated small areas, I cannot see backcountry snowmobile use reducing avalanche hazard, as the tracks will never carpet a slope densely enough. The authors should consider addressing this problematic conclusion that readers may come away with.

*>>This is an interesting comment. This has been added to the discussion.*

Sahn, K. (2010), 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.

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

Specific comments on the manuscript:

Line 25: These numbers have been removed in the rewrite

Line 27 (two comments): these are locations, and this has been removed

Line 30: I do not think that the specific numbers are relevant here

Line 35: “"of". Lots of careless errors here. Was this proof read?” *“of” was added. Much of this*

*text has been rewritten as per Reviewer 1.*
Line 48: “Why are these objectives important? What's the motivation? “ *The text has been rewritten, and a sentence has been added at the end of the Introduction to highlight the relevance of this work*
Line 77: “can you provide some numbers here? Medium and high relative to where? “ *These are based on observations by the authors, and USFS staff who helped with the fieldwork. A personal communication has been added.*
Line 101: “type of snowmobile; weight of snowmobile; and speed of snowmobile” *the following was added “driving a Skidoo brand snowmobile weighing about 300 kg with the rider (Figure 2d) at 10 km/h”*
Line 113: “You should note that your depth measurements are measured from the ground going up” *this is added, although it is the standard to measure snow depth from the ground up and thus assumed.*
Line 140: “maximum diameter I am assuming?” *The word “mean” has been added*
Line 143: “No, hardness is penetration resistance (Fierz et al. 2009, p 6). It usually measured in Newtons, which is g m s^-2. You should say something like "...in this study hardness is reported as force per unit area..."” *This has been changed/added*
Line 188: “I'd like to see the bulk density over time plotted or in a Table” *A figure has been added*
Line 243: “As with the bulk density, it would show your findings better if there were a plot of mean hardness over time or a table.” *A figure has been added*
Line 248: “These are interesting findings, especially for snow stability” *No change*
Line 310: “fix” *this sentence has been deleted*
Line 317: “constantly?” *this sentence has been deleted*
Line 323: “I don't like this description. Meteorology doesn't drive snowpack metamorphism from the surface down. It's the movement of water vapor through the snowpack that drives metamorphism. For instance, for basal depth hoar formation, the vapor flux is from the ground towards the snow surface.” *this sentence has been deleted*
Line 383: “so what? Observations of > 100 deg C m^-1 are not uncommon for a thin snowpack” *the citation and comment have been deleted.*
Line 383: “isothermal” *“al” has been added*
Line 392: “This belongs in the results” *this has been moved*
Line 437: “I am not convinced there's evidence from this study that snowmobile use increases SWE. In Section 4.5, you said the SWE was similar across all 3 sites.” *What was mean was the mass of the snowmobile, not SWE. This sentence has been removed.*
Line 469: “experiments” *an “s’ was added*
Figure 2: “perhaps, "8-Jun" ? The spacing on this axis is poorly chosen. 1st of the month for each month would be easier to follow or bimonthly” *This figure has been replaced.*
Figure 3: “Clarify in the caption whether depth is measured from the ground or the snow surface. It appears to be measured from the ground going up.” *The sentence “the ground is at zero snow depth” has been added to the caption.*

# **Snowmobile Impacts on the Physical and Mechanical Properties ~~Snowpacks in Colorado, U.S.A.~~**

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

## Abstract

~~Physical~~We ran a snowmobile over a series of test plot to examine the physical and material properties of the snowpack~~, including~~ due to compaction from a snowmobile. We measured the snow density, temperature, stratigraphy, hardness, and ram resistance ~~were measured~~ from snow pit profiles ~~to examine the statistical difference between no use and varying degrees of snowmobile use (low, medium and high). The properties were examined across the entire snowpack, from the surface to its base, and for the basal layer of the snowpack. Experimental snow compaction study plots were located near~~. Experiments were performed at two different experimental areas, specifically Rabbit Ears Pass near Steamboat Springs~~, Colorado~~ and at Fraser Experimental Forest near Fraser, Colorado~~.~~ USA. We examined the difference between no use and varying degrees of snowmobile use (low, medium and high) for different starts of snowmobile use, specifically on a shallow (the operational standard of 30 cm) and deeper snowpack (120 cm). Significant changes in snowpack properties ~~are associated with~~were measured due to snowmobile use beginning ~~early in the~~on a shallow snowpack. These snowpack property changes were more pronounced where there was less snow accumulation ~~season when the snowpack is shallow, as well as earlier in the winter and at the base of the snowpack. These effects were amplified when snowmobile use occurred on a shallow snow covered environment and with increasing degrees of snowmobile use. On the contrary, snowmobile use that began on a deeper snowpack showed no significant changes in snowpack properties suggesting later initiation of use minimizes impacts to snowpack properties from~~. When snowmobile use~~.~~ started on a deeper snow, in particular at 120cm, there was less difference compared to the control case of no snowmobile use.

## 1. Introduction

~~Winter recreation on snow is big business; in~~In the United States, ~~skiing accounted for over $12 billion in 2010 (Burakowski and Magnusson, 2012) while~~where annually snowmobiling ~~accounted~~accounts for between $7 billion (American Council of Snowmobile Associations, 2014) to $26 billion (International Snowmobile Manufacturers Association, 2016) ~~annually. Across the United States~~in revenue, much of the snowmobile use is on public land~~,~~ ~~such as~~. The United States National Forest System ~~with~~sees about 6 million annual snowmobile visits ~~annually~~ accessing about 327,000 km$^2$ of land (US Forest Service, 2010 and 2013a). ~~Across the six Colorado and one southern Wyoming National Forests (NFs) 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). Annually, snowmobiling added $130 million to the Colorado economy (Colorado Off-Highway Vehicle Coalition, 2016) and $125 millions to the Wyoming economy (Nagler et al., 2012).~~ As the number of people participating in ~~these activities increases annually~~winter recreation is increasing (Cook and Borrie, 1995; Winter Wildlands Alliance, 2006; US Forest Service, 2010; Nagler et al., 2012; US Forest Service, 2013a; Colorado Off-Highway Vehicle Coalition, 2016), the presence of ~~these human~~ activities~~, especially~~ like snowmobile use~~,~~ may ~~be influencing~~influence snowpack properties in these seasonally snow-covered environments. Further, as the climate changes, there will be reduced land available for snowmobiling (Tercek and Rodman, 2016), likely increasing the impact of snowmobile traffic.

There have been limited studies regarding the influence of snowmobile use on snowpack properties (Keddy et al., 1979; Thumlert et al., 2013~~). Snowmobile use on shallow snow (10 to~~

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

## 2. Study Sites

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

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

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

Another experimental snow compaction plot was established at the Fraser Experimental Forest (FEF) near the town of Fraser, Colorado in the Rocky Mountains of Central Colorado (Figure 1). The 93 km$^2$ experimental forest is a research unit of the United States Forest Service (USFS) Rocky Mountain Research Station (RMRS) located within the Arapaho NF. The FEF snow compaction site was located in a small meadow at an elevation of 2,851 m among lodgepole pine (*Pinus contorta*) forest. The Fraser Experimental Forest is closed to snowmobile use, but is used in the winter to access backcountry terrain by snowshoers, skiers, and snowboarders. The ~~Berthoud Summit~~Middle Fork Camp SNOTEL station, located at an elevation of ~~3,444~~2,725 m, was used to characterize the 2009-2010 winter at FEF.

## 3. Methods

### *3.1 Experimental snow compaction plots*

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

Transects were treated by driving a Skidoo brand snowmobile weighing about 300 kg with the rider (Figure 2d) at 10 km/h over the length of each transect five, 25 (FEF only) or 50 times, representing low, medium (FEF only), and high snowmobile use, respectively. Treatments began (Figure 2c) when non-compacted snow depths were approximately 30 cm (12 inches) for both locations, and when unpacked snow depths equaled approximately 120 cm (48 inches) for REP only~~.~~ (Figure 2a). Treatments were implemented (Figure 2e) monthly thereafter, until peak accumulation (Figure ~~2~~3). Snowpack sampling was performed within a week after each treatment~~,~~ (Figures 2 and ~~continued through the duration of the winter season (Figure 2~~3).

### 3.2 Snow pit analyses and data collection

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

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

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

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

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

The standard ram penetrometer is an instrument ~~used to~~ with a cone on the end of a tube onto which a hammer of known weight is dropped from a known height and the depth of penetration is recorded; it was used to vertically measure the relative hardness or resistance of a snow layers ~~(Greene et al., 2009) and was used to~~ in order to assess the change in ram resistance due to compaction ~~through the duration of the winter season.~~ (American Avalanche Association, 2016). A ram profile measurement was taken 0.5 meters from the edge of the snow pit wall subsequent to snow pit profile measurements. The mean ram resistance ($S_B$ in N) was determined by weighting each stratigraphic layer's ram resistance value obtained from the standard ram penetrometer measurement with the layer thickness. The ram resistance value associated with the bottom stratigraphic layer was measured to describe changes in ram resistance in the basal layer of the snowpack .

