

1 **Snowmobile Impacts on Snowpack Physical and Mechanical Properties**

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

14 **Abstract**

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

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31 **1. Introduction**

32 In the United States snowmobiling accounts for between \$7 billion (American Council of
33 Snowmobile Associations, 2014) to \$26 billion (International Snowmobile Manufacturers
34 Association, 2016) in annual revenue, and much of the snowmobile use occurs on public land.
35 The United States National Forest System records about 6 million snowmobile visits annually,
36 accessing about 327,000 km² of land (US Forest Service, 2010 and 2013a). With continued
37 increases in the number of people participating in winter recreation (Cook and Borrie, 1995;
38 Winter Wildlands Alliance, 2006; US Forest Service, 2010; Nagler et al., 2012; US Forest
39 Service, 2013a; Colorado Off-Highway Vehicle Coalition, 2016), activities like increased
40 snowmobile use may influence snowpack properties in these seasonally snow-covered
41 environments. Of additional concern, is that climate change will result in reduced land available
42 for snowmobiling (Tercek and Rodman, 2016), likely increasing the impact of snowmobile
43 traffic.

44 There have been limited studies regarding the influence of snowmobile use on snowpack
45 properties (Keddy et al., 1979; Thumlert et al., 2013; Thumlert and Jamieson, 2015). Studies
46 have however, examined how the snowpack changes due to snow grooming at ski resorts (Fahay
47 et al., 1999; Keller et al., 2004; Spandre et al., 2016a), or to traction and mobility of wheeled
48 vehicles across a snowpack (Abele and Gow, 1990; Shoop et al., 2006; Pytko, 2010). One of the
49 few studies on snowmobile use examined effects on very shallow snow (10 to 20 cm deep)
50 (Keddy et al., 1979). The authors found a doubling of fresh snow density and a compression of
51 the natural vegetation below the snow (Keddy et al., 1979). Examining deeper snow cover (>20
52 cm deep), Thumlert et al. (2013) and Thumlert and Jamieson (2015) examined the distribution of

53 stresses through the snowpack due to type of loading, depth and snowpack stratigraphy
54 (Thumlert et al., 2013).

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

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

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75 **2. Study Sites**

76 During the 2009-2010 snow season a set of snow compaction plots were located near
77 Rabbit Ears Pass (REP) in the Rocky Mountains of northern Colorado to southeast of the town of
78 Steamboat Springs. REP is within the Medicine Bow-Routt National Forest (NF) (Figure 1)
79 along the Continental Divide encompassing over 9,400 km² of land in Colorado and Wyoming.
80 Rabbit Ears Pass is especially popular during the winter season and is heavily used by
81 snowmobilers and other winter recreationalists due to the ease of access to backcountry terrain
82 from Colorado Highway 40. Due to heavy use and conflict among users during the winter
83 season, the Forest Service manages Rabbit Ears Pass for both non-motorized and motorized uses.
84 The west side of the pass is designated for non-motorized use and prohibits motorized winter
85 recreation while the east side of the pass is a mixed-use area and is open to motorized use (Figure
86 1). This study area was selected to determine if differences in snowpack properties will be
87 observed between the non-motorized and motorized use areas (e.g., Walton Creek versus
88 Dumont Lakes and Muddy Pass in Figure 1).

89 Two REP experimental snow compaction study plots were located adjacent to one
90 another within an open meadow north of Colorado Highway 40 at an elevation of approximately
91 3,059 m (Figure 1). The snow compaction sites were established within an area that prohibits
92 motorized use to protect the study sites from unintended impacts of snowmobilers. Data from the
93 Columbine snow telemetry (SNOTEL) station, located at an elevation of 2,792 m, was used to
94 show how the 2009-2010 winter compared to other winters at REP. The SNOTEL network was
95 established in the late 1970s across the Western United States by the Natural Resources
96 Conservation Service to monitor snowpack properties. Initially snow water equivalent and
97 precipitation were monitored, temperature and snow depth were added in the 1990s-2000s to aid
98 in operational runoff volume forecasting (see <wcc.nrcs.usda.gov>).

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

111 Another experimental snow compaction plot was established during the same winter
112 snow season of 2009-2010 at the Fraser Experimental Forest (FEF) near the town of Fraser,
113 Colorado in the Rocky Mountains of Central Colorado (Figure 1). The 93 km² experimental
114 forest is a research unit of the United States Forest Service (USFS) Rocky Mountain Research
115 Station (RMRS) located within the Arapaho NF. The FEF snow compaction site was located in a
116 small meadow at an elevation of 2,851 m surrounded by lodgepole pine (*Pinus contorta*) forest.
117 The Fraser Experimental Forest is closed to snowmobile use, but is used to access backcountry
118 terrain by snowshoers, skiers, and snowboarders. The Middle Fork Camp SNOTEL station,
119 located at an elevation of 2,725 m, was used to characterize the 2009-2010 winter at FEF.

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121 **3. Methods**

122 **3.1 *Experimental snow compaction plots***

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

132 Transects were treated by driving a Skidoo brand snowmobile weighing about 300 kg
133 including the rider (Figure 2d) at 10 km/h over the length of each transect five, 25 (FEF only) or
134 50 times, representing low, medium (FEF only), and high snowmobile use, respectively.
135 Treatments began (Figure 2c) when non-compacted snow depths were approximately 30 cm (12
136 inches) for both locations, and when unpacked snow depths equaled approximately 120 cm (48
137 inches) for REP only (Figure 2a). Treatments were implemented (Figure 2e) monthly thereafter,
138 until peak accumulation (Figure 3). Snowpack sampling was performed usually within a week
139 after each treatment (Figures 2 and 3). At FEF, snowpack sampling was performed prior to the
140 first treatment to illustrate range of spatial variability across the plots (first set of points in Figure
141 4b).

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143 **3.2 *Snow pit analyses and data collection***

144 Snow pit profiles were used to examine the physical properties of the snowpack at both
145 the experimental and at the operational sites. A vertical snow face was excavated by digging a pit
146 from the snow surface to the ground. Measurements of snow density, temperature, stratigraphy,
147 hardness and ram resistance were taken vertically along the snowpack profile. Total snow depth
148 was measured from the ground up, and combined with density to yield snow water equivalent
149 (SWE). Physical snowpack properties were compared between non-snowmobile (control) and
150 varying degrees (low, medium (FEF), and high) of snowmobile use (treatment).
151 Density was measured at 10 cm intervals, from the surface of the snowpack to the ground, by
152 extracting a 250 mL or 1000 mL snow sample using a stainless-steel wedge cutter
153 <snowmetrics.com> and measuring the mass on an electronic scale with a resolution of 1g. With
154 the 1000 mL wedge cutter, the density of the snow (ρ_s in kg/m^3) was read directly from the scale
155 as the volume of the cutter is 1/1000 of a cubic meter and a gram is 1/1000 of a kilogram. For the
156 250 mL cutter, the mass measurement results were multiplied by 4 to obtain density. Snowpack
157 density profiles were created from a continuous profile of discrete 10 cm measurements. The
158 bulk snowpack density was determined by averaging ~~the depth integrated~~ density measurements
159 over the entire depth of the snowpack. A mean of the density measurements for the bottom 10
160 cm of the snowpack were used to evaluate changes near the snow and ground interface (basal
161 layer).

