Snowmobile Impacts on the Physical and Mechanical Properties of Different

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

Abstract

We ran a snowmobile over a series of test plot to examine the physical and material properties of the snowpack due to compaction from a snowmobile. We measured the snow density, temperature, stratigraphy, hardness, and ram resistance from snow pit profiles. Experiments were performed at two different experimental areas, specifically Rabbit Ears Pass near Steamboat Springs and at Fraser Experimental Forest near Fraser, Colorado USA. We examined the difference between no use and varying degrees of snowmobile use (low, medium and high) for different starts of snowmobile use, specifically on a shallow (the operational standard of 30 cm) and deeper snowpack (120 cm). Significant changes in snowpack properties were measured due to snowmobile use beginning on a shallow snowpack. These snowpack property changes were more pronounced where there was less snow accumulation. When snowmobile use started on a deeper snow, in particular at 120cm, there was less difference compared to the control case of no snowmobile use.

1. Introduction

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

There have been limited studies regarding the influence snowmobile use on snowpack properties (Keddy et al., 1979; Thumlert et al., 2013; Thumlert and Jamieson, 2015). Various studies examine how the snowpack changes due to snow grooming at ski resorts (Fahay et al., 1999; Keller et al., 2004; Spandre et al., 2016a), or to traction and mobility of wheeled vehicles across a snowpack (Abele and Gow, 1990; Shoop et al., 2006; Pytka, 2010). One of these few studies has been for snowmobile use on shallow snow (10 to 20 cm deep) that caused a doubling of fresh snow density, little impact on the underlying old snow, but had a highly significant effect upon natural vegetation below the snow (Keddy et al., 1979). Examining deeper snow, Thumlert et al. (2013) and Thumlert and Jamieson (2015) examined the distribution of stresses through the snowpack due to type of loading, depth and snowpack stratigraphy (Thumlert et al., 2013). We specifically examined the effect of snowmobile use on the physical and material

52   properties of the snowpack. The objectives of this research were: (1) quantify changes to

53   physical snowpack properties due to compaction by snowmobiles; and (2) evaluate these changes

54   based on the amount of use, depth of snow when snowmobile use begins, and the snowfall

55   environment where snowmobiles operate. This work examines both the entire snowpack and the

56   basal layer. Since there are many snowmobile users and billions spent each year on

57   snowmobiling this work will benefit land managers who need to make decisions about multi-use

58   areas that are used by snowmobilers, among others.

59

60   **2. Study Sites**

61   During the 2009-2010 snow season a set of snow compaction plots were located near

62   Rabbit Ears Pass (REP) in the Rocky Mountains of northern Colorado to southeast of the town of

63   Steamboat Springs. REP is within the Medicine Bow-Routt NF (Figure 1) along the Continental

64   Divide encompassing over 9,400 km^2 of land in Colorado and Wyoming. Rabbit Ears Pass is

65   especially popular during the winter season and is heavily used by snowmobilers and other

66   winter recreationalists due to the ease of access to backcountry terrain from Colorado Highway

67   40. Due to heavy use and conflict among users during the winter season, the Forest Service

68   manages Rabbit Ears Pass for both non-motorized and motorized uses. The west side of pass is

69   designated for non-motorized users and prohibits the use of motorized winter recreation and, the

70   east side of the pass is a mixed use area and open to motorized users (Figure 1). If snowmobile

71   use impacts the snowpack, as we examine in this paper, then differences in snowpack properties

72   will be observed (e.g., Walton Creek versus Dumont Lakes and Muddy Pass in Figure 1).

73   Two REP experimental snow compaction study plots were located adjacent to one

74   another within an open meadow north of Colorado Highway 40 at an elevation of approximately

75   3,059 m (Figure 1). The snow compaction sites were established within an area that prohibits

76   motorized use to protect the study sites from unintended impacts of snowmobilers. The

77   Columbine snow telemetry (SNOTEL) station, located at an elevation of 2,792 m, was used to

78   show how 2009-2010 winter compared to other winters at REP. The SNOTEL network was

79   established in the late 1970s across the Western United States by the Natural Resources

80   Conservation Service to monitor snowpack properties (initially snow water equivalent and

81   precipitation, and temperature and snow depth were added in the 1990s-2000s) for operational

82   runoff volume forecasting (see <wcc.nrcs.usda.gov>).