### *3.3 Statistical analyses*

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

## 4. Results

The 2009-2010 winter at REP had ~~a below~~an average ~~SWE~~snow depth, based on the Columbine SNOTEL data (Figure ~~2). A~~ 3a), while the peak SWE of 556 mm ~~was observed~~ on 9 April~~,~~ ~~which~~ was ~~93 percent of~~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 ~~therefore represented a deep~~for Colorado was deemed to represent a deeper snow cover environment. From the ~~Berthoud Summit~~Middle Fork SNOTEL data, the 2009-2010 winter at FEF ~~had an above~~was less than average ~~SWE~~ compared to the ~~29~~15-year historical average (Figure ~~2). A peak SWE of 622 mm was observed on 16 May, which was 115 percent of the historical mean peak SWE. Measured~~3b). The measured snow depth at the FEF snow compaction study plot never exceeded 1 m, similar to the Middle Fork Camp, and therefore ~~represented~~was used to represent a ~~shallow~~shallower snow cover environment.

### *4.1 Density*

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

Bulk snowpack density also increased at the FEF snow compaction study site for all compaction treatments (low, medium, and high use) that began on 30 cm of snow (Figure ~~3c~~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 ~~3ciii~~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 ~~3cii~~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 ~~3cv~~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 ~~3ci~~4ci).

### 4.2 *Temperature*

Low and high use compaction treatments at the REP snow compaction study site that began on both a shallow snowpack of 30 cm and on a deep snowpack of 120 cm did not result in significant changes ~~to the~~in temperature gradient. The maximum temperature gradients were observed on 12 December 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~~, favoring sintering and bonding of snow crystals. The coldest basal layer temperatures were about -2 and -3°C on 12 December for all treatments compaction treatments began on deep and shallow snowpack, respectively.~~. Basal layer temperatures increased throughout the winter season until all uses exhibited a basal layer temperature of -1°C by 17 April.

Low, medium and high use compaction treatments at the FEF snow compaction study site did not significantly impact the temperature gradient. Maximum temperature gradients for low, medium, and high use were 30°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 ~~4b~~5b). The coldest 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 treatments. Basal layer temperatures increased for all uses throughout the winter season until basal layer temperatures reached -1°C by 26 April (Figure ~~4b~~5b).

### *4.3 Hardness*

Mean snowpack hardness increased at the REP snow compaction study site following low and high use compaction treatments that began on 30 cm of snow (Figure ~~5a~~6a), but only for high use ~~at the~~starting on a deeper snowpack (Figure ~~5b~~6b). Significant increases in hardness were observed between treatments that began on 30 cm of snow and the control, and between compaction treatments (low and high) that began on 120 cm of snow (Table 1). For the treatment that began on the shallow snowpack, the maximum mean hardness for the control was 82 kPa for the control on 17 April (Figure ~~5av~~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 ~~5b~~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 ~~5av~~6av and ~~5bv~~6bv).

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

Low, medium, and high use compaction treatments resulted in a significant increase in mean snowpack hardness following snow compaction treatments beginning on 30 cm of snow at the FEF snow compaction study site (Table 1). ~~These~~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 ~~5c~~6c). For the control, the maximum mean snowpack hardness was about 25 kPa  (on 26 March in Figure ~~5civ~~6civ) while the maximum treatment hardness was one to two orders of magnitude higher at 395 kPa (low treatment on 22 January, Figure ~~5cii~~6cii), 780 kPa (medium treatment on 26 March, Figure ~~5civ~~6civ) and 4,627 kPa (high treatment on 26 March, Figure ~~5civ~~6civ). Similarly, the maximum basal layer hardness for the control was only 4 kPa (on 26 March, Figure ~~5civ~~6civ) and 138, 352 and 728 kPa for low, medium and high use, respectively (Figure ~~5cii, 5civ~~6cii, 6civ, and ~~5civ~~6civ).

### *4.4 Ram resistance*

Low and high use compaction treatments at REP caused an increase in mean snowpack ram resistance (Figure ~~6a~~7a and ~~6b~~7b), but the difference was only significant for treatments that began on 30 cm of snow (Table 1). The maximum mean snowpack ram resistance was measured as 128, 203, and 496 N for the control, low and high use, respectively (Figure ~~6av, 6av~~7av, 7av, and ~~6aiii~~7aiii). After the initial snow compaction treatments mean snowpack ram resistance for low and high use was greater than the control for the entire study period, but by the end of the study period minimal differences were observed between treatments. Basal layer ram resistance increased as a result of low and high use compaction treatments that began on both 30 cm (44, 614, and 1,297 N for control, low and high use) and 120 cm of snow (44, 270 and 90 N for control, low and high use).

Snow compaction treatments at the FEF snow compaction study site caused a significant increase in mean snowpack ram resistance (Figure ~~6c~~7c; Table 1). Maximum mean snowpack ram resistance for the control was 18 N (26 March, Figure ~~6civ~~7civ), for low and medium use it was 544N and 591N (26 March, Figure ~~6civ~~7civ) respectively, while for high use it was measured at 866N (on 12 February, Figure ~~6c~~7c). Basal layer ram resistance increased following the initial snow compaction treatments and continued to increase throughout the duration of the winter season, with maximums of 28 (26 March), 1,220, 1,220, and 3,220 N for the control, low, medium, and high treatments (on 12 February for all the use treatments).

### *4.5 Grain Size*

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

### *4.~~5~~6 Experimental Site Time Series*

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

### *4.7 Operational Sites*

As illustrated by SWE (Figure ~~7d~~9d) and depth (Figure ~~7a~~9a), the amount of snow was similar for the snowpits dug at the three operational sites, but not the same since they were up to 6km apart (Figure 1). Also these were operational sites, i.e., the amount of treatment was not controlled and was based solely on permitted use. Patterns of increased density (Figure ~~7a~~9a), hardness (Figure ~~7b~~9b) and ram resistance (Figure ~~7c~~9c) were similar to the previous presented experiments (Figures ~~3, 5~~4, 6, and ~~6~~7) with the non-snowmobile snowpits being less dense (Figure ~~7a~~9a) and having layers that were less hard (Figure ~~7b~~9b). For visual inspection, Muddy Creek had the most snowmobile use and thus had the highest density throughout the winter, and the hardest snowpack for mid-winter (Figure ~~7bii~~9bii to ~~7biv~~9biv) but at times was similar to Dumont Lakes.

## 5. Discussion

~~At rest, a snowmobile and its rider exert 4 to 10 kPa of pressure to the underlying snowpack (assuming a track length from 0.9 to 1.4 m, width of 0.50 m, a snowmobile weight of 200 to 350 kg, and a rider weight of about 100 kg, data from <http://www.polarisindustries.com>). This increase by~~

The ~~less than an order of magnitude due to snowmobile movement (Thumlert et al., 2013 measured stresses of about 10 to 20 kPa at a depth of 30 cm below the surface of a deep snowpack).~~ ~~In comparison, fresh snow with a density of 100 kg/m$^3$ exerts a pressure of 0.003~~

~~kPa to 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. Thus, the snowpack results shown herein are transferrable to grooming machinery.~~

~~The snowpack is persistently changing, once snow starts to accumulate on the ground. The density of snow varies over space, time and with depth. For fresh snow, density ranges from 40 to 200 kg/m$^3$ (Diamond and Lowry, 1953; Schmidt and Gluns, 1991; Fassnacht and Soulis, 2002). The density of fresh snow 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 also gets more dense (Figures 3 and 7a).~~

~~Once snow accumulates on the ground, the meteorology alters the physical and material properties of the snowpack from the surface down, such as changing its density and hardness. Since the base of the snowpack remains at approximately 0°C due to warm summer temperatures and geothermal heating (Auerbach and Halfpenny, 1991; Pomeroy and Brun, 2001), variable atmospheric air temperatures fluctuate between the relatively warm days and relatively cold nights (McClung and Schaerer, 2006) and generate strong temperature and vapour pressure gradients causing kinetic growth metamorphism that creates cohesionless facetted snow grains. Conversely equilibrium metamorphism creates rounded grains that can easily sinter (Sommerfeld, 1970; Colbeck, 1982; Colbeck, 1983; Colbeck, 1987). Rounding increases density and snowpack strength. This~~ 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 ~~3a~~4a, and ~~5a~~6a), and later into the snow season for the shallower snowpack (FEF in Figures ~~3c~~4c, and ~~5c~~6c). Similar differences were found due to ski run grooming in an Australia snowpack with a 400% increase in hardness early in the snow season but only about a 40% increase later in the winter (Fahey et al., 1999). Snow grooming increased the average density by up to 36% compared to non-groomed ski slopes (Fahey et al., 1999, Rixen et al., 2001).

Compaction of the snowpack changes in density, hardness and ram resistance (Figures ~~3,~~ ~~5~~4, 6, 7, and ~~7~~9), and results in deformation of ~~snowthrough~~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 ~~3a, 5a~~4a, 6a, 7a versus Figures ~~3b, 5b~~4b, 6b, 7b) and for two different snow covered environments (Figures ~~3c, 5c~~4c, 6c, 7c).

~~Field observations prior to snowmelt have revealed maximum late season snowpack densities ranging from 290 kg/m$^3$ to 400 kg/m$^3$ with snow densities as high as 500 kg/m$^3$ during snowmelt (Gold, 1958; Longley, 1960), while densities of depth hoar layers prior to melt were about 300 kg/m$^3$ (Greene et al., 2009; Sturm et al., 2010).~~ 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 ~~3a~~4a), observed mid-winter (early February), similar to maximum late season natural snowpack densities ~~(Gold, 1958; Longley, 1960; Giddings and LaChapelle, 1962).~~. Density differences were greatest for a shallow snow cover environment (FEF), with high use resulting in 78% greater density (Figure ~~3c~~4c). Conversely, no significant differences in density were observed when snowmobile use began on a deep snowpack (120 cm) (Figures ~~3b~~4b, Table 1). The snowpack density varies spatial and temporally, such as between 40 to 200 kg/m$^3$ for fresh snow (Fassnacht and Soulis, 2002), but this can double with just one pass of a snowmobile on a very shallow snowpack (Keddy et al., 1979), and even with more accumulation, density will increase, but the underlying snow increases in density (Figures 4 and 9a).

