



1 **Snowmobile Impacts on the Physical and Mechanical Properties of Different Snowpacks in**
2 **Colorado, U.S.A.**

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



1 **Abstract**

2 Physical and material properties of the snowpack, including snow density, temperature,
3 stratigraphy, hardness, and ram resistance were measured from snow pit profiles to examine the
4 statistical difference between no use and varying degrees of snowmobile use (low, medium and
5 high). The properties were examined across the entire snowpack, from the surface to its base, and
6 for the basal layer of the snowpack. Experimental snow compaction study plots were located
7 near Rabbit Ears Pass near Steamboat Springs, Colorado and at Fraser Experimental Forest near
8 Fraser, Colorado. Significant changes in snowpack properties are associated with snowmobile
9 use beginning early in the snow accumulation season when the snowpack is shallow, as well as
10 earlier in the winter and at the base of the snowpack. These effects were amplified when
11 snowmobile use occurred on a shallow snow covered environment and with increasing degrees
12 of snowmobile use. On the contrary, snowmobile use that began on a deeper snowpack showed
13 no significant changes in snowpack properties suggesting later initiation of use minimizes
14 impacts to snowpack properties from snowmobile use.

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16




17 **1. Introduction**

18 Winter recreation on snow is big business; in the United States, skiing accounted for over
19 \$12 billion in 2010 (Burakowski and Magnusson, 2012) while snowmobiling accounted for
20 between \$7 billion (American Council of Snowmobile Associations, 2014) to \$26 billion
21 (International Snowmobile Manufacturers Association, 2016) annually. Across the United States,
22 much of the snowmobile use is on public land, such as United States National Forest System
23 with about 6 million snowmobile visits annually accessing about 327,000 km² of land (US Forest
24 Service, 2010 and 2013a). Across the six Colorado and one southern Wyoming National Forests
25 (NFs) there are 1.1 to 1.6 million annual snowmobile visits, with an increase from 580 thousand
26 to 690 thousand between 2010 to 2013 in northern Colorado (Routt NF and Arapaho-Roosevelt
27 NF) and southern Wyoming (Medicine Bow NF) (US Forest Service, 2010 and 2013a).
28 Annually, snowmobiling added \$130 million to the Colorado economy (Colorado Off-Highway
29 Vehicle Coalition, 2016) and \$125 millions to the Wyoming economy (Nagler et al., 2012). As
30 the number of people participating in these activities increases annually (Cook and Borrie, 1995;
31 Winter Wildlands Alliance, 2006), the presence of these human activities, especially snowmobile
32 use, may be influencing snowpack properties in seasonally snow-covered environments. Further,
33 as the climate changes, there will be reduced land available for snowmobiling (Tercek and
34 Rodman, 2016), likely increasing the impact of snowmobile traffic.

35 There have been limited studies regarding the influence of snowmobile use on snowpack
36 properties (Keddy et al., 1979; Thumlert et al., 2013). Snowmobile use on shallow snow (10 to
37 20 cm deep) caused a doubling of fresh snow density, but much less impact on the underlying
38 old snow, and had a highly significant effect upon natural vegetation below the snow (Keddy et
39 al., 1979). For deeper snow, variation in stress on the snowpack was attributed to the type of



40 loading, depth and snowpack stratigraphy, stress decreased with increased depth and layer
41 hardness, with more cohesive or supportive layers higher in the snowpack distributing the
42 surface load (Thumlert et al., 2013). Most relevant studies relate to snow grooming at ski resorts
43 (Fahay et al., 1999; Keller et al., 2004; Spandre et al., 2016a), or to traction and mobility of
44 wheeled vehicles across a snowpack (Abele and Gow, 1990; Shoop et al., 2006; Pytka, 2010).
45 We examined the effect of snowmobile use on the physical and material properties of the
46 snowpack. The objectives of this research were: (1) quantify changes to physical snowpack
47 properties due to compaction by snowmobiles; and (2) evaluate these changes based on the
48 amount of use, depth of snow when snowmobile use begins,  the snowfall environment where
49 snowmobiles operate. This work examines both the entire snowpack and the basal layer.

50

51 2. Study Sites

52 During the 2009-2010 snow season a set of snow compaction plots were located near
53 Rabbit Ears Pass (REP) in the Rocky Mountains of northern Colorado to southeast of the town of
54 Steamboat Springs. REP is within the Medicine Bow-Routt NF (Figure 1) along the Continental
55 Divide encompassing over 9,400 km² (2 million acres) of land in Colorado and Wyoming.
56 Rabbit Ears Pass is especially popular during the winter season and is heavily used by
57 snowmobilers and other winter recreationalists due to the ease of access to backcountry terrain
58 from Colorado Highway 40. Due to heavy use and conflict among users during the winter
59 season, the Forest Service manages Rabbit Ears Pass for both non-motorized and motorized uses.
60 The west side of pass is designated for non-motorized users and prohibits the use of motorized
61 winter recreation and, the east side of the pass is a mixed use area and open to motorized users
62 (Figure 1).



63 Two REP experimental snow compaction study plots were located adjacent to one
64 another within an open meadow north of Colorado Highway 40 at an elevation of approximately
65 3,059 m (Figure 1). The snow compaction sites were established within an area that prohibits
66 motorized use to protect the study sites from unintended impacts of snowmobilers. The
67 Columbine snow telemetry (SNOTEL) station, located at an elevation of 2,792 m, was used to
68 characterize the 2009-2010 winter on REP.

69 Three operational sites were identified along Colorado Highway 40 on REP (Figure 1 left
70 inset) where the specific amount of snowmobile use was unknown. The “natural” control site
71 was Walton Creek, located west of Rabbit Ears Pass in an open meadow at an elevation of 2,895
72 m within a managed area that prohibits motorized use. Snowshoers, skiers, and snowboarders
73 primarily use this area in the winter to access backcountry terrain. Two treatment sites were
74 located east of REP at an elevation of about 2,900 m within an area managed for motorized and
75 mixed uses; the Dumont Lakes and Muddy Creek sites were located in open meadows near their
76 trailheads (Figure 1). These trailheads provide backcountry access to snowmobilers and
77 snowmobile use in the meadows near the trailheads is medium to high, especially on weekends
78 and over holidays. The meadow near the Muddy Creek trailhead is more heavily used by
79 snowmobiles than the meadow near the Dumont Lakes trailhead.

80 Another experimental snow compaction plot was established at the Fraser Experimental
81 Forest (FEF) near the town of Fraser, Colorado in the Rocky Mountains of Central Colorado
82 (Figure 1). The 93 km² experimental forest is a research unit of the United States Forest Service
83 (USFS) Rocky Mountain Research Station (RMRS) located within the Arapaho NF. The FEF
84 snow compaction site was located in a small meadow at an elevation of 2,851 m among
85 lodgepole pine (*Pinus contorta*) forest. The Fraser Experimental Forest is closed to snowmobile




86 use, but is used in the winter to access backcountry terrain by snowshoers, skiers, and
87 snowboarders. The Berthoud Summit SNOTEL station, located at an elevation of 3,444 m, was
88 used to characterize the 2009-2010 winter at FEF.