162 Temperature measurements were obtained at 5 cm intervals from the top to the bottom of
163 the snowpack using a dial stem thermometer with $\pm 1^\circ\text{C}$ accuracy. Temperature gradients are well
164 represented by this instrument, and the repeatability of temperature measurements are better than
165 $\pm 1^\circ\text{C}$ (Elder et al., 2009; American Avalanche Association, 2016). Snowpack temperature
166 profiles and the corresponding bulk temperature gradient were compared. The temperature

167 gradient (T_G in °C/m) was calculated as the ratio of the change in temperature (ΔT in °C) with the
168 distance (d in m) over which the change in temperature occurred. The snowpack temperature
169 gradient was approximated as linear from an upper boundary that was 25-30 cm below the
170 surface to the lower boundary at 0 cm. For this study, the depth below the snow surface where
171 temperature did not fluctuate diurnally was used as the upper boundary to remove bias from
172 diurnal fluctuations (Pomeroy and Brun, 2001). Basal layer temperatures taken at 0 cm were
173 used to compare temperature changes near the snow and ground interface.

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

180 Hardness is the penetration resistance of the snowpack (Fierz et al., 2009), and is reported
181 as the force per unit area required to penetrate the structure of the snowpack (McClung and
182 Schaerer, 2006). It is affected by snowpack microstructure and bonding characteristics of the
183 snow grains (Shapiro et al., 1997). Hardness measurements were taken horizontally with a force
184 gauge in each stratigraphic layer using a Wagner Instruments Force Dial gauge
185 (<http://wagnerinstruments.com>) with maximum force measurements of 25 N and 100 N, and
186 fabricated circular metal plate attachments of 20 cm² in area. For each measurement, the circular
187 metal plate was pushed into the snow and the force required to penetrate the snow was recorded.
188 The snow hardness (h_i in N/m²) for each stratigraphic layer was calculated as the force required
189 to penetrate the snow (F in N) per unit area of the circular metal plate (A in m²). All layers

190 thicker than 5 cm were identified using the 5-cm diameter of the plate. The bulk snowpack
191 hardness (H_B in N/m^2) was determined by weighting each stratigraphic layer hardness
192 measurement by the stratigraphic layer thickness. The hardness associated with the bottom
193 stratigraphic layer for each transect was used to describe hardness changes in the basal layer of
194 the snowpack.

195 The standard ram penetrometer is an instrument with a cone on the end of a rod onto
196 which a hammer of defined weight is dropped from a given height and the depth of penetration is
197 recorded; it was used here to vertically measure the resistance of snow layers to assess the
198 change in ram resistance due to compaction (American Avalanche Association, 2016). A ram
199 profile measurement was taken 0.5 meters from the edge of the snow pit wall subsequent to snow
200 pit profile measurements. The mean ram resistance (S_B in N) was determined by weighting each
201 ram resistance value obtained from the standard ram penetrometer measurement with the depth
202 sampled. The ram resistance value associated with the bottom layer was measured to describe
203 changes in ram resistance in the basal layer of the snowpack.

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205 3.3 *Statistical analyses*

206 Data were analyzed using the Mann-Whitney-Wilcoxon rank sum test (Wilcoxon, 1945;
207 Mann and Whitney, 1947). This statistical test is non-parametric and determines whether two
208 independent samples were selected from populations having the same distribution. For this work,
209 the sets of samples compared were density, temperature, hardness, and ram resistance profiles for
210 the five different monthly measurements and the controls (Table 1). A statistical significance
211 was determined for the 95% (significant) and 99% (highly significant) confidence interval
212 ($p < 0.05$, and $p < 0.01$) and noted with an asterisk in Table 1.

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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, and the number of passes (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 below average snow depth compared to the 15-year mean, based on the Columbine SNOTEL data averaged from 2003-2017 (Figure 3a). A peak SWE value of 556 mm on 9 April was 93% of the historical average. 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 snow depth 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

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237 4.2.1 Density


238 Snowpack properties were very similar for all plots, both prior to treatment at the start of
239 the experiment and for the untreated control plots (Figure 4). The mean density values at the
240 FEF plots were almost the same at the end of the sampling period in April (Figure 5a_{ii}). The
241 mean snowpack density increased over the snow season (Figure 5a), with the exception of the
242 FEF control and at the high use site on 12 Feb 2010 due to fresh snow deposition. At the REP
243 snow compaction study site, mean density for high use compaction treatments starting on 30 cm
244 of snow was greater throughout the measurement period than the no use treatment ~~throughout the~~
245 ~~winter~~ (Figures 5_{ia}, 6_{ai}, and 6_{a_{ii}}), while the density from low use starting on the deeper
246 snowpack of 120 cm was very similar to that measured for no use. The snowpack was more
247 dense for low use on the shallower snowpack (start at 30 cm) than the control, expect for 13
248 March (Figure 5_{ia}). Density differences are more pronounced for the basal layer (Figure 5_{ib}); for
249 compaction treatments starting at 30 cm, the lowest layers were much more dense (Figure 6_a).
250 Since the deeper snow (120 cm) treatment at REP was initiated on February 1st, these treatment
251 densities (low and high use, start at 120 cm) were the same as the control (Figures 5_{ia} and 5_{ib}).
252 After treatment, the high use treatment snowpack was more dense (Figures 5_{ia} and 5_{ib}).
253 Densities for the compaction treatments starting at 30 cm were significantly different than the
254 control and compaction treatments beginning at 120 cm of snow (Table 1a). The density
255 differences between the treatments on the deep snow (120 cm) and the control were not
256 significantly different (Table 1a).

257 Density increases due to snowmobile use were much greater at Fraser (Figures 5_{ii_a} and
258 5_{ii_b}) than Rabbit Ears. All treatments at FEF were significantly different than the control, but the

259 difference among treatments was not significant (Table 1a). The density differences among
260 treatments are highlighted in the 10-cm individual density measurements (Figure 6a) and in the
261 basal layer (Figure 5iib).

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263 4.2.2 *Temperature*

264 Low and high use compaction treatments at the REP snow compaction study site that
265 began on both a shallow snowpack of 30 cm and on a deep snowpack of 120 cm did not result in
266 significant changes in temperature gradient. The maximum temperature gradients were observed
267 on the earliest sampling date (12 December, Figure 5c) as 18, 28, and 25°C/m for the control,
268 low use, and high use compaction treatments that began on a shallow snowpack, while they were
269 almost the same (23, 23, and 25°C/m) for the control, low use, and high use compaction
270 treatments that began on a deep snowpack. Temperature gradients for all treatments decreased
271 throughout the winter season, and were isothermal at 0°C/m by mid to late April (Figures 5ic and
272 5iic), since the snow had started to melt (Figure 3). Overall, temperature gradients were not very
273 different (Figure 5c) and were not found to be significant (Table 1b). 

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275 4.2.3 *Hardness*

276 The snowpack was harder for snowmobile use starting on 30cm than the control (no use)
277 for both sites (Figures 5d and 5e). Mean snowpack hardness did not change much over time
278 (Figure 5d), except once high use treatments started (06 Feb) on a deeper snowpack. However,
279 basal layer hardness did decline at REP for both high and low use starting on 30 cm (Figure 5ie).
280 With treatments at FEF, the hardness was always much higher than the control (Figure 5iid).
281 Hardness initially increased at the REP snow compaction study site following low and high use

282 compaction treatments that began on 30 cm of snow (Figure 5id), but these were about the same
283 as the control by 17 Apr, when melt had started. Significant increases in hardness were observed
284 between treatments that began on 30 cm of snow and the control, and between compaction
285 treatments (low and high) that began on 120 cm of snow (Table 1c). In contrast, mean snowpack
286 hardness was not significantly impacted by snow compaction treatments that began on 120 cm of
287 snow (Table 1c). Mean snowpack hardness increased following the initial snow compaction
288 treatments for low and high use, but subsequent compaction treatments did not appear to have a
289 large effect (Table 1c). Mean snowpack hardness for low and high use was greater than the
290 control following the initial snow compaction treatment for both initiation depths (30 cm and 120
291 cm), but there were minimal differences by the last sampling date (Figure 5ie).