83   Three operational sites that were not experimentally manipulated, i.e., where the specific

84   amount of snowmobile use was unknown, were identified along Colorado Highway 40 on REP

85   (Figure 1 left inset). The "natural" control site was Walton Creek, located west of Rabbit Ears

86   Pass in an open meadow at an elevation of 2,895 m within a managed area that prohibits

87   motorized use. Snowshoers, skiers, and snowboarders primarily use this area in the winter to

88   access backcountry terrain. Two treatment sites were located east of REP at an elevation of about

89   2,900 m within an area managed for motorized and mixed uses; the Dumont Lakes and Muddy

90   Creek sites were located in open meadows near their trailheads (Figure 1). These trailheads

91   provide backcountry access to snowmobilers and snowmobile use in the meadows near the

92   trailheads is medium to high, especially on weekends and over holidays. The meadow near the

93   Muddy Creek trailhead is more heavily used by snowmobiles than the meadow near the Dumont

94   Lakes trailhead.

95   Another experimental snow compaction plot was established at the Fraser Experimental

96   Forest (FEF) near the town of Fraser, Colorado in the Rocky Mountains of Central Colorado

97   (Figure 1). The 93 km^2 experimental forest is a research unit of the United States Forest Service

98   (USFS) Rocky Mountain Research Station (RMRS) located within the Arapaho NF. The FEF

99   snow compaction site was located in a small meadow at an elevation of 2,851 m among

100 lodgepole pine (*Pinus contorta*) forest. The Fraser Experimental Forest is closed to snowmobile

101 use, but is used in the winter to access backcountry terrain by snowshoers, skiers, and

102 snowboarders. The Middle Fork Camp SNOTEL station, located at an elevation of 2,725 m, was

103 used to characterize the 2009-2010 winter at FEF.

104

105 **3. Methods**

106 *3.1   Experimental snow compaction plots*

107 Snow compaction study plots were established in undisturbed areas at the REP and FEF

108 experimental snow compaction study areas. Each plot was 22 m wide and 15 m long (Figures 2a

109 and 2b). Plots were divided into equal width transects (2 m) and treated with low, medium (FEF

110 only), or high snowmobile use, including a no treatment control transect representing an

111 undisturbed snowpack. Two control transects were used at FEF to represent the undisturbed

112 snowpack. Integrating two controls in the study plot allowed for replication and determination of

113 variability. The location of control and treatment plots across each study site was randomly

114 selected. Each transect was separated by a three meter buffer to eliminate the influence of

115 compaction treatments on adjacent transects (Figures 2a and 2b).

116   Transects were treated by driving a snowmobile (Figure 2d) over the length of each

117 transect five, 25 (FEF only) or 50 times, representing low, medium (FEF only), and high

118 snowmobile use, respectively. Treatments began (Figure 2c) when non-compacted snow depths

119 were approximately 30 cm (12 inches) for both locations, and when unpacked snow depths

120 equaled approximately 120 cm (48 inches) for REP only (Figure 2a). Treatments were

121   implemented (Figure 2e) monthly thereafter, until peak accumulation (Figure 3). Snowpack

122   sampling was performed within a week after each treatment (Figures 2 and 3).

123

124   ### *3.2   Snow pit analyses and data collection*

125   Snow pit profiles were used to examine the physical properties of the snowpack in all study sites.

126   A vertical snow face was excavated by digging a pit from the snow surface to the ground.

127   Measurements of snow density, temperature, stratigraphy, hardness and ram resistance were

128   taken vertically along the snowpack profile. Total snow depth was measured and combined with

129   density to yield snow water equivalent (SWE). Physical snowpack properties were compared

130   between non-snowmobile (control) and varying degrees (low, medium (FEF), and high) of

131   snowmobile use (treatment).

132   Density was measured at 10 cm intervals, from the surface of the snowpack to the

133   ground, by extracting a 250 mL or 1000 mL snow sample using a stainless steel wedge cutter

134   <snowmetrics.com> and measuring the mass on an electronic scale with a resolution of 1g. The

135   density of the snow (ρ_s in kg/m^3) was determined by dividing the mass of the snow sample by the

136   volume of the wedge cutter. Snowpack density profiles were a continuous profile of discrete 10

137   cm measurements. The bulk snowpack density was determined by averaging the depth integrated

138   density measurements through the entire depth of the snowpack. A mean of the density

139   measurements for the bottom 10 cm of the snowpack were used to evaluate changes near the

140   snow and ground interface (basal layer).