89

90 **3. Methods**

91 **3.1 *Experimental snow compaction plots***

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

101 Transects were treated by driving  over the length of each transect five, 25
102 (FEF only) or 50 times, representing low, medium (FEF only), and high snowmobile use,
103 respectively. Treatments began when non-compacted snow depths were approximately 30 cm
104 (12 inches) for both locations, and when unpacked snow depths equaled approximately 120 cm
105 (48 inches) for REP only. Treatments were implemented monthly thereafter, until peak
106 accumulation (Figure 2). Snowpack sampling was performed within a week after each treatment,
107 and continued through the duration of the winter season (Figure 2).

108



109 **3.2 Snow pit analyses and data collection**

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

117 Density was measured at 10 cm intervals, from the surface of the snowpack to the
118 ground, by extracting a 250 mL or 1000 mL snow sample using a stainless steel wedge cutter
119 snowmeters.com and measuring the mass on an electronic scale with a resolution of 1g. The
120 density of the snow (ρ_s in kg/m^3) was determined by dividing the mass of the snow sample by the
121 volume of the wedge cutter. Snowpack density profiles and bulk snowpack density were
122 compared. The bulk snowpack density was determined by averaging the depth integrated density
123 measurements through the entire depth of the snowpack. A mean of the density measurements
124 for the bottom 10 cm of the snowpack were used to evaluate changes near the snow and ground
125 interface (basal layer).

126 Temperature measurements were obtained at 5 cm intervals from the top to the bottom of
127 the snowpack using a dial stem thermometer with $\pm 1^\circ\text{C}$ accuracy. However, repeatability for any
128 given temperature is better than $\pm 1^\circ\text{C}$ and temperature gradients are well represented by this
129 instrument (Elder et al., 2009; Greene et al., 2009). Snowpack temperature profiles and the
130 corresponding bulk temperature gradient were compared. The temperature gradient (T_G in $^\circ\text{C/m}$)
131 was calculated as the ratio of the change in temperature (ΔT in $^\circ\text{C}$) from the point of zero



132 amplitude (upper boundary, 25-30 cm below the surface) and the temperature at 0 cm (lower
133 boundary) with the distance (d in m) over which the change in temperature occurred. For this
134 study, the point of zero amplitude was used as the upper boundary to remove bias from diurnal
135 fluctuations (Pomeroy and Brun, 2001). Basal layer temperatures (0 cm) were used to compare
136 temperature changes near the snow and ground interface.

137 Stratigraphic measurements illustrate the evolution of the snowpack over time by
138 characterizing the shape and size of snow crystals within each stratified layer of the snowpack.
139 Classification of grain morphology was based on *The International Classification for Seasonal*
140 *Snow on the Ground* (Fierz et al., 2009) and grain shape was measured and recorded to the nearest
141 0.5 mm using a hand lens and a crystal card. The main crystal forms / layer types were fresh,
142 rounded, faceted, and ice layers.

143 Hardness is the snowpack's compressive strength and is measured as the force per unit
144 area required to penetrate the structure of the snowpack (McClung and Schaerer, 2006) due to
145 microstructure and bonding characteristics of the snow grains (Shapiro et al., 1997). Hardness
146 measurements were taken horizontally with a force gauge in each stratigraphic layer using a
147 Wagner Instruments Force Dial gauge (<http://wagnerinstruments.com>) with maximum force
148 measurements of 25 N and 100 N, and fabricated circular metal plate attachments of known area.
149 The circular metal plate was pushed into the snow and the force required to penetrate the snow
150 was recorded. The snow hardness (h_i in N/m^2) for each stratigraphic layer was calculated as the
151 force required to penetrate the snow (F in N) per unit area of the circular metal plate (A in m^2).
152 The bulk snowpack hardness (H_B in N/m^2) was determined by weighing each stratigraphic layer
153 hardness measurement by the stratigraphic layer thickness. The hardness associated with the



154 bottom stratigraphic layer for each transect was used to describe hardness changes in the basal
155 layer of the snowpack.

156 The standard ram penetrometer is an instrument used to vertically measure the relative
157 hardness or resistance of a snow layers (Greene et al., 2009) and was used to assess the change in
158 ram resistance due to compaction through the duration of the winter season. A ram profile
159 measurement was taken 0.5 meters from the edge of the snow pit wall subsequent to snow pit
160 profile measurements. The mean ram resistance (S_B in N) was determined by weighting each
161 stratigraphic layer's ram resistance value obtained from the standard ram penetrometer
162 measurement with the layer thickness. The ram resistance value associated with the bottom
163 stratigraphic layer was measured to describe changes in ram resistance in the basal layer of the
164 snowpack .

165

166 3.3 *Statistical analyses*

167 Data were analyzed using the Mann-Whitney-Wilcoxon rank sum test (Wilcoxon, 1945;
168 Mann and Whitney, 1947). This determines the statistical significance between two datasets,
169 herein different treatments compared to the control of no snowmobile use (Table 1). This
170 statistical test is non-parametric and determines whether two samples were selected from
171 populations having the same distribution. The sets samples of samples are comparable density,
172 temperature, hardness, and ram resistance profiles for the five different monthly measurements.
173 A statistical significance was determined to the 95% and 99% confidence interval ($p < 0.05$, and
174 $p < 0.01$) and noted with an asterisk in Table 1.

175


176 4. Results



177 The 2009-2010 winter at REP had a below average SWE based on the Columbine SNOTEL data
178 (Figure 2). A peak SWE of 556 mm was observed on 9 April, which was 93 percent of the
179 historical average peak SWE. Maximum snow depth measured at the REP snow compaction
180 study plot was approximately 1.5 m and therefore represented a deep snow cover environment.
181 From the Berthoud Summit SNOTEL data, the 2009-2010 winter at FEF had an above average
182 SWE compared to the 29-year historical average (Figure 2). A peak SWE of 622 mm was
183 observed on 16 May, which was 115 percent of the historical mean peak SWE. Measured snow
184 depth at the FEF snow compaction study plot never exceeded 1 m and therefore represented a
185 shallow snow cover environment.

186

187 **4.1 Density**

188  snowpack density increased at the REP snow compaction study site when low and high use
189 compaction treatments began on 30 cm of snow (Figure 3a). As a result, low and high use
190 compaction treatments were significantly different between these treatments (low and high) and
191 the control, and compared to both low and high use compaction treatments beginning on 120 cm
192 of snow (Table 1). The largest bulk snowpack density difference was observed on 6 February
193 when the control bulk density was 246 kg/m³, while the low and high use compaction treatments
194 yielded an increase to 285 kg/m³ and 328 kg/m³, respectively (Figure 3a). In contrast,
195 compaction treatments (low and high) beginning on 120 cm of snow (Figure 3b) did not
196 significantly alter the bulk snowpack density compared to the control (Table 1). While the bulk
197 snowpack density increased through the duration of the study period, by the last sampling date
198 bulk snowpack density was similar between the control and treated transects (Figure 3av and
199 3bv). Treatment increased the density in the basal layer of the snowpack, with the largest



200 difference of 75% (density of 351 kg/m^3) and 88% (377 kg/m^3) for low and high use compaction
201 treatments observed on 12 December, respectively, compared to just over 200 kg/m^3 for the
202 control (Figure 3ai). Snow compaction treatments had little impact on basal layer densities when
203 treatments began on 120 cm of snow with the largest difference being observed on 6 February as
204 229 , 234 , and 268 kg/m^3 for the control, low and high treatments, respectively (Figure 3biii).