292 Snow compaction treatments that began on 30 cm of snow increased basal layer hardness
293 (Figure 5ie), but treatments that began on 120 cm of snow did not impact basal layer hardness
294 (Figure 5ie). For both controls and all treatments that began on 120 cm of snow (Figure 5ie), the
295 maximum basal layer hardness was about 6 kPa. Increased hardness due to snowmobile use
296 showed similar temporal patterns to densification (Figures 5a and 5d). At REP, snowmobile use
297 compacted the second layer below the surface, and high use (50 passes) made that layer about 10
298 times harder than the low use (5 passes) snowpack (Figures 6bi and 6bii).

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

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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 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 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 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 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 found in the basal layer of the treated plots, which began rounding by the last sampling date (Figure 5iif). The shallower snow at FEF enabled large faceted crystals to grow in the basal layer, up to 9 mm in size (Figure 5iif).

328 4.3 *Operational Sites*

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

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341 4.4 *Bulk Snowpack Density Change Model*

342 A non-linear bulk snowpack density change model was created using data from the
343 experiments prior to onset of melt conditions (Fassnacht et al., 2010); before the last sampling
344 date (Figure 3) and prior to when the difference in density between the control and treatments
345 was small (Figure 5a). Additionally, treatments starting on a deep snowpack at REP were not
346 significantly different than the control (Figure 5a, Table 1) and were not used in fitting the
347 model. The variables of number of passes per treatment, depth, and bulk density were tested for
348 correlation that might result in model over-fitting. Cross-correlation results were small
349 ($R^2 < 0.04$), so these variables were used to create the model. Change in bulk density due to
350 snowmobile use is a function of the number of passes and bulk density, but it is inversely related

351 to snow depth (Figure 8a). The optimal model had a NSCE of 0.81 (Figure 8a), which is
352 considered very good (Moriassi et al., 2007). The model was calibrated on the experimental data
353 (Figure 8a) and applied to the operational sites (Figure 8b), with no passes occurring equivalent
354 to a density change of 0 kg/m^3 . The evaluation results were less optimal, with a NSCE of -0.79
355 for the four dates tested in December through March (Figure 8b). The poorer performance of the
356 model at the operational sites is due to an unknown number of snowmobile passes at each site
357 and from limited snowmobile use early in the season (December), resulting in minimal
358 differences between compaction levels at that time (Figures 7 and 8b). Removal of the December
359 data points and using only the January through March dates improved the model fit to a NSCE of
360 0.34 (Figure 8b).

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362 **5. Discussion**

363 **5.1 Observed Changes to Snowpack Properties**

364 Snowpack changes were observed for varying snowmobile use beginning with two
365 different snow depths (REP only in Figure 5 or 6i and 6ii) and for two different snow-covered
366 environments (Figures 5 and 6). A total of 101 snowpits (50 at REP, 15 at the operational sites,
367 and 36 at FEF) were dug and sampled for this work. The increase in density and hardness from
368 snowmobile use is greatest compared to an untreated snowpack in early to mid-season (January)
369 for a deeper snowpack at REP, with density increases of 7-33% and hardness 4 to 13 times
370 greater than the control (Figures 5ia and 5id). For a shallower snowpack at FEF, density
371 increased by 64-76% and hardness was 500-2000 times greater than the control (Figures 5iia and
372 5iid).

373 Similar differences were found from ski run grooming in an Australia snowpack with a
374 400% increase in hardness early in the snow season but only about a 40% increase later in the
375 winter (Fahey et al., 1999). Snow grooming increased the average density by up to 36%
376 compared to non-groomed ski slopes (Fahey et al., 1999, Rixen et al., 2001).

377 At rest, a snowmobile and its rider exert 4 to 10 kPa of pressure to the underlying
378 snowpack. This assumes a track length from 0.9 to 1.4 m, width of 0.50 m, a snowmobile weight
379 of 200 to 350 kg, and a rider weight of about 100 kg (data from <polarisindustries.com>). There
380 is an increase of less than an order of magnitude due to snowmobile movement. Thumlert et al.
381 (2013), measured stresses of about 10 to 20 kPa at a depth of 30 cm below the surface of a deep
382 snowpack. At 20 cm below the snow surface, the induced stress from a snowmobile is already
383 much less than 10 cm below the surface (Thumlert et al., 2013). Grooming vehicles add a force
384 similar to snowmobiles (Pytko, 2010) based on mass and track size. The snowpack property
385 changes we observed could therefore also be representative of impacts from both types of
386 vehicles. Snowpack loading by wheeled vehicles on a shallow snowpack was much greater than
387 that of a snowmobile, peaking at about 350 kPa (Pytko, 2010). In comparison, fresh snow with a
388 density of 100 kg/m^3 exerts a pressure of 0.003 kPa on the underlying snowpack (Moynier,
389 2006).

390 Compaction due to snowmobile use increased density of the snowpack which influences
391 snow hardness (Figure 5d and 5e) and ram resistance (Figure 6c). Compaction altered snow
392 characteristics (Figures 5, 6, and 7), fragmented faceted grains (Figure 5iif), and reduced the
393 growth of faceted grains (Figure 5f). While density measurements for fresh and/or uncompacted
394 snow vary spatially and temporally (Figure 4) and can range from 40 to 200 kg/m^3 depending on
395 the environment (Fassnacht and Soulis, 2002), these values can double with just one pass of a

396 snowmobile on a very shallow snowpack (Keddy et al., 1979). The snowpack properties of a
397 shallow snow environment can be more greatly affected by compaction from snowmobile use
398 than those for an area that receives more snow (e.g., Figure 3b versus Figure 3a). With more
399 snow accumulation, density also increases, but high levels of snowmobile use will tend to
400 increase the density above what is observed with non-snowmobile impacted snow (Figures 5, 6,
401 and 7).

402 Density differences were greatest for a shallow snow cover environment (FEF), while no
403 significant differences in density were observed when snowmobile use began on a deep
404 snowpack (120 cm) (Figure 5a, Table 1). Snowmobile use beginning on a shallow snowpack (30
405 cm) for an overall deeper snowpack (REP) resulted in a 2- and 6-fold increase in maximum snow
406 hardness for low and high use compared to no use (Figures 5id and 5ie), whereas at a shallow
407 snow study site (FEF), a 15-, 30- and nearly 200-fold increase in maximum snow hardness for
408 low, medium, and high use was observed (Figures 5iid and 5iie). The impact of snowmobile use
409 on snowpack ram resistance has only previously been observed by Pruitt (2005), who stated that
410 the ram resistance of fresh snow and layers with limited metamorphism was less than 1N and
411 could increase by 70N due to two passes of a snowmobile. The change in ram resistance seen at
412 REP and FEF mirrored what was observed with changes in hardness (Figures 6b and 6c, 7b and
413 7c).

414

415 **5.2 Limitations of the Measurements**

416

417 Variability in snow conditions were observed from site to site (Figure 4) and through time,
418 with the mean snowpack density being less in February (Figure 6) than January at FEF (Figure
419 5ii). From the operational sites, specific hard layers and high values of ram resistance were

420 measured that did not persist until the next monthly sampling (Figure 7; and observed in the
421 experimental treatments- not shown graphically). These variations were possibly a combination
422 of naturally occurring spatio-temporal snowpack variability and sampling errors; it can be
423 difficult to obtain reliable hardness measurements in snow disturbed by snowmobiles. Future
424 investigations could focus on specific aspects of this study, such as using a finer temporal
425 resolution, but with fewer treatments.