Increased densification of the snowpack due to snowmobile use influences snow hardness (Figure ~~5~~6) and ram resistance (Figure ~~6) due to changes in the arrangement of ice grains.~~7). In this study, snow-hardness gauges and circular metal plates of known area were used (McClung and ~~Shaerer~~Schaerer, 2006), rather than the more simplistic in situ ~~(avalanche evaluation)~~ hand hardness test (~~Greene et al., 2009~~American Avalanche Association, 2016). Snowmobile use beginning on a shallow snowpack (30 cm) for a deep snowpack (REP) resulted in a 2- and 6-fold increase in maximum snow hardness for low and high use compared to no use, whereas at a shallow snow study site (FEF), a 15-, 30- and nearly 200-fold increase in maximum snow hardness for low, medium, and high use was observed. A shallow snow environment is more susceptible to large changes in snow hardness due to varying snowmobile use.

Ram resistance values ranged from 0 N to just below 1000 N, which is a normal range for snowpack strength measurements (Colbeck et al., 1990). The precision of the ram penetrometer used in this study was 10N, so the ram resistance of ~~an undisturbed~~a fresh snow and layers of the snowpack~~,~~ with limited metamorphism could not be measured as it is typically in ~~he~~the range of 0.5N (Pruitt, 2005~~), could not be measured.~~). 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 ~~6~~7). The impact of snowmobile use on a snowpack ram resistance (Figures ~~6~~7 and ~~7c~~9c) has only been observed by Pruitt (2005).More frequent fresh snowfall events (REP, Figure ~~6a~~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 ~~6b~~7b).

As crystals become compacted due to snowmobile use, there is an increase in bonding between crystals and early compaction impedes further kinetic growth. Temperature gradients were as high as $33^{o}C\ m^{-1}$ at the beginning of the season, ~~about twice what was observed by de Quervain (1958) in alpine snowpacks,~~ and approached $0^{o}C\ m^{-1}$ as the snowpack became isothermal at the end of the winter season. ~~However, temperature gradients in this study were unaffected by compaction from snowmobile use (Figure 4, Table 1) potentially due to the edge effect of heat transfer from the warmer ground adjacent to the plots, heat transfer from the buffer areas located parallel to compaction transects, and diurnal changes in ambient air temperatures.~~ The temperature gradient was sufficient for kinetic growth metamorphism for most of the winter season ($T_G > 10^{o}C\ m^{-1}$), as seen by less dense lower snowpack layers for the controls (Figures ~~3a, 3c, 7a~~4a, 4c, 9a) and the deep snowpack where snowmobile use started at 120 cm (Figure ~~3b~~4b).

At rest, a snowmobile and its rider exert 4 to 10 kPa of pressure to the underlying snowpack (assuming a track length from 0.9 to 1.4 m, width of 0.50 m, a snowmobile weight of 200 to 350 kg, and a rider weight of about 100 kg, data from <polarisindustries.com>). There is an increase of less than an order of magnitude due to snowmobile movement (Thumlert et al., 2013 measured stresses of about 10 to 20 kPa at a depth of 30 cm below the surface of a deep snowpack). In comparison, fresh snow with a density of 100 $kg/m^3$ exerts a pressure of 0.003 kPa on the underlying snowpack (Moynier, 2006). Snowpack loading by wheeled vehicles on a shallow snowpack was much greater, peaking at about 350 kPa (Pytka, 2010). Grooming vehicles added a load similar to snowmobiles (Pytka, 2010), due to the larger track size and results may be transferrable.

~~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). ~~Similarly, this~~This trend was also observed on REP,~~ although the deeper snow environment allowed growth of depth hoar~~ 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 ~~6~~7) was statistically significant between the control (no snowmobile use) and all treatments, ~~expect~~except when treatments were initiated on a deep snowpack (Figures ~~3b, 5b~~4b, 6b, and ~~6b~~7b, Table 1). The measured depth of influence for a snowmobile is about 90 cm (Thumlert et al., 2013). At 20 cm below the snow surface, the induced stress is already much less than 10 cm below the surface from a snowmobile (Thumlert et al., 2013) or a grooming machine (Pytka, 2010). Most ski resorts in the French Alps required a minimum snow depth of 40 cm to offer skiing, with a range from 60 cm in February to 40 cm in April (Spandre et al., 2016b). The US Forest Service (2013b) recommends a minimum of 30 cm before the use of snowmobiles. Increasing the minimum snow depth before allowing snowmobile traffic will reduce changes to the snowpack due to snowmobiles (Table 1). Where the experiments were undertaken, i.e., Colorado, there are 1.1 to 1.6 million annual snowmobile visits, with an increase from 580 thousand to 690 thousand between 2010 to 2013 in northern Colorado (Routt NF and Arapaho-Roosevelt NF) and southern Wyoming (Medicine Bow NF) (US Forest Service, 2010 and 2013a), with an annual economic impact of more than $125 million to each state (Nagler et al., 2012; Colorado Off-Highway Vehicle Coalition, 2016). Thus snowmobile use will continue to change to the snowpack, and the impacts are expected to become greater with the anticipated increases in snowmobile activity.

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

Snowmobile use was found to have a highly significant effect upon natural vegetation below the snow (Keddy et al., 1979), with grooming shown to delay the blooming of alpine plants (Rixen et al., 2001) due to a later snowmelt and a significantly cooler soil (Fassnacht and Soulis, 2002). Deeper snowpack were found to not have a cooler soil temperature under the snowpack (Keller et al., 2004), but did melt out four weeks later~~, and this resulted in a cooler snowpack at the end of the summer~~ (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.

~~Snow~~Without wind, snow depth will ~~likely~~ be less for areas with snowmobile traffic (~~Figure 3~~Figures 2d, 2e, and 4; Rixen et al., 2001; Spandre et al., 2016a). However, ~~this depends upon the meteorological conditions, specifically the frequency and magnitude of wind~~wind is often present in open areas where snowmobiling occurs. The local terrain features and position and extent of canopy influence how the wind interacts with the snowpack (Pomeroy and Brun, 2001). In an Australia case study, SWE increased by 45% in groomed areas (Fahey et al., 1999); at the Rabbit Ears Pass recreational use areas, SWE also increased (Figure ~~7d)~~9d) likely due to snow blowing into the depressions created by snowmobile tracks~~.~~ (Figure 2d). The increased load could further impact the underlying snowpack properties.

~~Snowmaking is performed~~Further, snowmaking (Spandre et al., 2016a) to supplement natural snow conditions~~. In the French Alps, about of third of the ski slopes equipped are equipped with snowmaking facilities~~ and~~ this is expected to increase, due in part to a changing climate (Spandre et al., 2016b). Artificial snow has substantially different properties than natural snow, and adds an additional load to the underlying snowpack (Spandre et al., 2016a). This additional snow compacts the snowpack below it, and may create surface different conditions (Howard and Stull, 2014). Grooming of artificial snow further compressed the snowpack (Spandre et al., 2016a). If the results presented in this paper are extended to ski areas, the addition of artificial snow must be considered.~~ ~~In Colorado alone, the economic impact of the ski industry was $4.8 billion during the 2013-14 ski season (Colorado Ski Country USA, 2015). Regardless of the use, adding mass to the snowpack, through snowmaking (Spandre et al., 2016a),~~/or grooming (Fahey et al., 1999; Rixen et al., 2001; Spandre et al., ~~2016a), or snowmobile use (Figure 7), will alter the snowpack (Figure 3-6). A~~2016a) compacts the snowpack below it, and alters the underlying snowpack properties (Howard and Stull, 2014; Spandre et al., 2016a; Spandre et al., 2016b). Also, a changing climate will likely reduce the extent of terrain and decrease the length of the winter recreation season (Laxar and Williams, 2008; Steiger, 2010; Dawson and Scott, 2013; Marke et al., 2015; Tercek and Rodman, 2016). ~~In~~

~~all cases, due to climate change, more snowmaking will be required (Steiger, 2010; Spandre et al., 2015) and this artificial snow will impact the snowpack properties (Spandre et al., 2016a). The results presented herein are useful when modeling the impact of grooming or snowmaking on the snowpack of ski runs (e.g., Howard and Stull, 2014; Marke et al., 2015; Spandre et al., 2016a).~~

## 6. Conclusion

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

~~Snowpack properties of varying snowpack environments (shallow vs. deep) respond differently to snowmobile use. Shallow snow covers experience an increase in snowpack density, ram resistance, and hardness that are more pronounced than changes to these properties when snowmobile use operates on a deep snowpack. These changes in the physical properties of the~~

~~snowpack are due to snowmobile use operating on an already compacted snowpack yielding thick layers of dense, strong, hard snow. Deep snow covers experience more snowfall events that create "cushions" of relatively undisturbed snow between compaction events lessening the effect of snowmobile use on snowpack properties. These differences between snow environments suggest that shallow snowpacks are more susceptible to larger changes in snowpack properties.~~

## Author contribution

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

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Appreciation goes to Robert Skorkowsky, Kent Foster and Becky Jones of the Hahns Peak/Bears Ears Ranger District of the US Forest Service for their help and support with compaction treatments at the Rabbit Ears Pass study site. Additional thanks goes to James zumBrunnen of the Colorado State University Statistics Department for his assistance with statistical interpretation. Jared Heath would also like to recognize the Colorado Mountain Club for their help supporting this project with a generous grant. Dr. Jim Halfpenny, Ned Bair, and ~~two~~three anonymous reviewers provided insight into clarifying this paper, and resulted in the creation of new figures. TC editor Dr. Guillaume Chambon provided additional comments and an important citation that helped reformulate the discussion.