205 Bulk snowpack density also increased at the FEF snow compaction study site for all
206 compaction treatments (low, medium, and high use) that began on 30 cm of snow (Figure 3c).
207 Significant differences were observed between all treatments and the control. However, there
208 were no significant differences between the varying treatments (Table 1). For low and medium
209 use compaction treatments the largest difference in bulk snowpack density compared to the
210 control was on 12 February when density was measured at 177 , 296 , and 311 kg/m^3 , for the
211 control, low and medium treatment, respectively (Figure 3ciii). Snowpack density measured for
212 high use had the largest difference from the control on 22 January when bulk snowpack density
213 was 341 kg/m^3 compared to a bulk density of 192 kg/m^3 for the control (Figure 3cii). Bulk
214 snowpack density generally increased during the study period, but by the end of the study period
215 there were minimal differences between the control and varying degrees of compaction (Figure
216 3cv). Basal layer density increased from all compaction treatments. After the first treatment on
217 27 December, the basal layer density increased by 148% (288 kg/m^3) for low use to about 190%
218 of medium and high use, compared to 116 kg/m^3 for the control (Figure 3ci).

219

220 4.2 Temperature

221 Low and high use compaction treatments at the REP snow compaction study site that began on
222 both a shallow snowpack of 30 cm and on a deep snowpack of 120 cm did not result in




223 significant changes to the temperature gradient. The maximum temperature gradients were
224 observed on 12 December as 18, 28, and $25^{\circ}\text{C m}^{-1}$ for the control, low use, and high use
225 compaction treatments that began on a shallow snowpack, while they were almost the same (23,
226 23, and $25^{\circ}\text{C m}^{-1}$) for the control, low use, and high use compaction treatments that began on a
227 deep snowpack. Temperature gradients for all treatments decreased throughout the winter season
228 until all uses exhibited a temperature gradient approaching 0°C m^{-1} by 17 April, favoring
229 sintering and bonding of snow crystals. The coldest basal layer temperatures were about -2 and -
230 3°C on 12 December for all treatments compaction treatments began on deep and shallow
231 snowpack, respectively. Basal layer temperatures increased throughout the winter season until all
232 uses exhibited a basal layer temperature of -1°C by 17 April.

233 Low, medium and high use compaction treatments at the FEF snow compaction study site
234 did not significantly impact the temperature gradient. Maximum temperature gradients for low,
235 medium, and high use were $30^{\circ}\text{C m}^{-1}$, $13^{\circ}\text{C m}^{-1}$, and $20^{\circ}\text{C m}^{-1}$ on 27 December compared to 20°C
236 m^{-1} measured at the control. Temperature gradients decreased throughout the winter season until
237 all uses exhibited a temperature gradient near 0°C m^{-1} by 26 April (Figure 4b). The coldest basal
238 layer temperature was for medium use on 22 January (-6°C), with a basal layer temperature of -
239 5°C on 27 December for all other treatments. Basal layer temperatures increased for all uses
240 throughout the winter season until basal layer temperatures reached -1°C by 26 April (Figure 4b).
241

242 4.3 Hardness

243 Measured snowpack hardness increased at the REP snow compaction study site following low and
244 high use compaction treatments that began on 30 cm of snow (Figure 5a), but only for high use
245 at the deeper snowpack (Figure 5b). Significant increases in hardness were observed between



246 treatments that began on 30 cm of snow and the control, and between compaction treatments
247 (low and high) that began on 120 cm of snow (Table 1). For the treatment  that began on the
248 shallow snowpack, the maximum mean hardness for the control was 82 kPa for the control on 17
249 April (Figure 5av) while for the low use treatment a maximum of 174 kPa was measured on 12
250 December and for the high use treatment, a maximum of 487 kPa was measured on 6 February.
251 In contrast, mean snowpack hardness was not significantly impacted by snow compaction
252 treatments that began on 120 cm of snow (Table 1). Mean snowpack hardness increased
253 following the initial snow compaction treatments for low and high use, but subsequent
254 compaction treatments did not appear to have a large effect (Figure 5b and Table 1). Mean
255 snowpack hardness for low and high use was greater than the control following the initial snow
256 compaction treatment for both initiation depths (30 cm and 120 cm), but there were minimal
257 differences by the last sampling date (Figure 5av and 5bv).

258 Snow compaction treatments that began on 30 cm of snow increased basal layer hardness
259 (Figure 5a), but treatments that began on 120 cm of snow did not impact basal layer hardness
260 (Figure 5b). For the former, the maximum basal layer hardness was measured at 188 kPa (Figure
261 5ai) and 158 kPa (Figure 5aiii) for the low and high treatments, respectively. For both controls
262 and all treatments that began on 120 cm of snow (Figure 5b), the maximum basal layer hardness
263 was about 6 kPa.

264 Low, medium, and high use compaction treatments resulted in a significant increase in
265 mean snowpack hardness following snow compaction treatments beginning on 30 cm of snow at
266 the FEF snow compaction study site (Table 1). These generally increased during the study
267 period; however, treated transects were approaching control values by the last sampling date
268 (Figure 5c). For the control, the maximum mean snowpack hardness was about 25 kPa (on 26



269 March in Figure 5civ) while the maximum treatment hardness was orders of magnitude higher at
270 395 kPa (low treatment on 22 January, Figure 5cii), 780 kPa (medium treatment on 26 March,
271 Figure 5civ) and 4,627 kPa (high treatment on 26 March, Figure 5civ). Similarly, the maximum
272 basal layer hardness for the control was only 4 kPa (on 26 March, Figure 5civ) and 138, 352 and
273 728 kPa for low, medium and high use, respectively (Figure 5cii, 5civ, and 5civ).

274

275 **4.4 Ram resistance**

276 Low and high use compaction treatments at REP caused an increase in mean snowpack ram
277 resistance (Figure 6a and 6b), but the difference was only significant for treatments that began on
278 30 cm of snow (Table 1). The maximum mean snowpack ram resistance was measured as 128,
279 203, and 496 N for the control, low and high use, respectively (Figure 6av, 6av, and 6aiii). After
280 the initial snow compaction treatments mean snowpack ram resistance for low and high use was
281 greater than the control for the entire study period, but by the end of the study period minimal
282 differences were observed between treatments. Basal layer ram resistance increased as a result of
283 low and high use compaction treatments that began on both 30 cm (44, 614, and 1,297 N for
284 control, low and high use) and 120 cm of snow (44, 270 and 90 N for control, low and high use).

285 Snow compaction treatments at the FEF snow compaction study site caused a significant
286 increase in mean snowpack ram resistance (Figure 6c; Table 1). Maximum mean snowpack ram
287 resistance for the control was 18 N (26 March, Figure 6civ), for low and medium use it was
288 544N and 591N (26 March, Figure 6civ) respectively, while for high use it was measured at
289 866N (on 12 February, Figure 6c). Basal layer ram resistance increased following the initial
290 snow compaction treatments and continued to increase throughout the duration of the winter



291 season, with maximums of 28 (26 March), 1,220, 1,220, and 3,220 N for the control, low,
292 medium, and high treatments (on 12 February for all the use treatments).