426 Another source of variability or bias is the type of equipment used for sampling. Density
427 and temperature were measured at 10-cm intervals using the Snowmetrics wedge cutter and dial
428 gauge thermometers. A different sampler could be used to measure the density over each layer
429 and other types of thermometers could be used. Snow-hardness gauges and circular metal plates
430 of known area were used for hardness testing (McClung and Schaerer, 2006), rather than the
431 more simplistic in situ hand hardness test (American Avalanche Association, 2016). However,
432 the hardness of thin layers could not be measured as the circular metal plate used for
433 measurements had a diameter of 5 cm, omitting the possible measurement of these thin layers.
434 Thus, bulk hardness was possibly under-estimated. Also, due to compaction of the snow grains
435 by the high use 30-cm start treatment at REP the hardness could not be measured (Figure 5id).
436 Different equipment may resolve this issue.

437

438 **5.3 Significance of the Changes to Snowpack Properties from Snowmobile Use**

439 Snowmobile use was found to have a highly significant effect upon natural vegetation
440 below the snow (Keddy et al., 1979), and by extension from snowmaking as well (Rixen et al.,
441 2003). Ski grooming has been shown to delay the blooming of alpine plants (Rixen et al., 2001)
442 due to later snowmelt and significantly cooler soil temperatures (Fassnacht and Soulis, 2002).
443 Deeper snowpacks were found to not have cooler soil temperatures under the snowpack (Keller

444 et al., 2004), but melted out four weeks later than thinner snowpacks (Keller et al., 2004). Since
445 the changes due to snowmobile traffic on a shallow snowpack were significant (Table 1), the
446 effects of snowmobile use on the soil and vegetation underlying a shallow snowpack should be
447 further investigated.

448 Snowmobile use, starting with a shallow or thin (30 cm) snowpack, resulted in a denser
449 and harder snowpack with a decrease in grain size throughout the season, and rounded crystals or
450 facets observed with the last measurements (Figure 5f). If compaction penetrates deep enough
451 into the snowpack, it could affect weak layers that cause avalanches (Saly et al., 2016), which are
452 typically composed of soft layers consisting of large faceted grains (e.g. Schweizer and
453 Jamieson, 2003; van Herwijnen and Jamieson, 2007). While this may be useful in very limited
454 and small areas, such as that performed in boot packing programs (e.g. Sahn, 2010) to strengthen
455 snowpacks likely to fail on basal facets, it is very difficult to properly align and reproduce the
456 intensity of repetitive tracks, as done experimentally here (Figure 2). The effects of snowmobile
457 use for avalanche hazard reduction through changing snow stability properties requires more
458 investigation.

459 Other factors acting in concert with snowmobile traffic to affect snowpack properties
460 include wind, snowmaking/grooming, and a changing climate. Without the effects of wind, snow
461 depth will generally be lower for areas with snowmobile traffic (Figures 2d, 2e, and 7; Rixen et
462 al., 2001; Spandre et al., 2016a). However, wind is often present in open areas where
463 snowmobiling occurs. Local terrain features and position and extent of canopy cover influence
464 how the wind interacts with the snowpack (Pomeroy and Brun, 2001). In an Australian case
465 study, SWE increased by 45% in groomed areas (Fahey et al., 1999); at the Rabbit Ears Pass
466 recreational use areas, SWE also increased (Figure 7d) likely due to snow blowing into the

467 depressions created by snowmobile tracks (Figure 2d). The increased load could further impact
468 the underlying snowpack properties. Further, snowmaking (Spandre et al., 2016a) to supplement
469 natural snow conditions and /or grooming (Fahey et al., 1999; Rixen et al., 2001; Spandre et al.,
470 2016a) compacts the snowpack below it, and alters the underlying snowpack properties (Howard
471 and Stull, 2014; Spandre et al., 2016a; Spandre et al., 2016b). Also, a changing climate will
472 likely reduce the extent of snow-covered terrain and decrease the length of the winter recreation
473 season (Lazar and Williams, 2008; Steiger, 2010; Dawson and Scott, 2013; Marke et al., 2015;
474 Schmucki et al., 2015; Tercek and Rodman, 2016; Marty et al., 2017). In addition to possible
475 effects from a changing climate, inter-annual variability of snowpack patterns can be large in
476 Colorado (Fassnacht and Hultstrand, 2015; Fassnacht and Records, 2015; Fassnacht et al., 2017).
477 The effects of this variability should be included in long term motorized use land management
478 considerations.

479 The significant change to snowpack properties by snowmobiles, except when treatments/use
480 were initiated on a deep snowpack (Table 1), could impact land management decisions for multi-
481 use public lands. The measured depth of influence for a snowmobile is about 90 cm according to
482 work done by Thumlert et al. (2013), but additional work could test starting depths such as 30,
483 60 and 90 cm in differing snow conditions to identify the depth when snowmobile use has no
484 significant impact. Most ski resorts in the French Alps required a minimum snow depth of 40 cm
485 to offer skiing, with a range from 60 cm in February to 40 cm in April (Spandre et al., 2016b).
486 The US Forest Service (2013b) recommends a minimum of 30 cm before the use of
487 snowmobiles. Increasing the minimum snow depth before allowing snowmobile traffic will
488 reduce changes to the snowpack due to snowmobile traffic (Table 1). Additionally, the non-
489 linear bulk density change model developed here and applied to operational sites could be used

490 predictively for management needs. This model may be useful in terms of estimating when to
491 limit snowmobile use given changes in specific snow depth and density conditions.

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

500

501 **6. Conclusion**

502 Snowmobiling is a multimillion dollar industry that impacts local and regional economies
503 and public recreation lands. There have been limited studies regarding the influence of
504 snowmobile use on snowpack properties. We examined the effect of snowmobile use on the
505 physical and material properties of the snowpack at sites with varying snowmobile use and
506 seasonal snow conditions. Low, medium, and high snowmobile use was simulated on
507 experimental transects and snowpack sampling results from the treated sites were compared to
508 the snowpack properties observed at undisturbed control sites, and at operational sites with
509 varying levels of use. A non-linear bulk snowpack density change model was developed relating
510 changes in bulk density to snowmobile use as a function of the number of passes, snow depth
511 (inverse relation) and bulk density. The largest differences in snowpack properties occur with
512 snowmobile use beginning on a shallow snowpack (30 cm) compared to no use, which increases

513 snowpack density, hardness, and ram resistance. These increases are directly related to
514 increasing snowmobile use (from low to medium to high). Conversely, snowmobile use that
515 begins on a deep snowpack (120 cm) has a limited effect on the snowpack properties of density,
516 temperature, hardness, and ram resistance as compared to an undisturbed snowpack. These
517 results suggest that from a management standpoint, it may be desirable to limit snowmobile use
518 in shallower snow conditions to avoid increases in density, hardness, and ram resistance that
519 could possibly impact land resources below the snowpack.

520

521 **Author contribution**

522 The experiments were designed by J.T. Heath and S.R. Fassnacht with input from K.J. Elder. J.T.
523 Heath performed the experiments with assistance from K.J. Elder at the Fraser site. The initial
524 manuscript was written by J.T. Heath, S.R. Fassnacht, and K.J. Elder. The final version of the
525 manuscript was written by S.R. Fassnacht and N.B.H Venable. S.R. Fassnacht generated the
526 figures and created the density model.

527

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537 this paper, and resulted in the creation of new figures. While the comments from this reviewer
538 provided a challenge, they were appreciated after they had been addressed. TC editor Dr.
539 Guillaume Chambon provided additional comments and an important citation that helped
540 reformulate the discussion.