141   Temperature measurements were obtained at 5 cm intervals from the top to the bottom of

142   the snowpack using a dial stem thermometer with $\pm1^\mathrm{o}$C accuracy. The repeatability in the

143   temperature measurement was better than $\pm1^\mathrm{o}$C, and temperature gradients are well represented

144   by this instrument (Elder et al., 2009; American Avalanche Association, 2016). Snowpack

145   temperature profiles and the corresponding bulk temperature gradient were compared. The

146   temperature gradient (T_G in $^{\circ}$C/m) was calculated as the ratio of the change in temperature (ΔT in

147    $^{\circ}$C) from the snowpack depth where the temperature gradient was linear (upper boundary, 25-30

148   cm below the surface) and the temperature at 0 cm (lower boundary) with the distance (d in m)

149   over which the change in temperature occurred. For this study, the point of zero amplitude was

150   used as the upper boundary to remove bias from diurnal fluctuations (Pomeroy and Brun, 2001).

151   Basal layer temperatures (0 cm) were used to compare temperature changes near the snow and

152   ground interface.

153   Stratigraphic measurements illustrate the evolution of the snowpack over time by

154   characterizing the shape and size of snow crystals within each stratified layer of the snowpack.

155   Classification of grain morphology was based on *The International Classification for Seasonal*

156   *Snow on the Ground* (Fierz et al., 2009) and grain size was measured and recorded to the nearest

157   0.5 mm using a hand lens and a crystal card. The crystal forms were identified as fresh, rounded,

158   faceted, and ice layers.

159   Hardness is the snowpack's compressive strength and is measured as the force per unit

160   area required to penetrate the structure of the snowpack (McClung and Schaerer, 2006) due to

161   microstructure and bonding characteristics of the snow grains (Shapiro et al., 1997). Hardness

162   measurements were taken horizontally with a force gauge in each stratigraphic layer using a

163   Wagner Instruments Force Dial gauge (<http://wagnerinstruments.com>) with maximum force

164   measurements of 25 N and 100 N, and fabricated circular metal plate attachments of known area

165   (20 cm^2) . The circular metal plate was pushed into the snow and the force required to penetrate

166   the snow was recorded. The snow hardness (h_i in N/m^2) for each stratigraphic layer was

167 calculated as the force required to penetrate the snow (F in N) per unit area of the circular metal

168 plate (A in m^2). The bulk snowpack hardness (H_B in N/m^2) was determined by weighing each

169 stratigraphic layer hardness measurement by the stratigraphic layer thickness. The hardness

170 associated with the bottom stratigraphic layer for each transect was used to describe hardness

171 changes in the basal layer of the snowpack.

172   The standard ram penetrometer is an instrument with a cone on the end of a tube onto

173 which a hammer of known weight is dropped from a known height and the depth of penetration

174 is recorded; it was used to vertically measure the relative hardness or resistance of a snow layers

175 in order to assess the change in ram resistance due to compaction (American Avalanche

176 Association, 2016). A ram profile measurement was taken 0.5 meters from the edge of the snow

177 pit wall subsequent to snow pit profile measurements. The mean ram resistance (S_B in N) was

178 determined by weighting each stratigraphic layer's ram resistance value obtained from the

179 standard ram penetrometer measurement with the layer thickness. The ram resistance value

180 associated with the bottom stratigraphic layer was measured to describe changes in ram

181 resistance in the basal layer of the snowpack .

182

183 *3.3   Statistical analyses*

184   Data were analyzed using the Mann-Whitney-Wilcoxon rank sum test (Wilcoxon, 1945;

185 Mann and Whitney, 1947). This determines the statistical significance between two datasets,

186 herein different treatments compared to the control of no snowmobile use (Table 1). This

187 statistical test is non-parametric and determines whether two samples were selected from

188 populations having the same distribution. The sets of samples are comparable density,

189 temperature, hardness, and ram resistance profiles for the five different monthly measurements.

190 A statistical significance was determined to the 95% (significant) and 99% (highly significant)

191 confidence interval (p<0.05, and p<0.01) and noted with an asterisk in Table 1.