293

294 **4.5 Operational Sites**

295 As illustrated by SWE (Figure 7d) and depth (Figure 7a), the amount of snow was similar for the
296 snowpits dug at the three operational sites, but not the same since they were up to 6km apart
297 (Figure 1). Also these were operational sites, i.e., the amount of treatment was not controlled and
298 was based solely on permitted use. Patterns of increased density (Figure 7a), hardness (Figure
299 7b) and ram resistance (Figure 7c) were similar to the previous presented experiments (Figures 3,
300 5, and 6) with the non-snowmobile snowpits being less dense (Figure 7a) and having layers that
301 were less hard (Figure 7b). For visual inspection, Muddy Creek had the most snowmobile use
302 and thus had the highest density throughout the winter, and the hardest snowpack for mid-winter
303 (Figure 7bii to 7biv) but at times was similar to Dumont Lakes.

304

305 **5. Discussion**

306 At rest, a snowmobile and its rider exert 4 to 10 kPa of pressure to the underlying
307 snowpack (assuming a track length from 0.9 to 1.4 m, width of 0.50 m, a snowmobile weight of
308 200 to 350 kg, and a rider weight of about 100 kg, data from
309 <http://www.polarisindustries.com>). This increase by less than an order of magnitude due to
310 snowmobile movement (Thumlert et al., 2013 measured stresses of about 10 to 20 kPa at a depth
311 of 30 cm below the surface of a deep snowpack). In comparison, fresh snow with a density of
312 100 kg/m³ exerts a pressure of 0.003 kPa to the underlying snowpack (Moynier, 2006).
313 Snowpack loading by wheeled vehicles on a shallow snowpack was much greater, peaking at



314 about 350 kPa (Pytka, 2010). Grooming vehicles added a load similar to snowmobiles (Pytka,
315 2010), due to the larger track size. Thus, the snowpack results shown herein are transferrable to
316 grooming machinery.

317 The snowpack is persistently changing, once snow starts to accumulate on the ground.
318 The density of snow varies over space, time and with depth. For fresh snow, density ranges from
319 40 to 200 kg/m³ (Diamond and Lowry, 1953; Schmidt and Gluns, 1991; Fassnacht and Soulis,
320 2002). The density of fresh snow can double with just one pass of a snowmobile on a very
321 shallow snowpack (Keddy et al., 1979), and even with more accumulation, density will increase,
322 but the underlying snow also gets more dense (Figures 3 and 7a).

323 Once snow accumulates on the ground, the morphology alters the physical and material
324 properties of the snowpack from the surface down, such as changing its density and hardness.
325 Since the base of the snowpack remains at approximately 0°C due to warm summer temperatures
326 and geothermal heating (Auerbach and Halfpenny, 1991; Pomeroy and Brun, 2001), variable
327 atmospheric air temperatures fluctuate between the relatively warm days and relatively cold
328 nights (McClung and Schaerer, 2006) and generate strong temperature and vapour pressure
329 gradients causing kinetic growth metamorphism that creates cohesionless faceted snow grains.
330 Conversely equilibrium metamorphism creates rounded grains that can easily sinter
331 (Sommerfeld, 1970; Colbeck, 1982; Colbeck, 1983; Colbeck, 1987). Rounding increases density
332 and snowpack strength. This increase in density and hardness is greatest compared to an
333 untreated snowpack in early to mid-season (January) for a deeper snowpack (REP in Figures 3a,
334 and 5a), and later into the snow season for the shallower snowpack (FEF in Figures 3c, and 5c).
335 Similar differences were found due to ski run grooming in an Australia snowpack with a 400%
336 increase in hardness early in the snow season but only about a 40% increase later in the winter



337 (Fahey et al., 1999). Snow grooming increased the average density by up to 36% compared to
338 non-groomed ski slopes (Fahey et al., 1999, Rixen et al., 2001).

339 Compaction of the snowpack changes in density, hardness and ram resistance (Figures 3,
340 5, 6, and 7), and results in deformation of snowthrough alterations in the ice matrix
341 (bonding/grain contacts) (Shapiro et al., 1997). Since hardness depends predominantly on grain
342 characteristics, such as bonding and grain contacts (Shapiro et al., 1997) and decreasing grain
343 size results in increased density, then compaction due to snowmobile use may alter the
344 microstructure of the snowpack (Table 2), directly influencing these physical and mechanical
345 properties (Table 1). Such changes were observed for varying snowmobile use beginning on two
346 different snow depths (REP only in Figures 3a, 5a, 6a versus Figures 3b, 5b, 6b) and for two
347 different snow covered environments (Figures 3c, 5c, 6c).

348 Field observations prior to snowmelt have revealed maximum late season snowpack
349 densities ranging from 290 kg/m³ to 400 kg/m³ with snow densities as high as 500 kg/m³ during
350 snowmelt (Gold, 1958; Longley, 1960), while densities of depth hoar layers prior to melt were
351 about 300 kg/m³ (Greene et al., 2009; Sturm et al., 2010). For a deep snow cover environment
352 (REP), compaction treatments beginning on a shallow snowpack (30 cm) resulted in a 15% and
353 33% increase in density for low and high use treatments, respectively (Figure 3a), observed mid-
354 winter (early February), similar to maximum late season natural snowpack densities (Gold, 1958;
355 Longley, 1960; Giddings and LaChapelle, 1962). Density differences were greatest for a shallow
356 snow cover environment (FEF), with high use resulting in 78% greater density (Figure 3c).
357 Conversely, no significant differences in density were observed when snowmobile use began on
358 a deep snowpack (120 cm) (Figures 3b, Table 1).



359 Increased densification of the snowpack due to snowmobile use influences snow hardness
360 (Figure 5) and ram resistance (Figure 6) due to changes in the arrangement of ice grains. In this
361 study, snow-hardness gauges and circular metal plates of known area were used (McClung and
362 Shaerer, 2006), rather than the in situ (avalanche evaluation) hand hardness test (Greene et al.,
363 2009). Snowmobile use beginning on a shallow snowpack (30 cm) for a deep snowpack (REP)
364 resulted in a 2- and 6-fold increase in maximum snow hardness for low and high use compared
365 to no use, whereas at a shallow snow study site (FEF), a 15-, 30- and nearly 200-fold increase in
366 maximum snow hardness for low, medium, and high use was observed. A shallow snow
367 environment is more susceptible to large changes in snow hardness due to varying snowmobile
368 use.

369 Ram resistance values ranged from 0 N to just below 1000 N, which is a normal range for
370 snowpack strength measurements (Colbeck et al., 1990). The precision of the ram penetrometer
371 used in this study was 10N so the ram resistance of an undisturbed snowpack, typically in the
372 range of 0.5N (Pruitt, 2005), could not be measured. These values can increase to as much as
373 70N as a result of two passes with one person on a snowmobile (Pruitt, 2005). Similar to
374 hardness observations, snowmobile use beginning on a shallow snowpack yielded ram resistance
375 1.5- and 4-fold greater than the natural snowpack (Figure 6). The impact of snowmobile use on a
376 snowpack ram resistance (Figures 6 and 7c) has only been observed by Pruitt (2005). More
377 frequent fresh snowfall events (REP, Figure 6a) with compaction treatments can produce a
378 snowpack of stratified strong and weak layers, and a deeper snowpack is capable of lessening the
379 effect of compaction from snowmobile use (Figure 6b).