541

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699

700 **Table 1.** Statistical difference (p-values) between no snowmobile use (control) and varying snow
 701 compaction treatments on snowpack properties at the study plots located at Rabbit Ears Pass
 702 (REP) and Fraser Experimental Forest (FEF), Colorado during the 2009-2010 winter season for
 703 a) density, b) temperature, c) hardness, and e) ram resistance. Statistically significant differences
 704 at the p<0.05 confident level are highlighted in grey, and highly significant (p<0.01) difference
 705 are denoted with an asterisk.
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 707

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

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

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

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

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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 5 through 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/>).
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).
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 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.
6. a) Density, b) hardness, and c) ram resistance profiles for the February sampling dates (06 Feb at REP and 12 Feb at FEF) measured at the REP snow compaction study plot for no (control), low, and high use treatments beginning on i) 30 cm and ii) 120 cm of snow, and iii) the FEF snow compaction study plot for no (control), low, medium, and high use treatments beginning on 30 cm of snow. Note that free floating measurements represent overlapping density measurements. The ground is at zero snow depth.

7. 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, d) SWE, and e) snow depth. For a through c, the left panel (i) is the mean snowpack value and the right panel (ii) is the basal layer value.

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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).

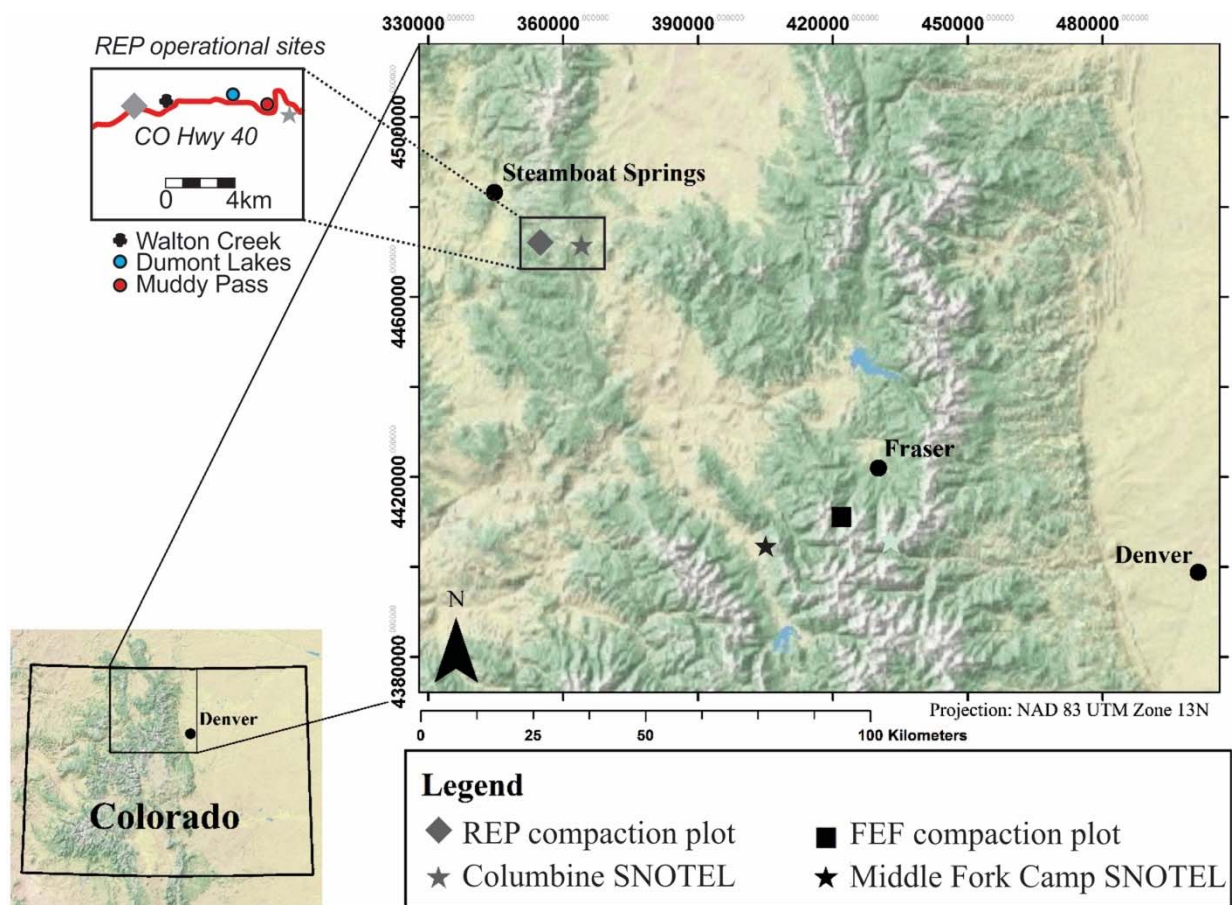


Figure 1. The snow compaction study plots are located in north-central Colorado. The Rabbit Ears Pass (REP) site is within the Routt National Forest near the town of Steamboat Springs, as are the three operational (non-experimentally manipulated) sites (Walton Creek with no use, Dumont Lakes with low 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.