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

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

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

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

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

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

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

~~2.~~3. Mean snow depth from 2003-2017, and 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). Data ~~was~~were obtained online from the Natural Resource Conservation Service (NRCS) National Water and Climate Center (http://www.wcc.nrcs.usda.gov/).

~~3.~~4. Density profiles for five dates (i to v) measured at the REP snow compaction study plot for no (control), low, and high use treatments beginning on a) 30 cm and b) 120 cm of snow, and c) the FEF snow compaction study plot for no (control), low, medium, and high use treatments beginning on 30 cm of snow. Note that free floating measurements represent overlapping density measurements. The ground is at zero snow depth.

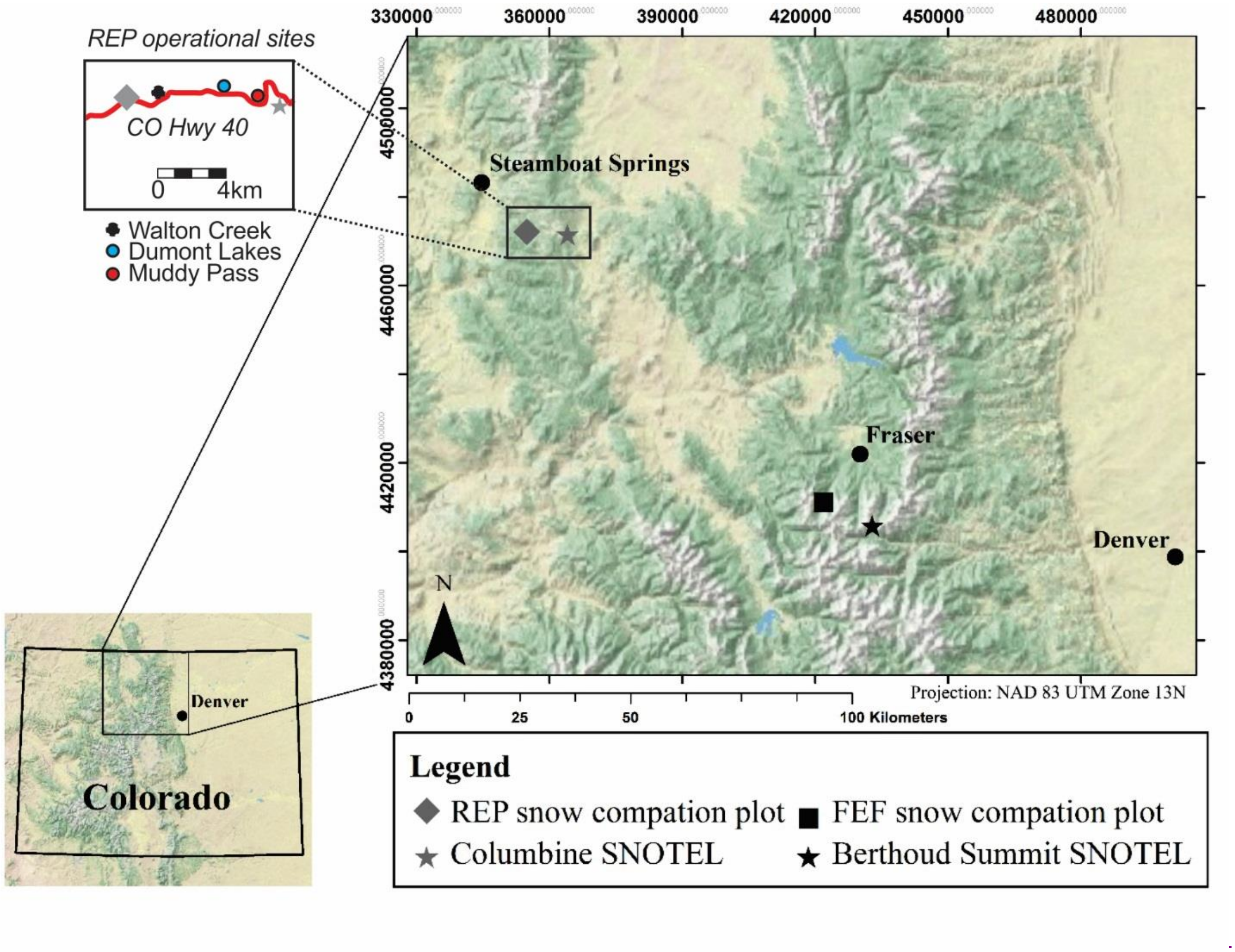
~~4.~~5. Temperature profiles measured at a) the REP snow compaction study plot on February 06, 2010 for no, low, and high use treatments beginning on 30 cm and 120 cm of snow and b) the FEF snow compaction study plot on March 26, 2010 for no, low, medium, and high use treatments beginning on 30 cm of snow.

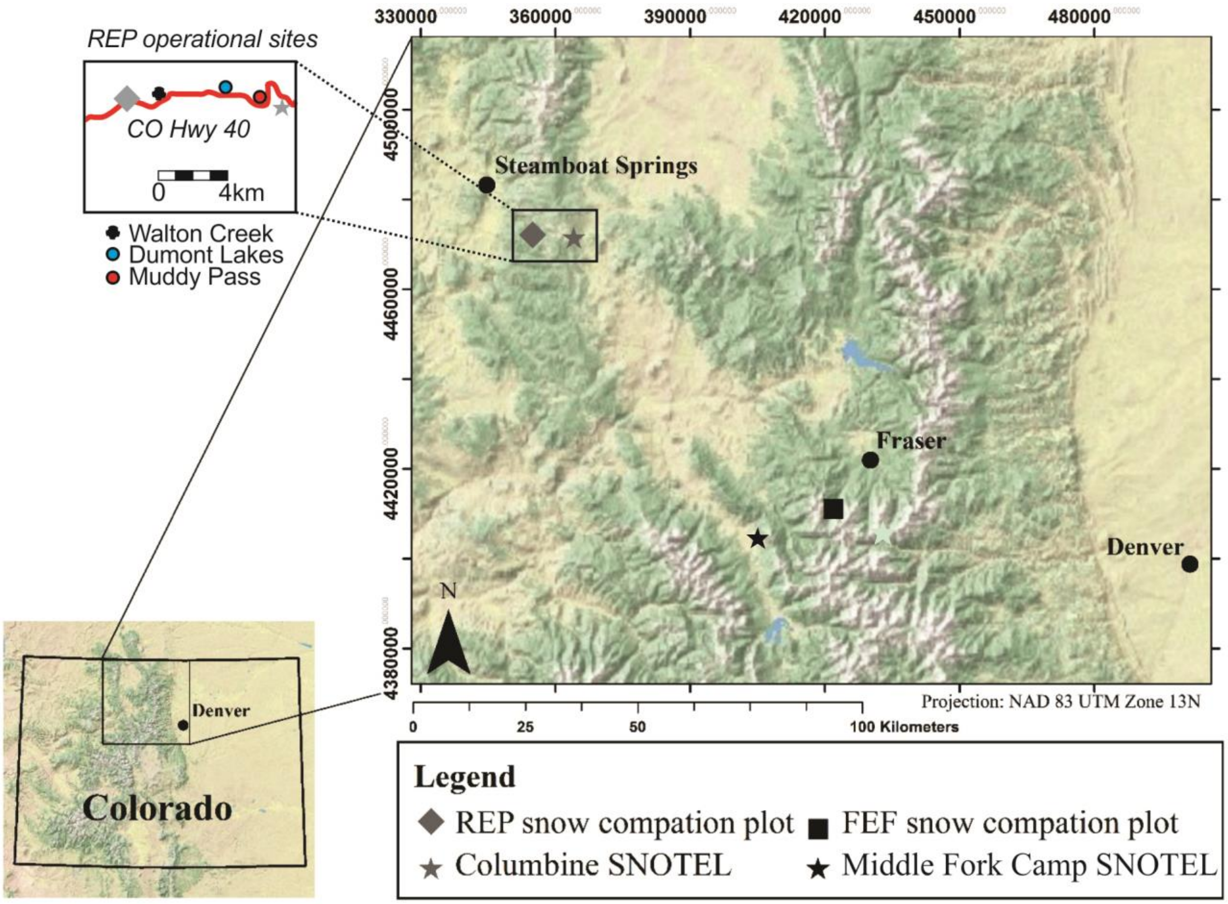
~~5.~~6. Hardness profiles for five dates (i to v) measured at the REP snow compaction study plot for no, low, and high use treatments beginning on a) 30 cm and b) 120 cm of snow, and c) the FEF snow compaction study plot for no, low, medium, and high use treatments beginning on 30 cm of snow.

~~6.~~7. 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.

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.