380 As crystals become compacted due to snowmobile use, there is an increase in bonding
381 between crystals and early compaction impedes further kinetic growth. Temperature gradients



382 were as high as $33^{\circ}\text{C m}^{-1}$ at the beginning of the season, about twice what was observed by de
383 Quervain (1958) in alpine snowpacks, and approached 0°C m^{-1} as the snowpack became isothermal
384 at the end of the winter season. However, temperature gradients in this study were unaffected by
385 compaction from snowmobile use (Figure 4, Table 1) potentially due to the edge effect of heat
386 transfer from the warmer ground adjacent to the plots, heat transfer from the buffer areas located
387 parallel to compaction transects, and diurnal changes in ambient air temperatures. The
388 temperature gradient was sufficient for kinetic growth metamorphism for most of the winter
389 season ($T_G > 10^{\circ}\text{C m}^{-1}$), as seen by less dense lower snowpack layers for the controls (Figures 3a,
390 3c, 7a) and the deep snowpack where snowmobile use started at 120 cm (Figure 3b).

391 A decrease in crystal size was observed for both the deep and shallow snowpacks
392 subjected to snowmobile use (Table 2). Specifically, depth hoar crystals for the controls at FEF
393 reached a maximum average size of 9.0 mm, while low, medium, and high use resulted in
394 average crystal sizes of 1.3 mm, 2.5 mm and 1.5 mm, respectively (Table 2). While the
395 temperature profile differences between control and snowmobile use were not significant,
396 temperature gradients and thus vapour pressure gradients were less, decreasing depth hoar
397 growth (Table 2). Similarly, this trend was observed on REP, although the deeper snow
398 environment allowed growth of depth hoar but the difference in depth hoar crystal sizes between
399 control and treatments was less (Table 2).

400 The overall increase in density, hardness and ram resistance (Figure 6) was statistically
401 significant between the control (no snowmobile use) and all treatments, except when treatments
402 were initiated on a deep snowpack (Figures 3b, 5b, and 6b, Table 1). The measured depth of
403 influence for a snowmobile is about 90 cm (Thumlert et al., 2013). At 20 cm below the snow
404 surface, the induced stress is already much less than 10 cm below the surface from a snowmobile



405 (Thumlert et al., 2013) or a grooming machine (Pytka, 2010). Most ski resorts in the French Alps
406 required a minimum snow depth of 40 cm to offer skiing, with a range from 60 cm in February to
407 40 cm in April (Spandre et al., 2016b). The US Forest Service (2013b) recommends a minimum
408 of 30 cm before the use of snowmobiles. Increasing the minimum snow depth before allowing
409 snowmobile traffic will reduce changes to the snowpack due to snowmobiles (Table 1).

410 Snowmobile use was found to have a highly significant effect upon natural vegetation
411 below the snow (Keddy et al., 1979), with grooming shown to delay the blooming of alpine
412 plants (Rixen et al., 2001) due to a later snowmelt and a significantly cooler soil (Fassnacht and
413 Soulis, 2002). Deeper snowpack were found to not have a cooler soil temperature under the
414 snowpack (Keller et al., 2004), but did melt out four weeks later, and this resulted in a cooler
415 snowpack at the end of the summer (Keller et al., 2004). Since the snowpack changes due to
416 snowmobile traffic on a shallow snowpack were significant (Table 1), the effects of snowmobile
417 use on the soil and vegetation underlying a shallow snowpack should be further investigated.

418 Snow depth will likely be less for areas with snowmobile traffic (Figure 3; Rixen et al.,
419 2001; Spandre et al., 2016a). However, this depends upon the meteorological conditions,
420 specifically the frequency and magnitude of wind. The local terrain features and position and
421 extent of canopy influence how the wind interacts with the snowpack (Pomeroy and Brun, 2001).
422 In an Australia case study, SWE increased by 45% in groomed areas (Fahey et al., 1999); at the
423 Rabbit Ears Pass recreational use areas, SWE also increased (Figure 7d) due to snow blowing
424 into the depressions created by snowmobile tracks. The increased load could further impact the
425 underlying snowpack properties.

426 Snowmaking is performed to supplement natural snow conditions. In the French Alps,
427 about of third of the ski slopes equipped are equipped with snowmaking facilities and this is



428 expected to increase, due in part to a changing climate (Spandre et al., 2016b). Artificial snow
429 has substantially different properties than natural snow, and adds an additional load to the
430 underlying snowpack (Spandre et al., 2016a). This additional snow compacts the snowpack
431 below it, and may create surface different conditions (Howard and Stull, 2014). Grooming of
432 artificial snow further compressed the snowpack (Spandre et al., 2016a). If the results presented
433 in this paper are extended to ski areas, the addition of artificial snow must be considered.

434 In Colorado alone, the economic impact of the ski industry was \$4.8 billion during the
435 2013-14 ski season (Colorado Ski Country USA, 2015). Regardless of the use, adding mass to
436 the snowpack, through snowmaking (Spandre et al., 2016a), grooming (Fahey et al., 1999; Rixen
437 et al., 2001; Spandre et al., 2016a), or snowmobile use (figure 7), will alter the snowpack
438 (Figure 3-6). A changing climate will likely reduce the extent of terrain and decrease the length
439 of the winter recreation season (Laxar and Williams, 2008; Steiger, 2010; Dawson and Scott,
440 2013; Marke et al., 2015; Tercek and Rodman, 2016). In all cases, due to climate change, more
441 snowmaking will be required (Steiger, 2010; Spandre et al., 2015) and this artificial snow will
442 impact the snowpack properties (Spandre et al., 2016a). The results presented herein are useful
443 when modeling the impact of grooming or snowmaking on the snowpack of ski runs (e.g.,
444 Howard and Stull, 2014; Marke et al., 2015; Spandre et al., 2016a).

445

446 6. Conclusion

447 This study examined the effect of compaction from snowmobile use on snowpack properties. It
448 showed that snowpack properties change with varying use of snowmobile use, with the amount
449 of snowfall, and at the initiation of use. Snowmobile use creates compaction that influences the
450 physical and mechanical properties of the snowpack. In particular, this increases snowpack



451 density, hardness, and ram resistance when winter recreational use occurs. The largest
452 differences in snowpack properties are associated with snowmobile use beginning on a shallow
453 snowpack (30 cm), which increases snowpack density, hardness, and ram resistance. These
454 increases are directly related to increasing snowmobile use (from low to medium to high).
455 Conversely, snowmobile use that begins on a deep snowpack (120 cm) has a limited effect on
456 snowpack properties as seen by density, temperature, hardness, and ram resistance measurements
457 comparable to an undisturbed snowpack.

458 Snowpack properties of varying snowpack environments (shallow vs. deep) respond
459 differently to snowmobile use. Shallow snow covers experience an increase in snowpack density,
460 ram resistance, and hardness that are more pronounced than changes to these properties when
461 snowmobile use operates on a deep snowpack. These changes in the physical properties of the
462 snowpack are due to snowmobile use operating on an already compacted snowpack yielding
463 thick layers of dense, strong, hard snow. Deep snow covers experience more snowfall events that
464 create “cushions” of relatively undisturbed snow between compaction events lessening the effect
465 of snowmobile use on snowpack properties. These differences between snow environments
466 suggest that shallow snowpacks are more susceptible to larger changes in snowpack properties.

467

468 **Author contribution**

469 The exper^{iment}it were designed by J.T. Heath and S.R. Fassnacht with input from K.J. Elder. J.T.
470 Heath performed the experiments with assistance from K.J. Elder at the Fraser site. All authors
471 contributed to the writing of the manuscript.