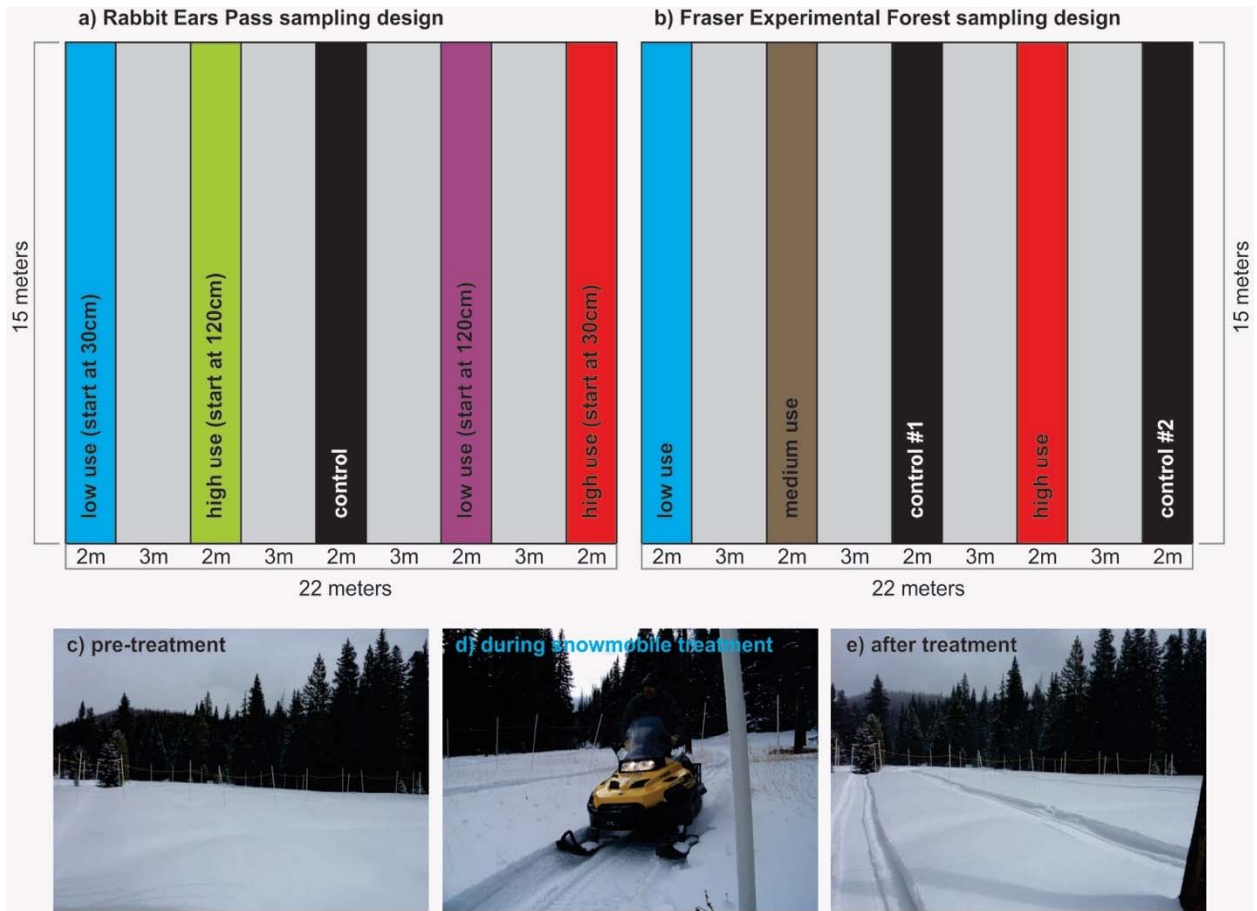


Figure 2. The sampling design for the snow compaction plots at a) Rabbit Ears Pass, b) Fraser Experimental Forest, and photographs of the study plots c) pre-treatment, d) during treatment, and e) after treatment. The colors used for the control and treatment plots are used in Figures 5 through 8.

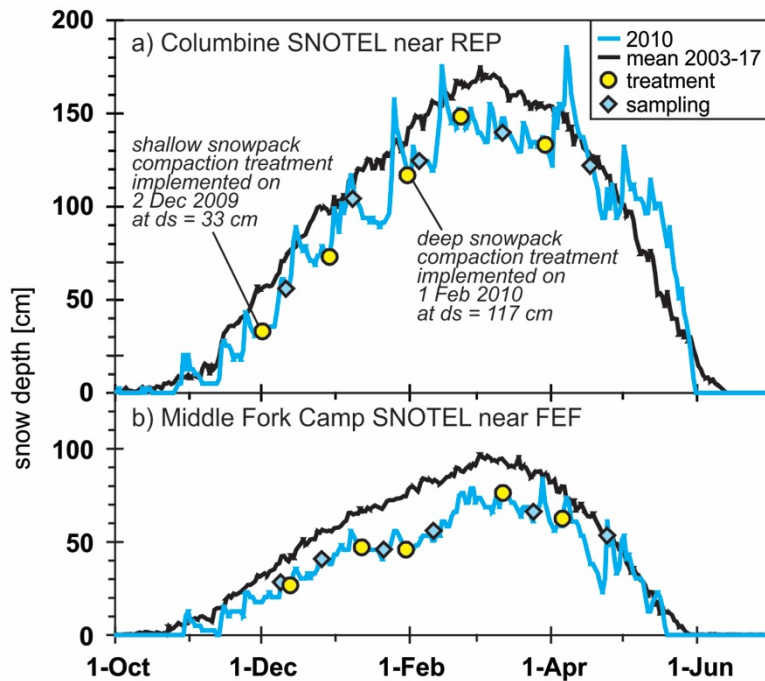


Figure 3. Mean snow depth from 2003-2017, and for the 2010 water year (WY2010) measured at a) the Columbine SNOTEL site near Rabbit Ears Pass (REP), Colorado and b) the Middle Fork Camp SNOTEL near Fraser Experimental Forest (FEF), Colorado, illustrating the dates of treatment and dates of sampling.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

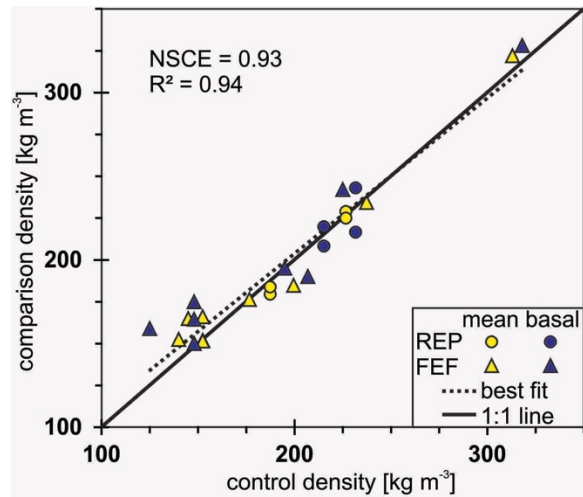
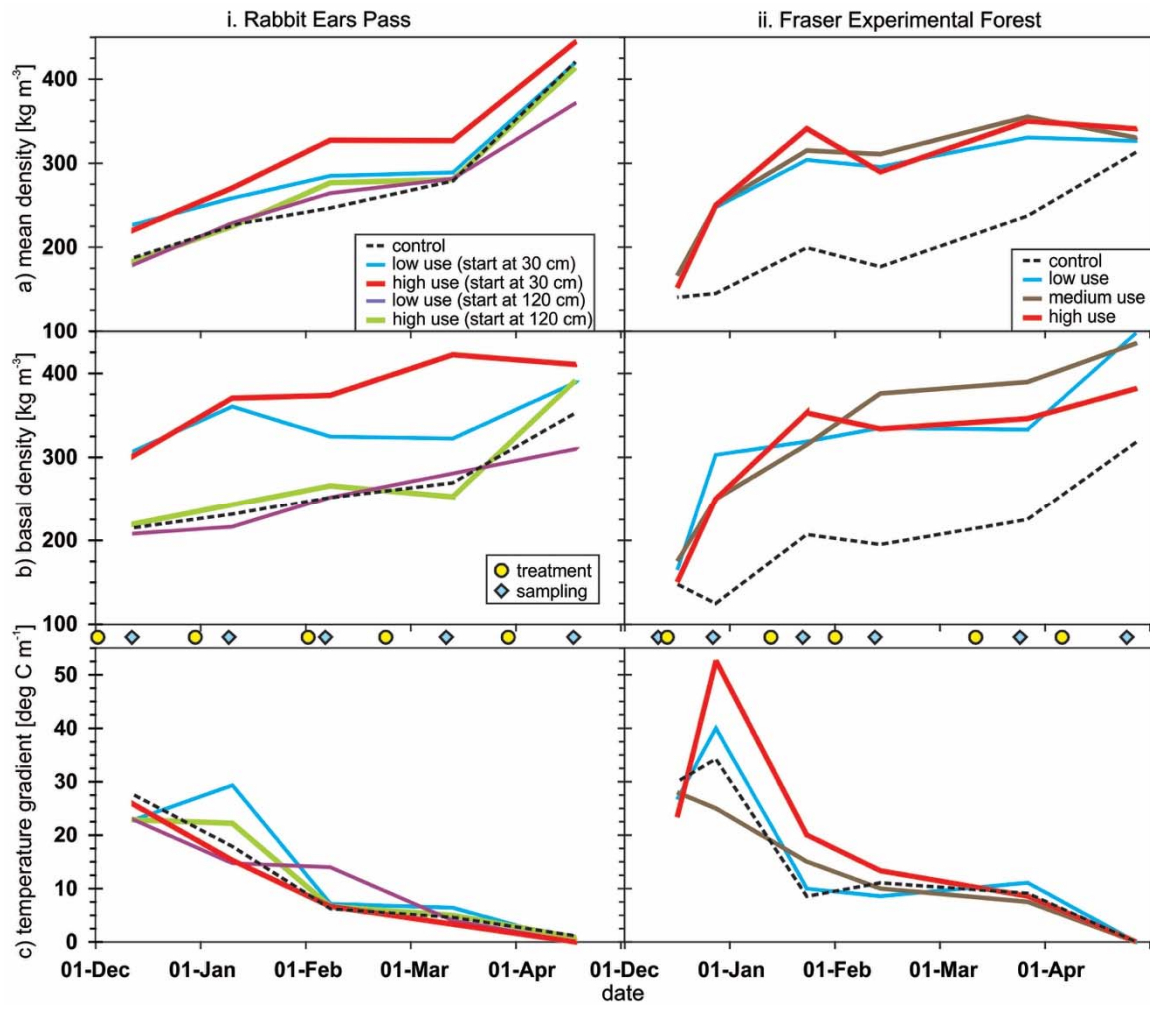


Figure 4. Spatial variability of mean (yellow) and basal (blue) snowpack density by comparison of values at the Rabbit Ears Pass (REP shown with circles) deep snow (120 cm) compaction treatments (low and high use) and the control on the first two sampling dates, and at the Frase Experiment Forest (FEF 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).