~~7.~~9. Snowpit data for Walton Creek (no snowmobile use), Dumont Lakes (moderate snowmobile use) and Muddy Creek (high snowmobile use) in the Rabbit Ears Pass recreational use areas illustrating a) density, b) hardness, c) ram resistance, and d) SWE.


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 snow compation plot
FEF snow compation plot
Columbine SNOTEL
Berthoud Summit SNOTEL



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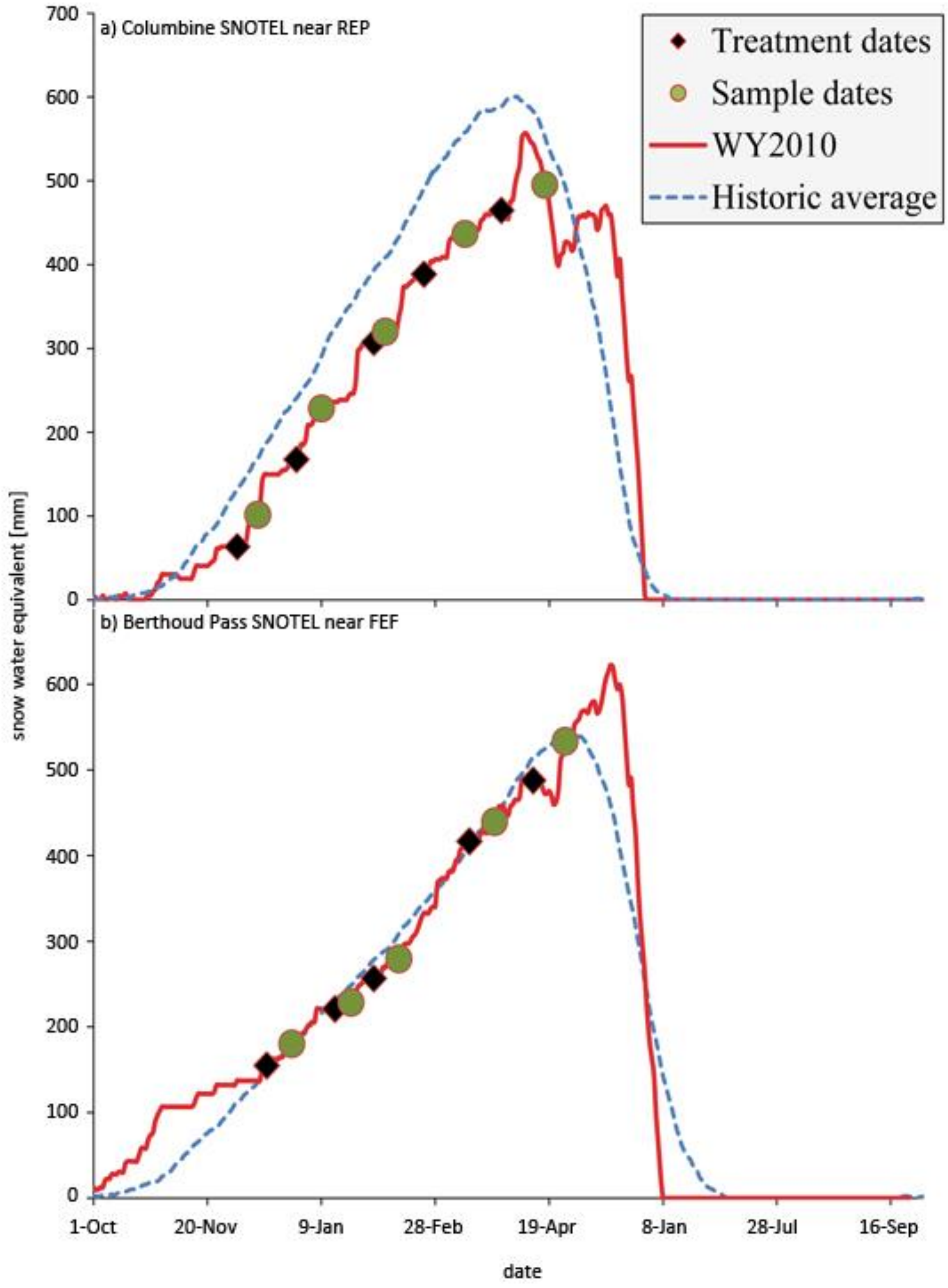
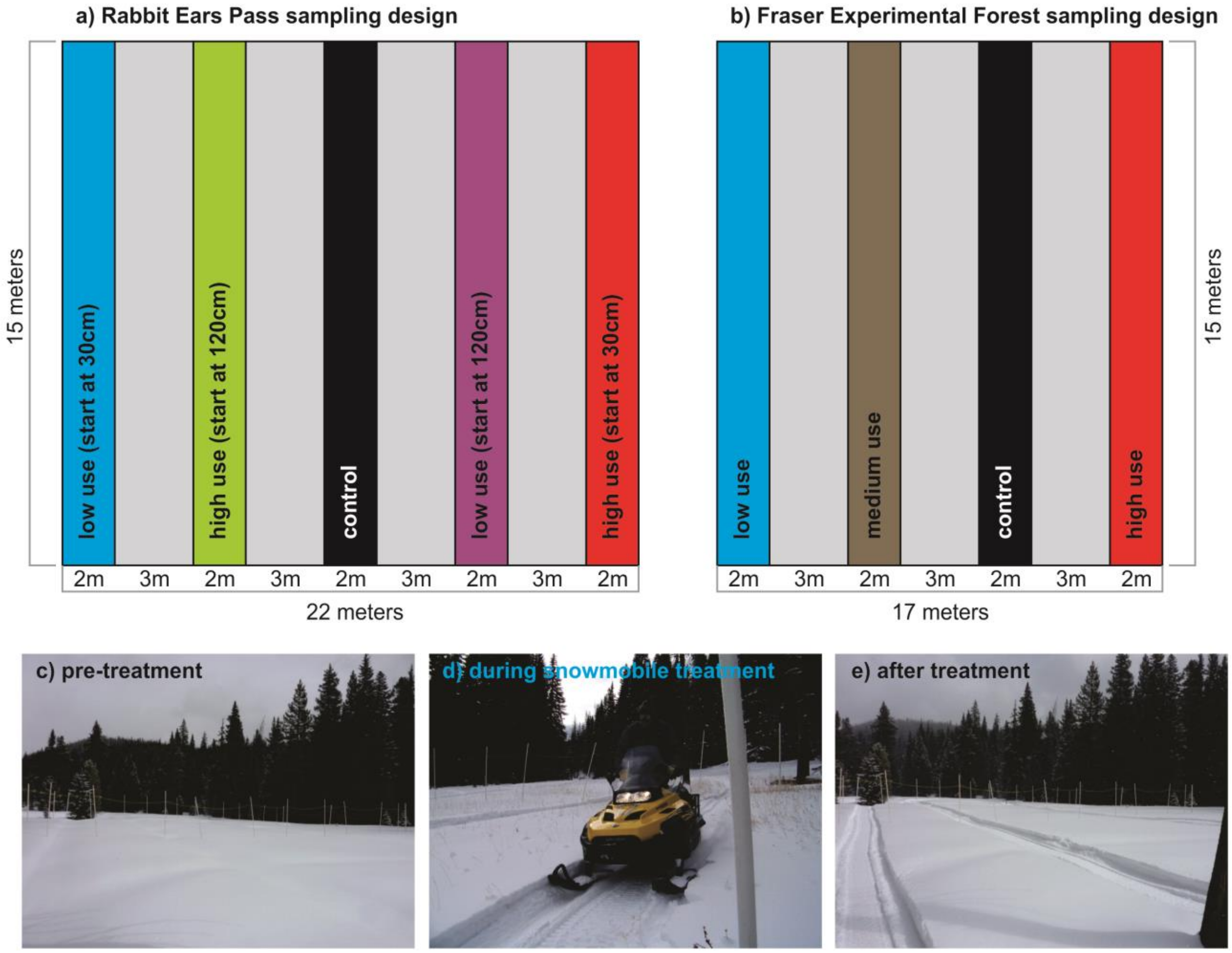


near the town of Fraser. The Middle Fork Camp SNOTEL site was used to represent the year's snowfall.