472



473 **Acknowledgments**

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

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621



622 **Table 1.** Statistical difference (p-values) between no snowmobile use (control) and varying snow
 623 compaction treatments on snowpack properties at the study plots located at Rabbit Ears Pass
 624 (REP) and Fraser Experimental Forest (FEF), Colorado during the 2009-2010 winter season for
 625 a) density, b) temperature, c) hardness, and e) ram resistance. Statistically significant differences
 626 at the $p < 0.05$ confident level are highlighted in grey, and highly significant ($p < 0.01$) difference
 627 are denoted with an asterisk.
 628

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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636 **Table 2.** Depth hoar grain size at the snow compaction study plots located at Rabbit Ears Pass
 637 (REP) and Fraser Experimental Forest (FEF), Colorado during the 2009-2010 winter season.
 638

		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

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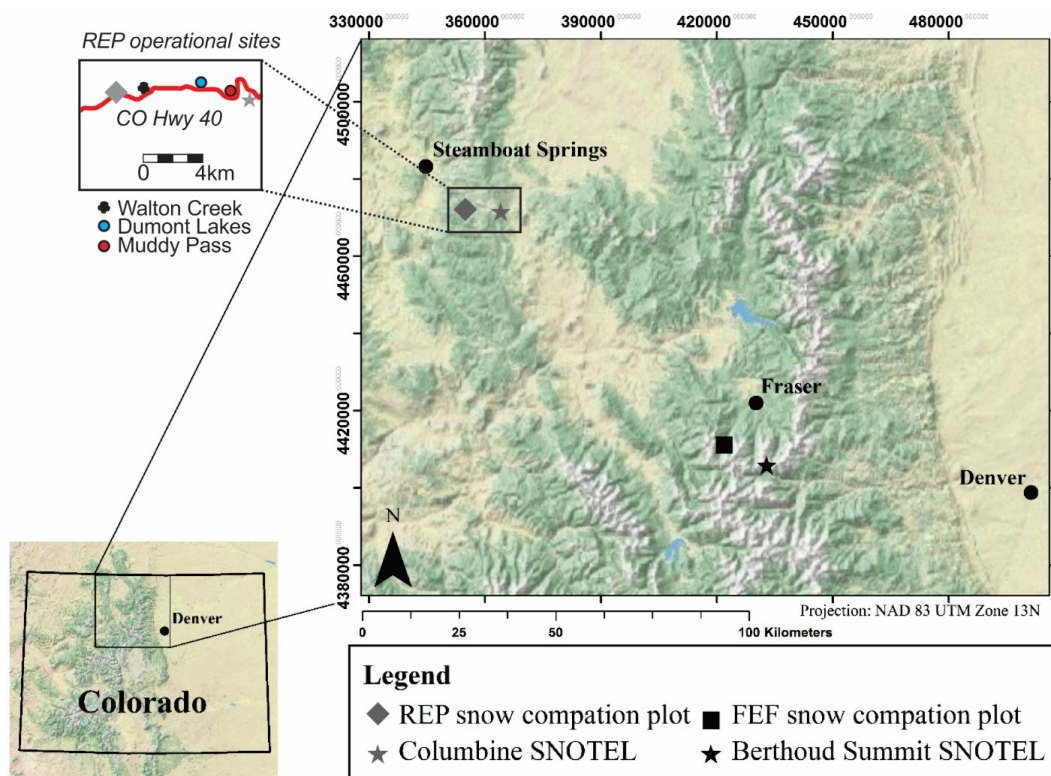


Figure 1. The snow compaction study plots are located near Rabbit Ears Pass in Routt National Forest and Fraser Experimental Forest in the Arapaho-Roosevelt National Forest, Colorado.