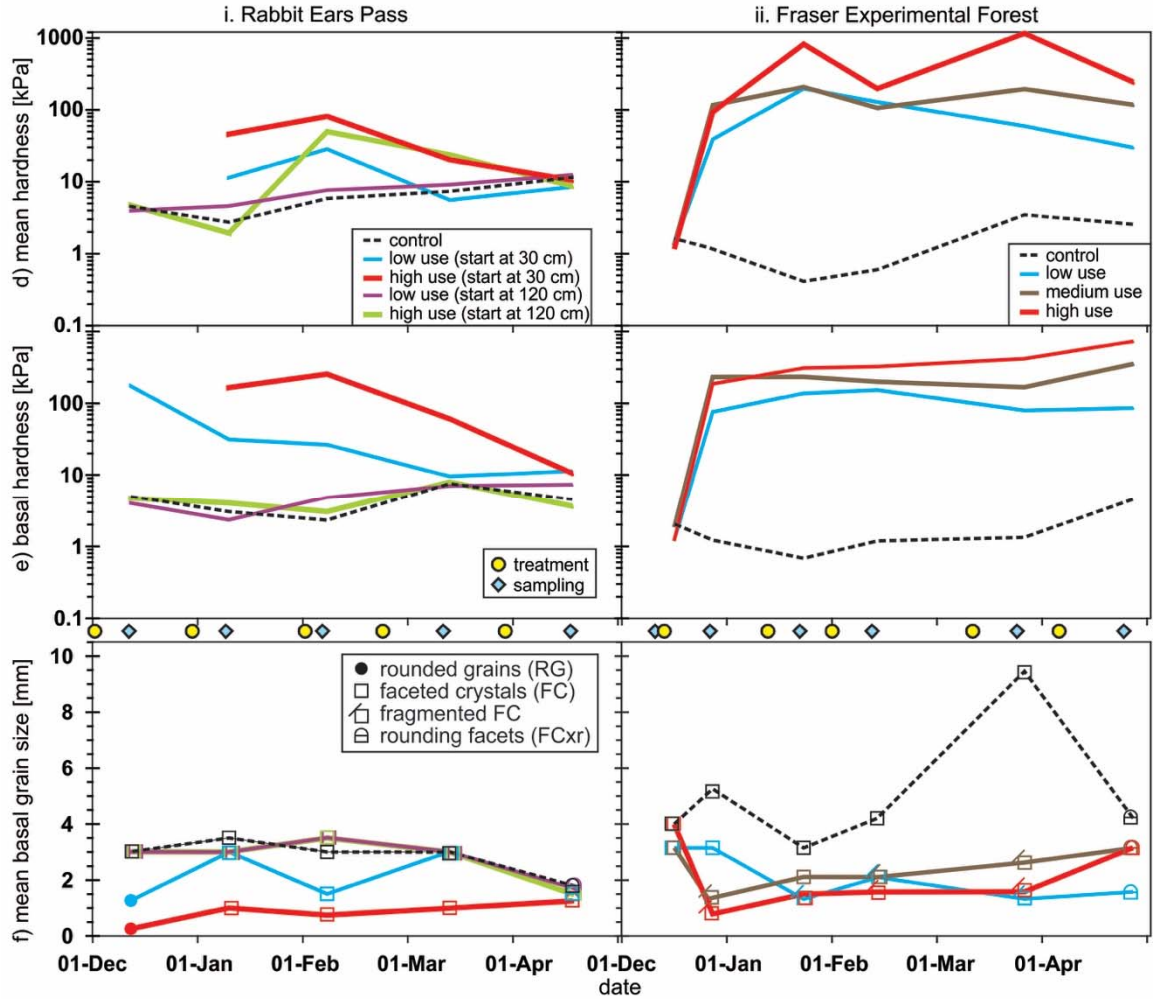


Figure 5. Time series for i. Rabbit Ear Pass (REP) and ii. Fraser Experimental Forest (FEF) at the different sampling dates of a) mean snowpack density, b) basal snowpack density, c) snowpack temperature gradient, d) mean snowpack hardness, e) basal layer hardness, and f) mean basal crystal size and shape. The crystal shape is included as per Fierz et al. (2009), with the exception of 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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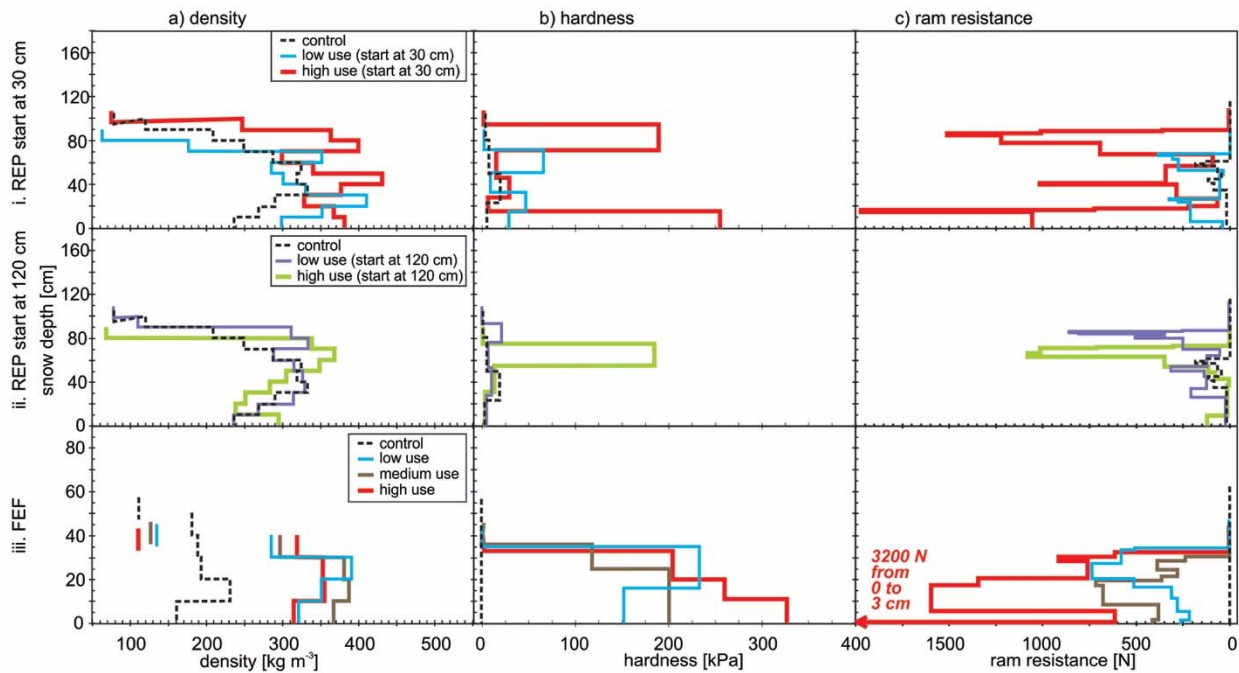


Figure 6. a) Density, b) hardness, and c) ram resistance profiles for the February sampling dates (06 Feb at REP and 12 Feb at FEF) measured at the REP snow compaction study plot for no (control), low, and high use treatments beginning on i) 30 cm and ii) 120 cm of snow, and iii) the FEF snow compaction study plot for no (control), low, medium, and high use treatments beginning on 30 cm of snow. Note that free floating measurements represent overlapping density measurements. The ground is at zero snow depth.