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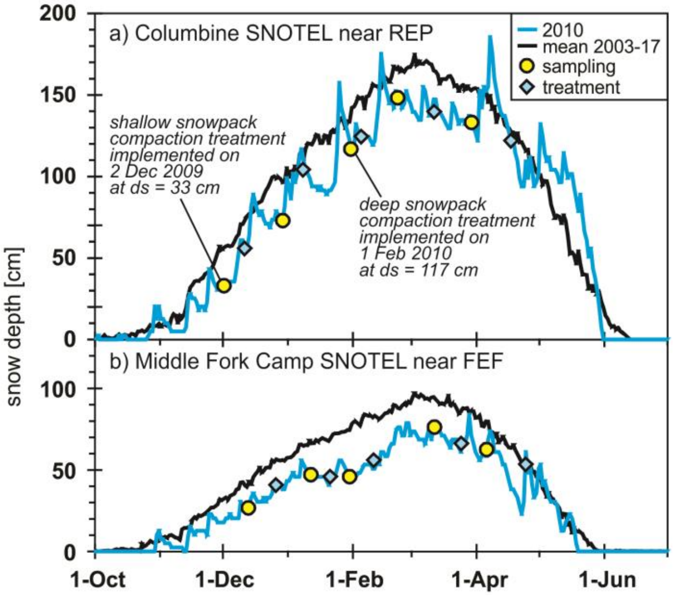


**Figure 3.** Mean snow depth from 2003-2017, and for the 2010 water year (WY2010) measured at a) the Columbine SNOTEL site near Rabbit Ears Pass~~,~~ (REP), Colorado and b) the ~~Berthoud Summit~~Middle Fork Camp SNOTEL near Fraser Experimental Forest~~.~~ (FEF). Data ~~was~~were obtained online from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

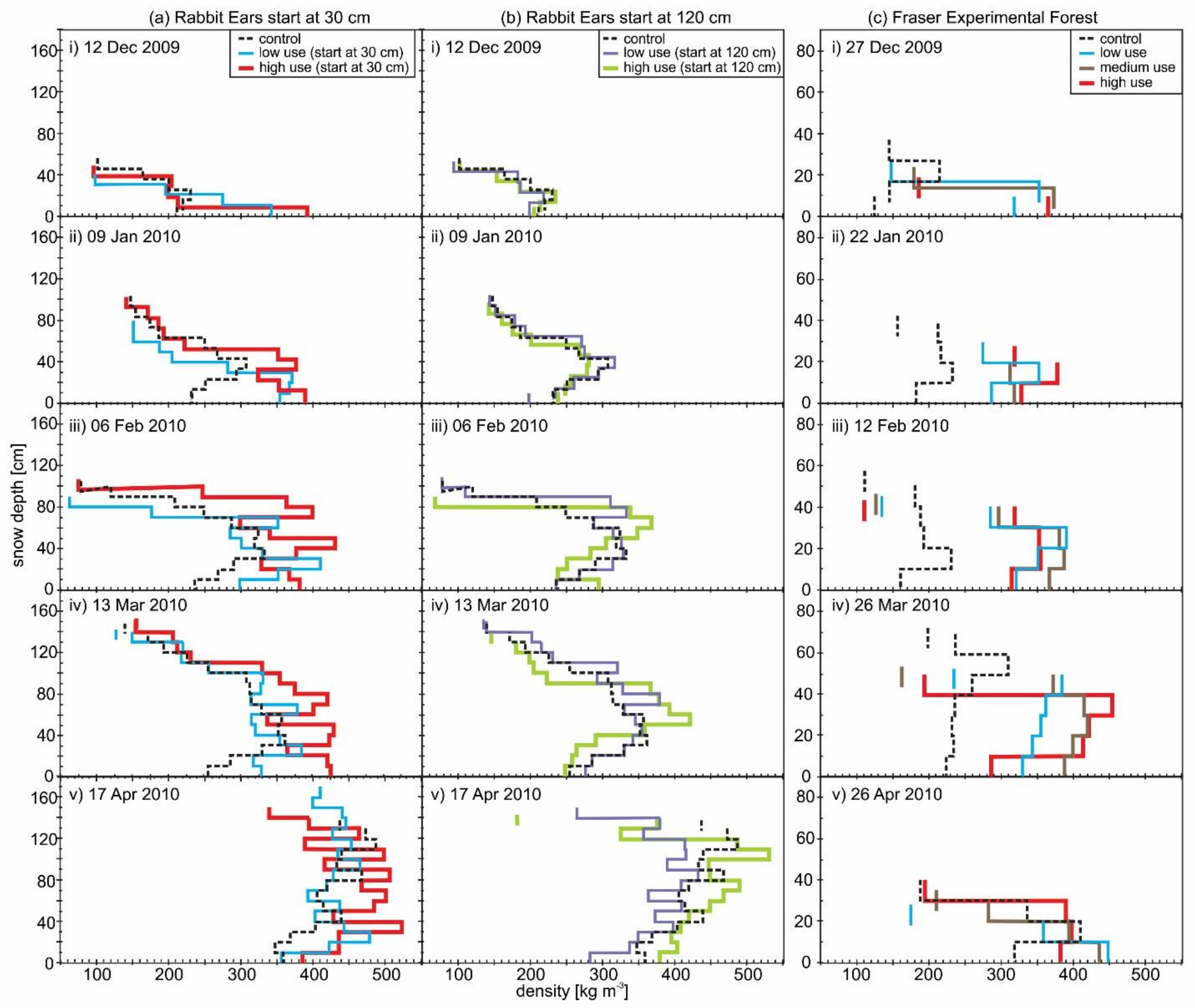
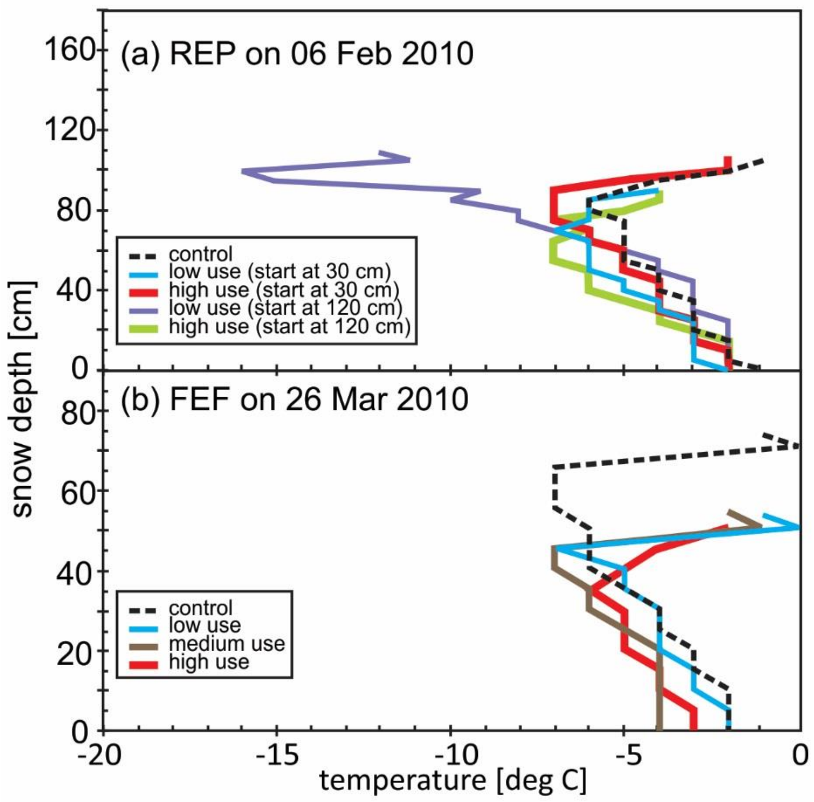


**Figure ~~3~~4.** Density profiles for five dates (i to v) measured at the REP snow compaction study plot for no (control), low, and high use treatments beginning on a) 30 cm and b) 120 cm of snow, and c) the FEF snow compaction study plot for no (control), low, medium, and high use treatments beginning on 30 cm of snow. Note that free floating measurements represent overlapping density measurements. The ground is at zero snow depth.



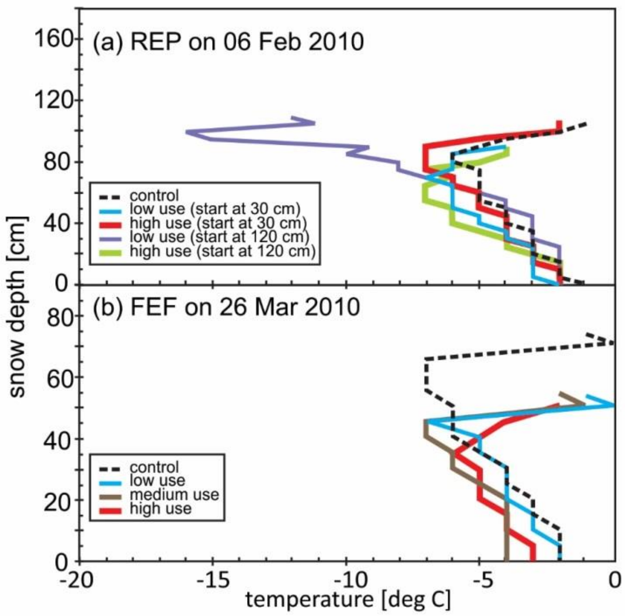


**Figure 45.** Temperature profiles measured at a) the REP snow compaction study plot on February 06, 2010 for no, low, and high use treatments beginning on 30 cm and 120 cm of snow and b) the FEF snow compaction study plot on March 26, 2010 for no, low, medium, and high use treatments beginning on 30 cm of snow.