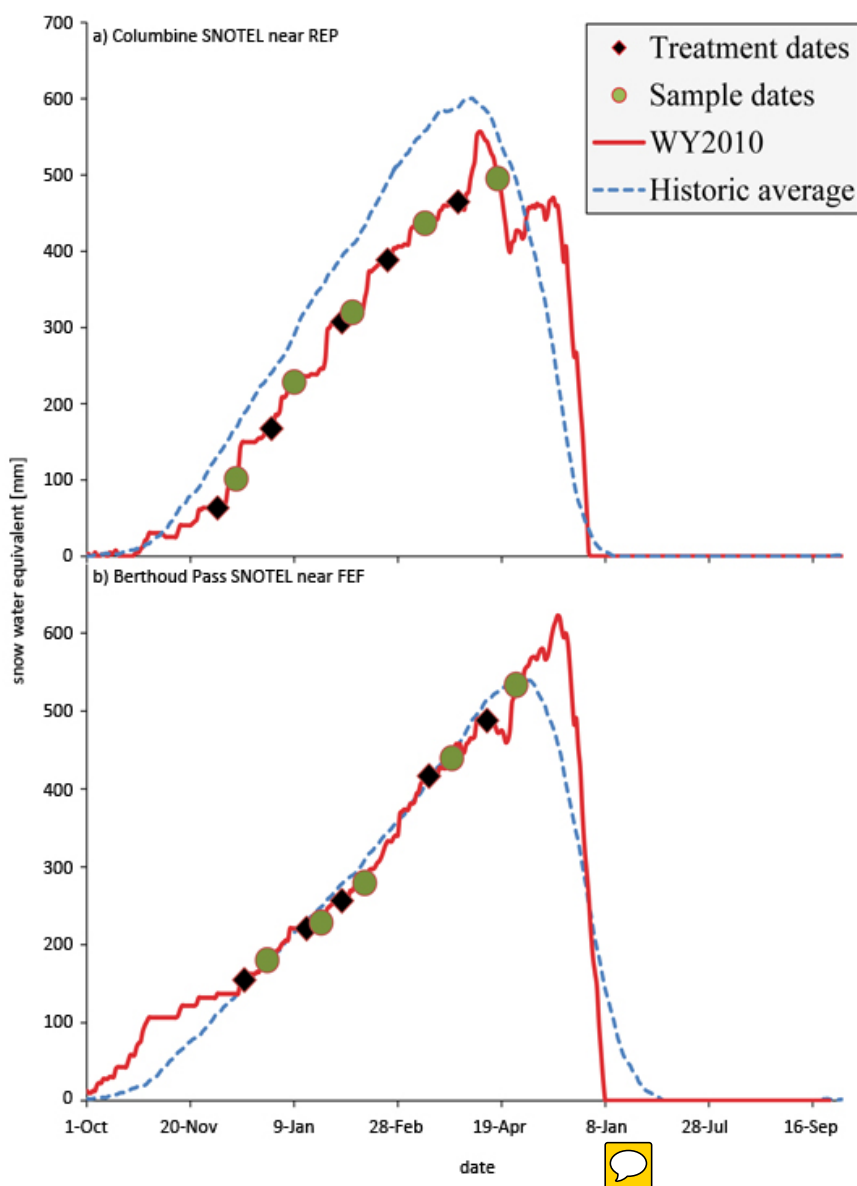


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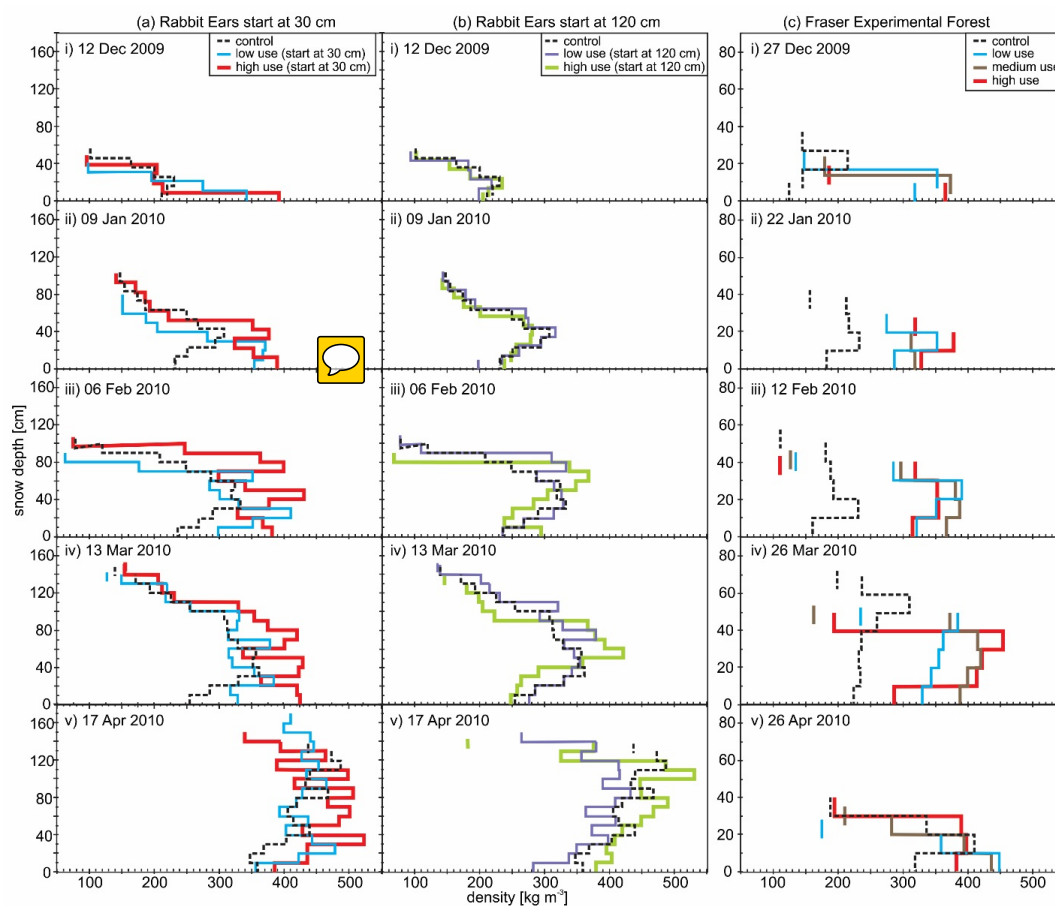


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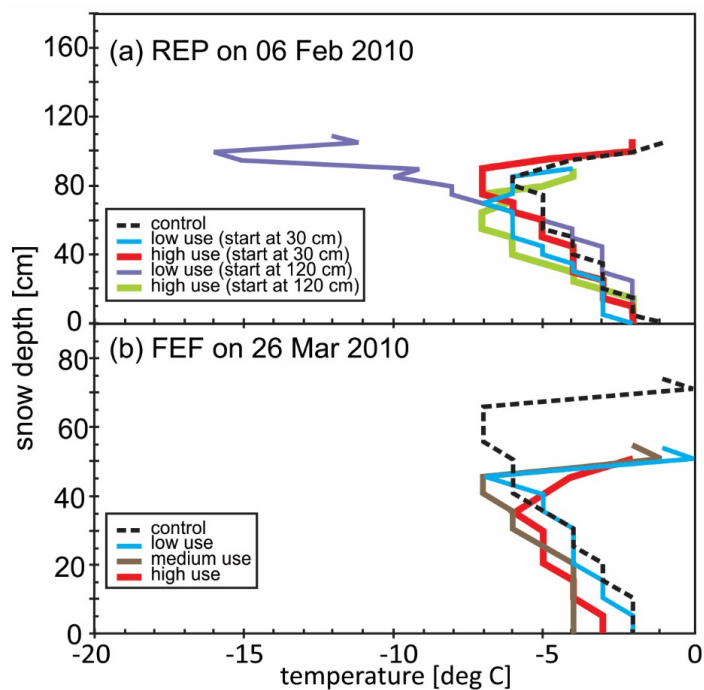


Figure 4. Temperature profiles measured at a) the REP snow compaction study plot on February 06, 2010 for no, low, and high use treatments beginning on 30 cm and 120 cm of snow and b) the FEF snow compaction study plot on March 26, 2010 for no, low, medium, and high use treatments beginning on 30 cm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

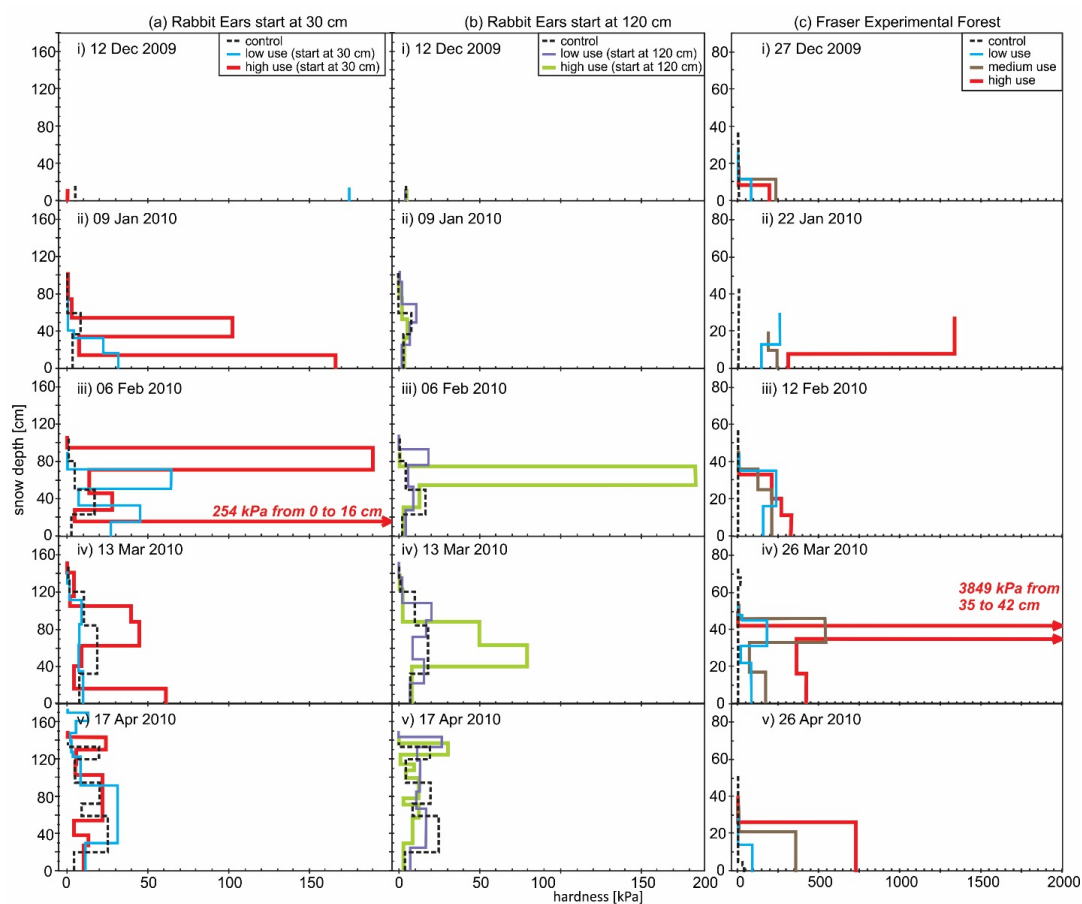


Figure 5. Hardness profiles for five dates (i to v) measured at the REP snow compaction study plot for no, low, and high use treatments beginning on a) 30 cm and b) 120 cm of snow, and c) the FEF snow compaction study plot for no, low, medium, and high use treatments beginning on 30 cm of snow.