192

193 **4. Results**

194 The 2009-2010 winter at REP had an average snow depth, based on the Columbine SNOTEL

195 data (Figure 3a), while the peak SWE of 556 mm on 9 April was less than the historical average

196 peak SWE at 93%. Maximum snow depth measured at the REP snow compaction study plot was

197 approximately 1.5 m and for Colorado was deemed to represent a deeper snow cover

198 environment. From the Middle Fork SNOTEL data, the 2009-2010 winter at FEF was less than

199 average compared to the 15-year historical average (Figure 3b). The measured snow depth at the

200 FEF snow compaction study plot never exceeded 1 m, similar to the Middle Fork Camp, and

201 therefore was used to represent a shallower snow cover environment.

202

203 *4.1   Density*

204 Bulk snowpack density increased at the REP snow compaction study site when low and high use

205 compaction treatments began on 30 cm of snow (Figure 4a). As a result, low and high use

206 compaction treatments were significantly different between these treatments (low and high) and

207 the control, and compared to both low and high use compaction treatments beginning on 120 cm

208 of snow (Table 1). The largest bulk snowpack density difference was observed on 6 February

209 when the control bulk density was 246 kg/m^3, while the low and high use compaction treatments

210 yielded an increase to 285 kg/m^3 and 328 kg/m^3, respectively (Figure 4a). In contrast,

211 compaction treatments (low and high) beginning on 120 cm of snow (Figure 4b) did not

212 significantly alter the bulk snowpack density compared to the control (Table 1). While the bulk

213   snowpack density increased through the duration of the study period, by the last sampling date

214   bulk snowpack density was similar between the control and treated transects (Figure 4av and

215   4bv). Treatment increased the density in the basal layer of the snowpack, with the largest

216   difference of 75% (density of 351 kg/m^3) and 88% (377 kg/m^3) for low and high use compaction

217   treatments observed on 12 December, respectively, compared to just over 200 kg/m^3 for the

218   control (Figure 3ai). Snow compaction treatments had little impact on basal layer densities when

219   treatments began on 120 cm of snow with the largest difference being observed on 6 February as

220   229, 234, and 268 kg/m^3 for the control, low and high treatments, respectively (Figure 4biii).

221   Bulk snowpack density also increased at the FEF snow compaction study site for all

222   compaction treatments (low, medium, and high use) that began on 30 cm of snow (Figure 4c).

223   Significant differences were observed between all treatments and the control. However, there

224   were no significant differences between the varying treatments (Table 1). For low and medium

225   use compaction treatments the largest difference in bulk snowpack density compared to the

226   control was on 12 February when density was measured at 177, 296, and 311 kg/m^3, for the

227   control, low and medium treatment, respectively (Figure 4ciii). Snowpack density measured for

228   high use had the largest difference from the control on 22 January when bulk snowpack density

229   was 341 kg/m^3 compared to a bulk density of 192 kg/m^3 for the control (Figure 4cii). Bulk

230   snowpack density generally increased during the study period, but by the end of the study period

231   there were minimal differences between the control and varying degrees of compaction (Figure

232   4cv). Basal layer density increased from all compaction treatments. After the first treatment on

233   27 December, the basal layer density increased by 148% (288 kg/m^3) for low use to about 190%

234   of medium and high use, compared to 116 kg/m^3 for the control (Figure 4ci).

235

236 *4.2   Temperature*

237 Low and high use compaction treatments at the REP snow compaction study site that began on

238 both a shallow snowpack of 30 cm and on a deep snowpack of 120 cm did not result in

239 significant changes in temperature gradient. The maximum temperature gradients were observed

240 on 12 December as 18, 28, and 25°C m^{-1} for the control, low use, and high use compaction

241 treatments that began on a shallow snowpack, while they were almost the same (23, 23, and 25°C

242 m^{-1}) for the control, low use, and high use compaction treatments that began on a deep

243 snowpack. Temperature gradients for all treatments decreased throughout the winter season until

244 all uses exhibited a temperature gradient approaching 0°C m^{-1} by 17 April. Basal layer

245 temperatures increased throughout the winter season until all uses exhibited a basal layer

246 temperature of -1°C by 17 April.

247   Low, medium and high use compaction treatments at the FEF snow compaction study site

248 did not significantly impact the temperature gradient. Maximum temperature gradients for low,

249 medium, and high use were 30°C m^{-1}, 13°C m^{-1}, and 20°C m^{-1} on 27 December compared to 20°C

250 m^{-1} measured at the control. Temperature gradients decreased throughout the winter season until

251 all uses exhibited a temperature gradient near 0°C m^{-1} by 26 April (Figure 5b). The coldest basal

252 layer temperature was for medium use on 22 January (-6°C), with a basal layer temperature of -

253 5°C on 27 December for all other treatments. Basal layer temperatures increased for all uses

254 throughout the winter season until basal layer temperatures reached -1°C by 26 April (Figure 5b).