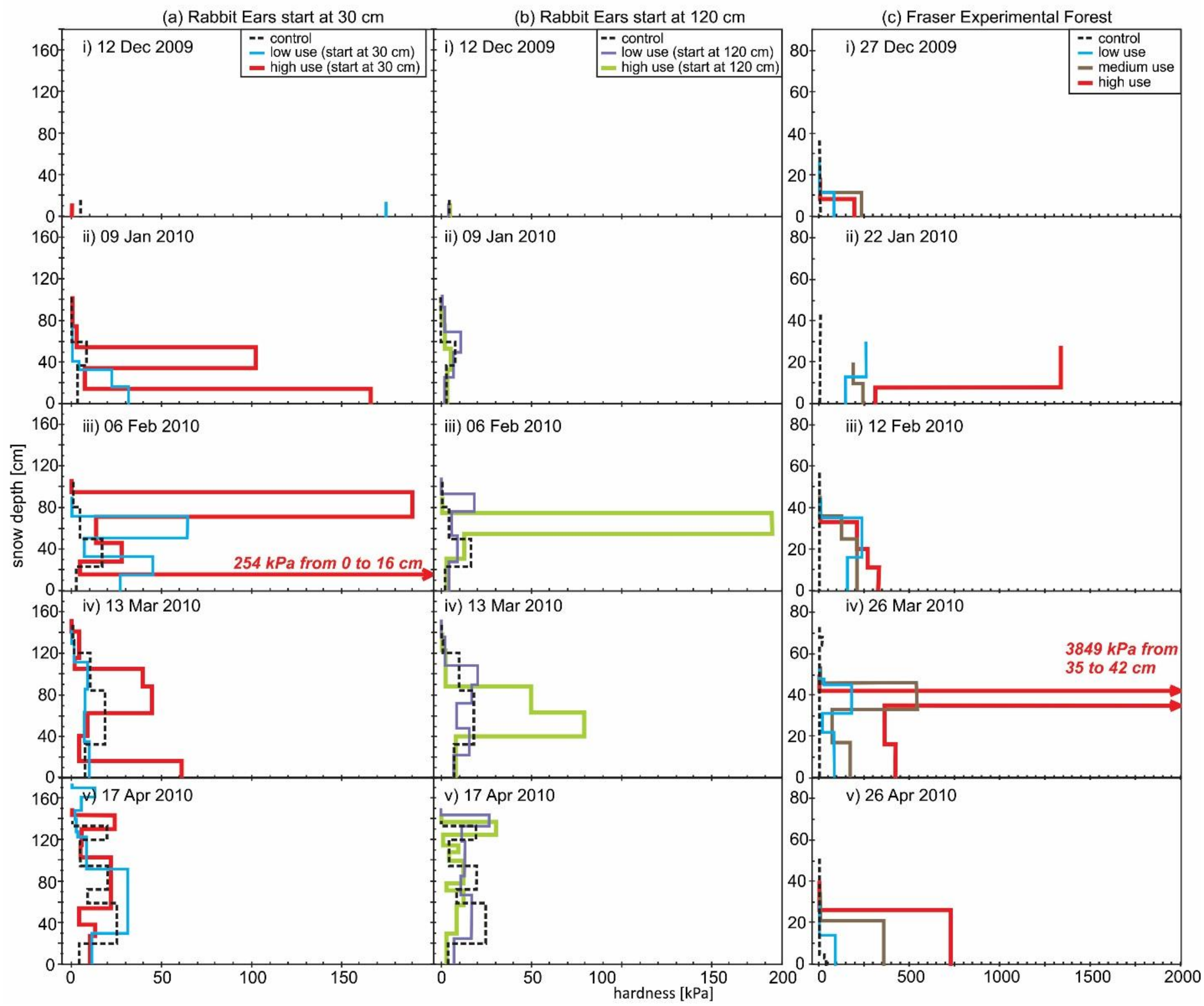


**Figure ~~5~~6.** Hardness profiles for five dates (i to v) measured at the REP snow compaction study plot for no, low, and high use treatments beginning on a) 30 cm and b) 120 cm of snow, and c) the FEF snow compaction study plot for no, low, medium, and high use treatments beginning on 30 cm of snow.

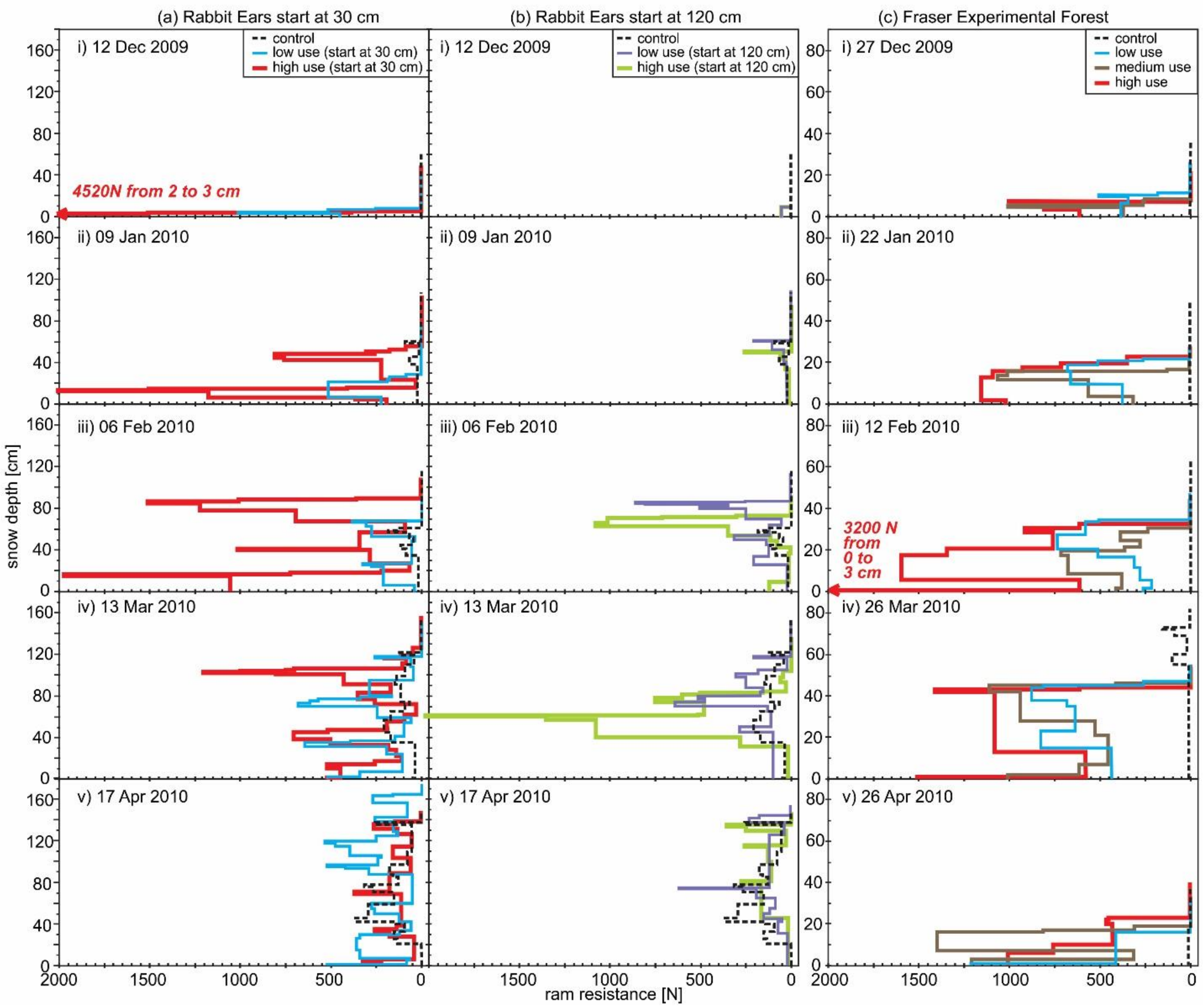
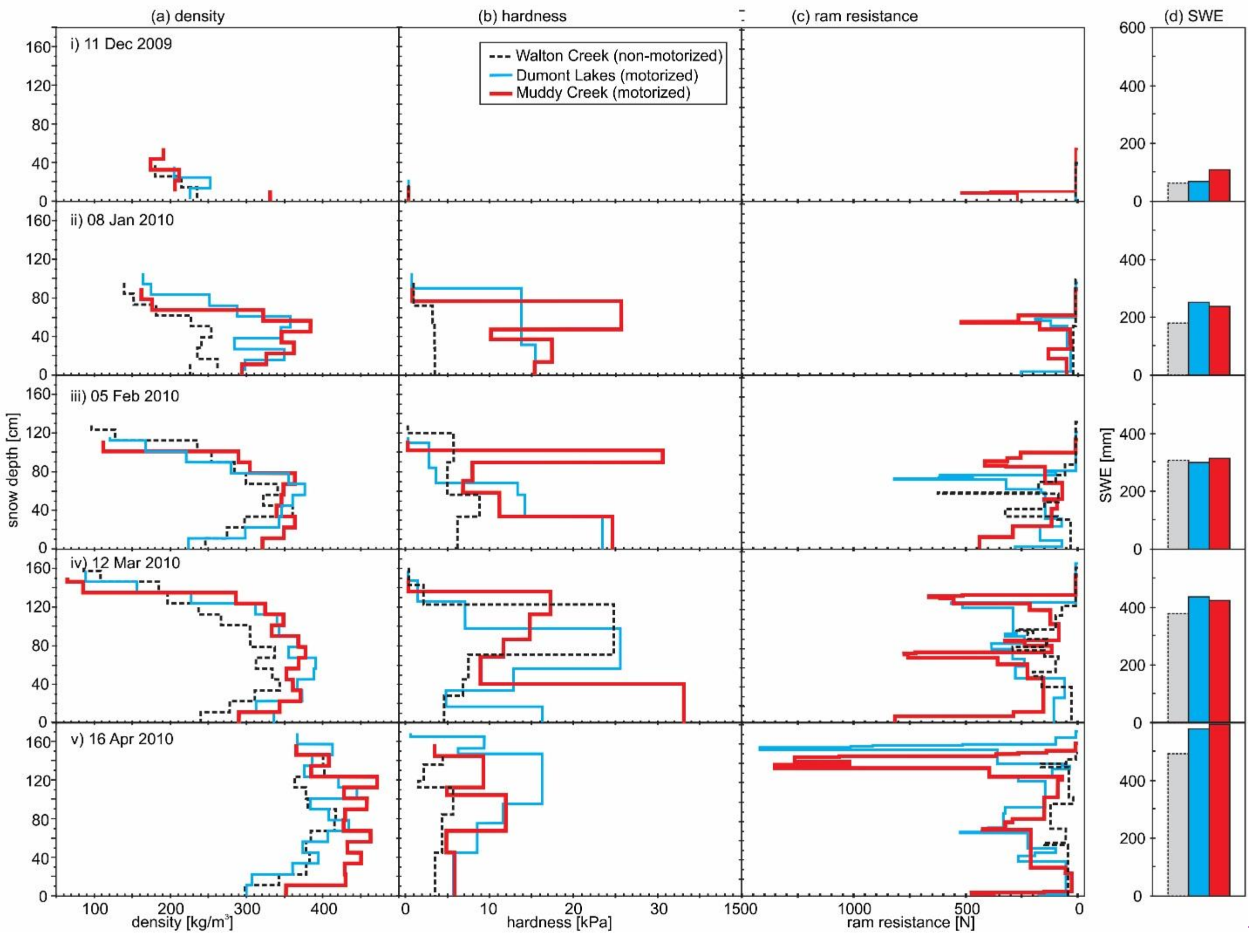
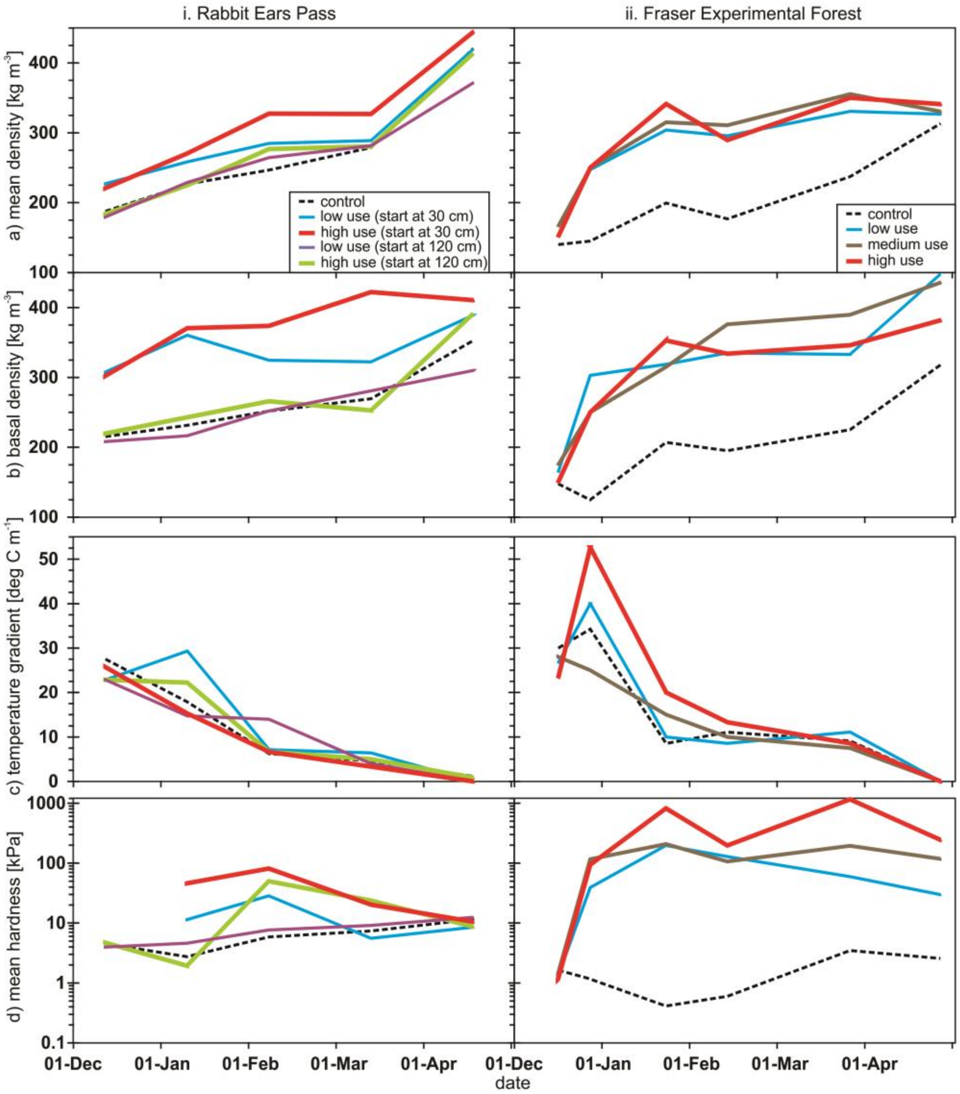