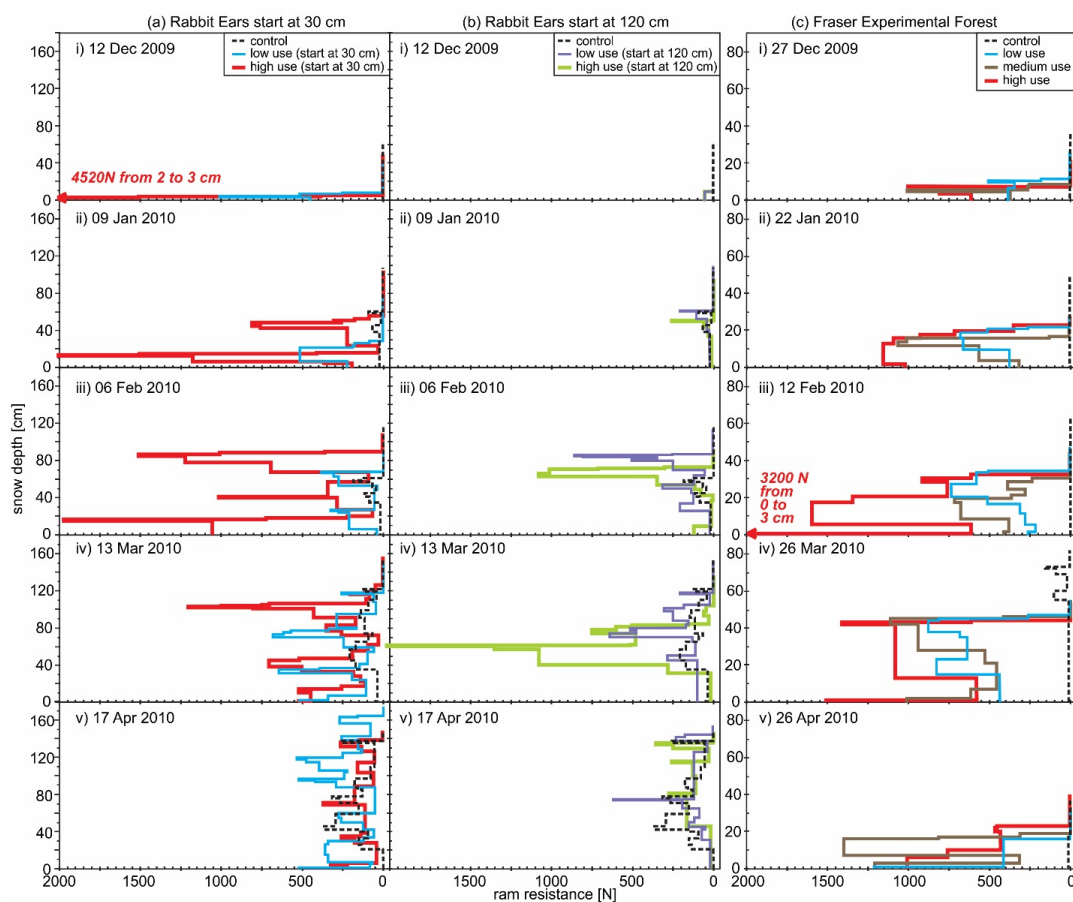


Figure 6. Ram resistance for five dates (i to v) profiles measured at the REP snow compaction study plot for no, low, and high use treatments beginning on a) 30 cm and b) 120 cm of snow, and c) the FEF snow compaction study plot for no, low, medium, and high use treatments beginning on 30 cm of snow.

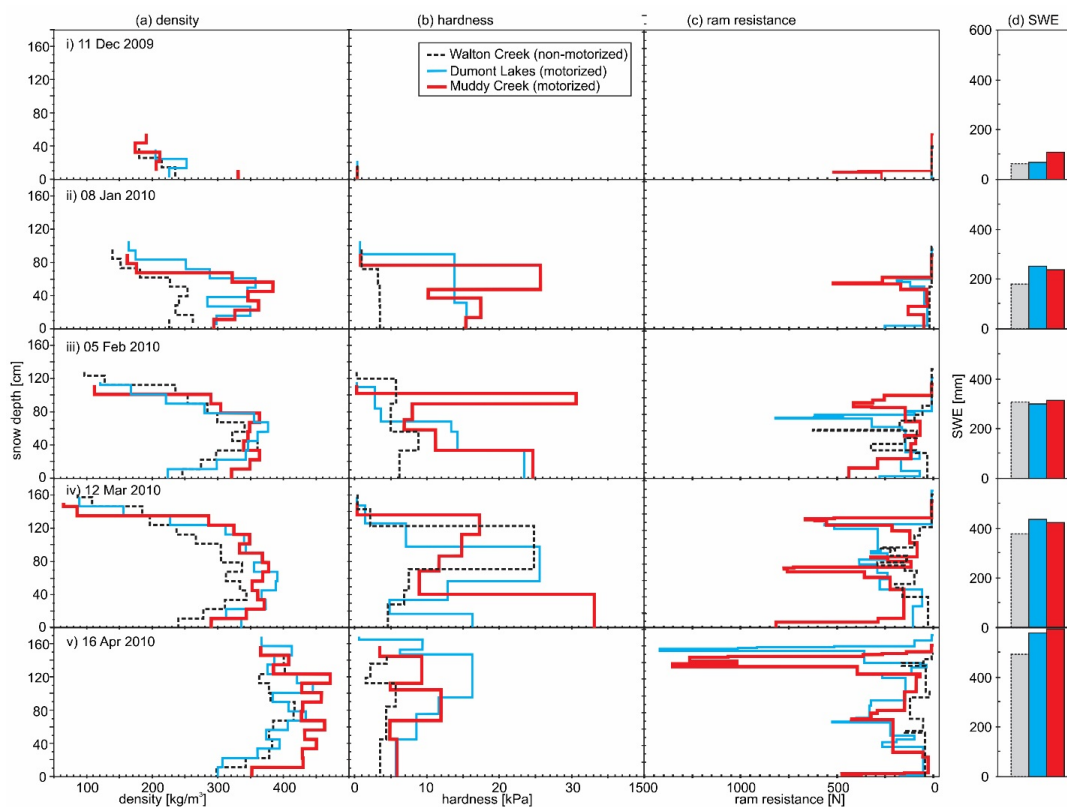


Figure 7. Snowpit data for Walton Creek (no snowmobile use), Dumont Lakes (moderate snowmobile use) and Muddy Creek (high snowmobile use) in the Rabbit Ears Pass recreational use areas illustrating a) density, b) hardness, c) ram resistance, and d) SWE.