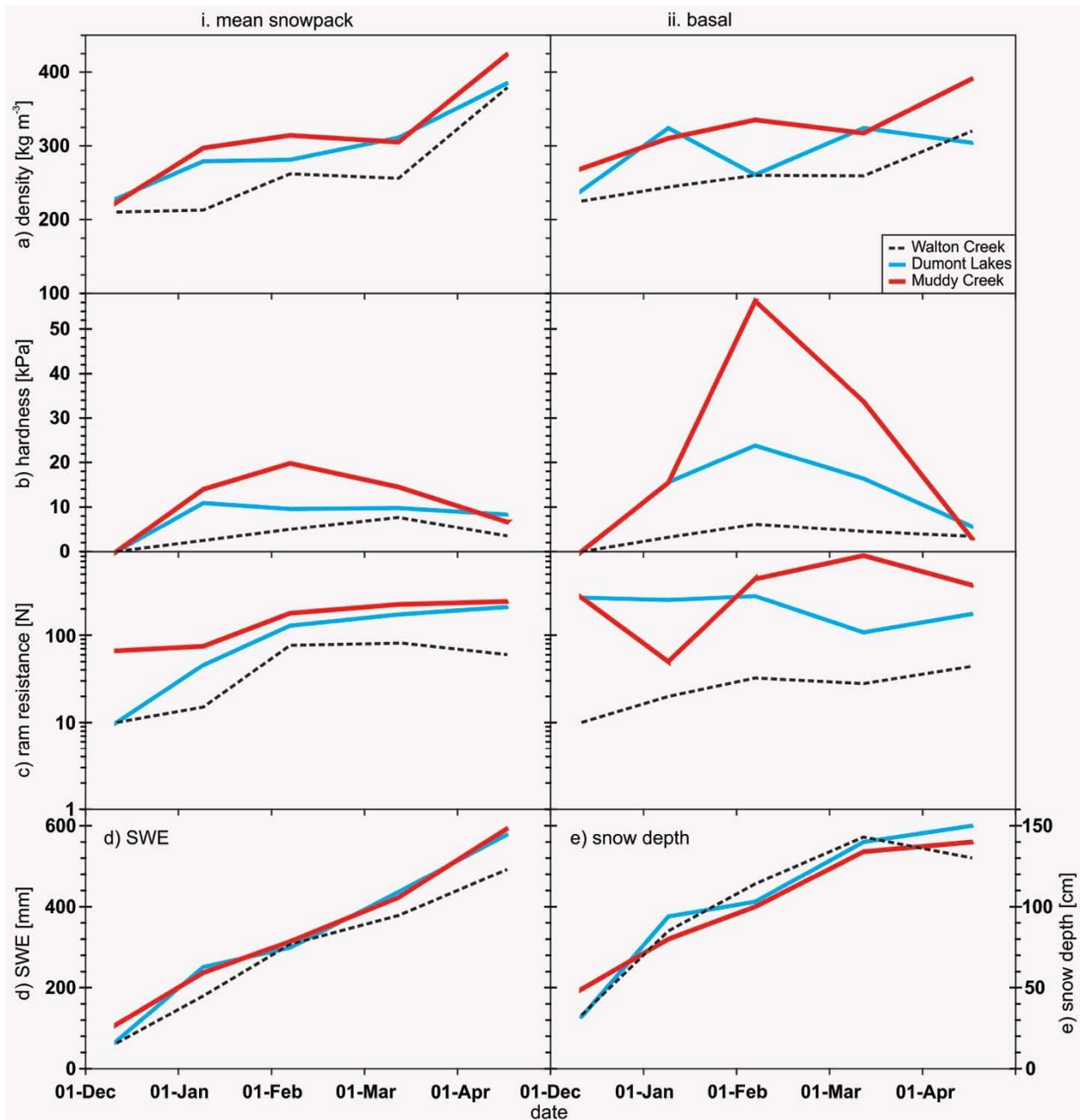


Figure 7. Snowpit data for Walton Creek (no snowmobile use), Dumont Lakes (moderate snowmobile use) and Muddy Creek (high snowmobile use) in the Rabbit Ears Pass recreational use areas illustrating a) density, b) hardness, c) ram resistance, d) SWE, and e) snow depth. For a through c, the left panel (i) is the mean snowpack value and the right panel (ii) is the basal layer value.

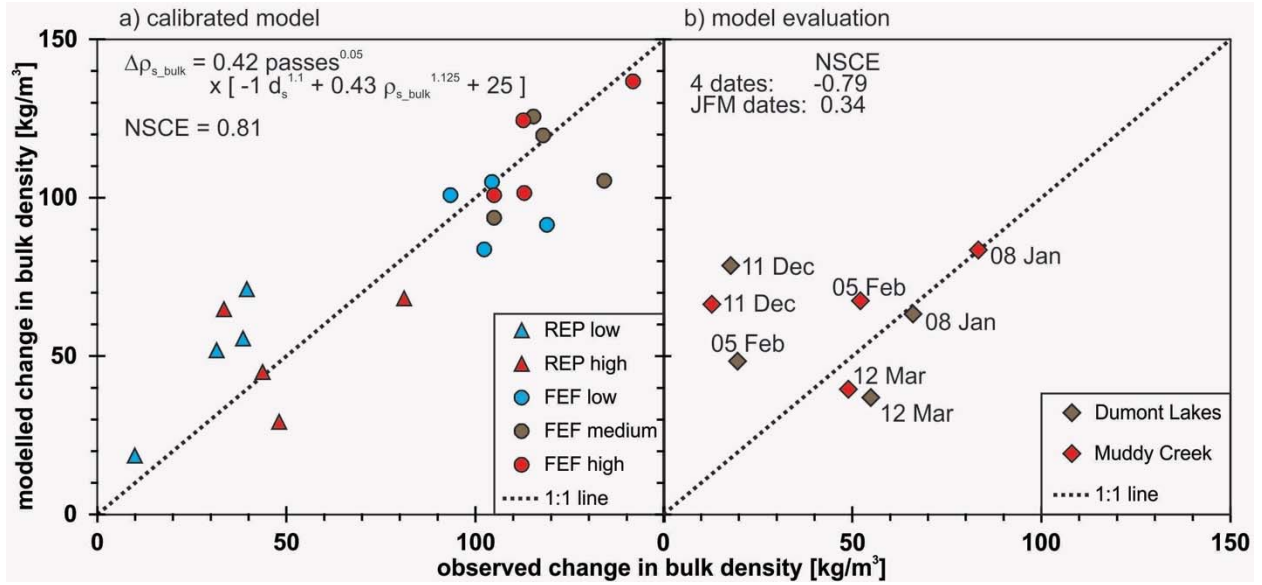


Figure 8. Bulk snowpack density change model for different amounts of use compared to the control of no use a) calibrated for the two experiment sites (Rabbit Ears Pass, REP and Fraser Experimental Forest, FEF), and b) applied to the operational sites (Dumont Lakes and Muddy Creek), compared to the no 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).