**Figure ~~6~~7.** Ram resistance for five dates (i to v) profiles measured at the REP snow compaction study plot for no, low, and high use treatments beginning on a) 30 cm and b) 120 cm of snow, and c) the FEF snow compaction study plot for no, low, medium, and high use treatments beginning on 30 cm of snow.


(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)
Dumont Lakes (motorized)
Muddy Creek (motorized)
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



~~**Figure 7.**~~

**Figure 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 (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.

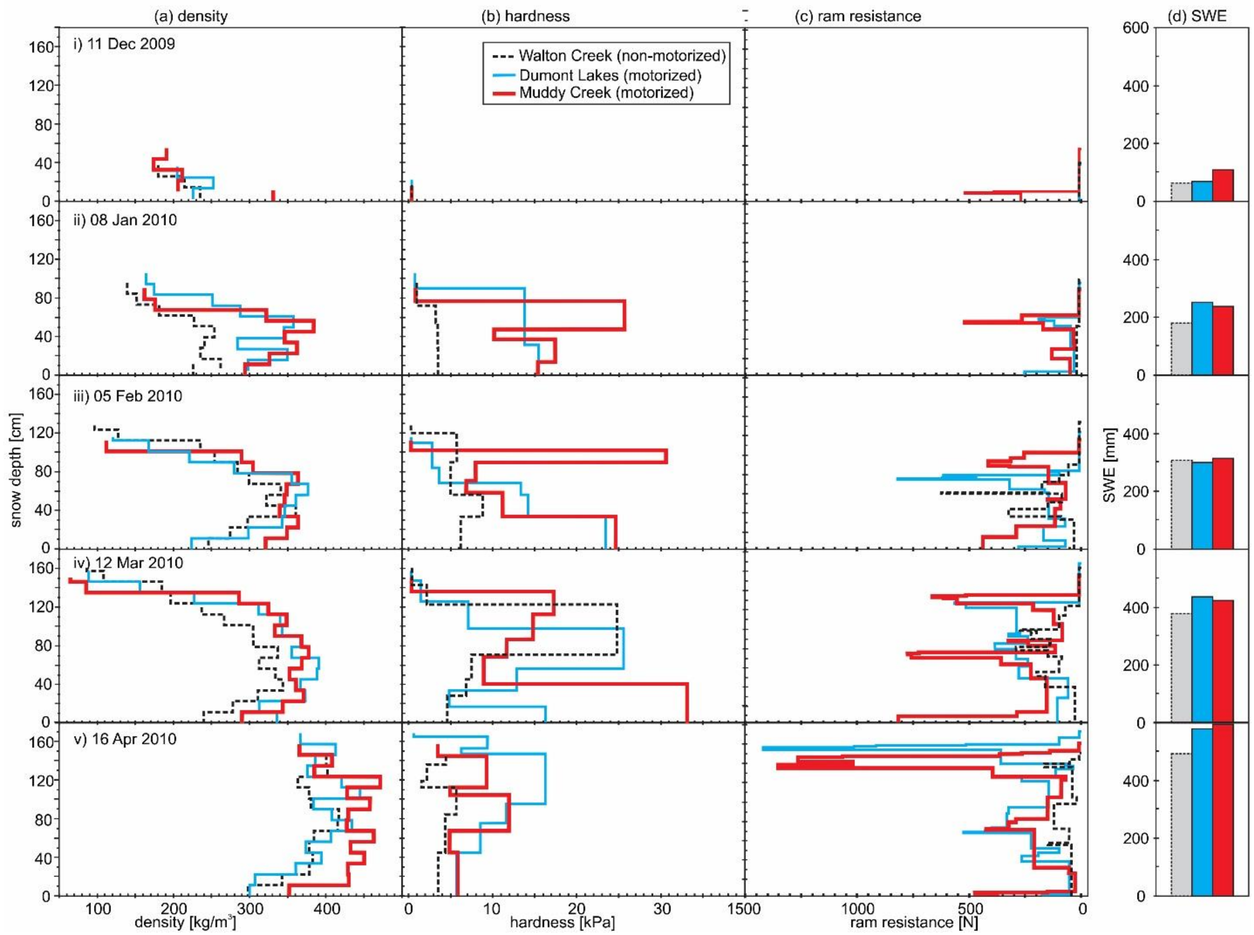


**Figure 9.** Snowpit data for Walton Creek (no snowmobile use), Dumont Lakes (moderate snowmobile use) and Muddy Creek (high snowmobile use) in the Rabbit Ears Pass recreational use areas illustrating a) density, b) hardness, c) ram resistance, and d) SWE.