255

256 *4.3   Hardness*

257 Mean snowpack hardness increased at the REP snow compaction study site following low and

258 high use compaction treatments that began on 30 cm of snow (Figure 6a), but only for high use

259   starting on a deeper snowpack (Figure 6b). Significant increases in hardness were observed

260   between treatments that began on 30 cm of snow and the control, and between compaction

261   treatments (low and high) that began on 120 cm of snow (Table 1). For the treatment that began

262   on the shallow snowpack, the maximum mean hardness for the control was 82 kPa for the

263   control on 17 April (Figure 6av) while for the low use treatment a maximum of 174 kPa was

264   measured on 12 December and for the high use treatment, a maximum of 487 kPa was measured

265   on 6 February. In contrast, mean snowpack hardness was not significantly impacted by snow

266   compaction treatments that began on 120 cm of snow (Table 1). Mean snowpack hardness

267   increased following the initial snow compaction treatments for low and high use, but subsequent

268   compaction treatments did not appear to have a large effect (Figure 6b and Table 1). Mean

269   snowpack hardness for low and high use was greater than the control following the initial snow

270   compaction treatment for both initiation depths (30 cm and 120 cm), but there were minimal

271   differences by the last sampling date (Figure 6av and 6bv).

272   Snow compaction treatments that began on 30 cm of snow increased basal layer hardness

273   (Figure 5a), but treatments that began on 120 cm of snow did not impact basal layer hardness

274   (Figure 5b). For the former, the maximum basal layer hardness was measured at 188 kPa (Figure

275   6ai) and 158 kPa (Figure 6aiii) for the low and high treatments, respectively. For both controls

276   and all treatments that began on 120 cm of snow (Figure 6b), the maximum basal layer hardness

277   was about 6 kPa.

278   Low, medium, and high use compaction treatments resulted in a significant increase in

279   mean snowpack hardness following snow compaction treatments beginning on 30 cm of snow at

280   the FEF snow compaction study site (Table 1). Hardness generally increased during the study

281   period; however, hardness at the treated transects were approaching control values by the last

282 sampling date (17 April; Figure 6c). For the control, the maximum mean snowpack hardness was

283 about 25 kPa (on 26 March in Figure 6civ) while the maximum treatment hardness was one to

284 two orders of magnitude higher at 395 kPa (low treatment on 22 January, Figure 6cii), 780 kPa

285 (medium treatment on 26 March, Figure 6civ) and 4,627 kPa (high treatment on 26 March,

286 Figure 6civ). Similarly, the maximum basal layer hardness for the control was only 4 kPa (on 26

287 March, Figure 6civ) and 138, 352 and 728 kPa for low, medium and high use, respectively

288 (Figure 6cii, 6civ, and 6civ).

289

290 *4.4   Ram resistance*

291 Low and high use compaction treatments at REP caused an increase in mean snowpack ram

292 resistance (Figure 7a and 7b), but the difference was only significant for treatments that began on

293 30 cm of snow (Table 1). The maximum mean snowpack ram resistance was measured as 128,

294 203, and 496 N for the control, low and high use, respectively (Figure 7av, 7av, and 7aiii). After

295 the initial snow compaction treatments mean snowpack ram resistance for low and high use was

296 greater than the control for the entire study period, but by the end of the study period minimal

297 differences were observed between treatments. Basal layer ram resistance increased as a result of

298 low and high use compaction treatments that began on both 30 cm (44, 614, and 1,297 N for

299 control, low and high use) and 120 cm of snow (44, 270 and 90 N for control, low and high use).

300   Snow compaction treatments at the FEF snow compaction study site caused a significant

301 increase in mean snowpack ram resistance (Figure 7c; Table 1). Maximum mean snowpack ram

302 resistance for the control was 18 N (26 March, Figure 7civ), for low and medium use it was

303 544N and 591N (26 March, Figure 7civ) respectively, while for high use it was measured at

304 866N (on 12 February, Figure 7c). Basal layer ram resistance increased following the initial

305   snow compaction treatments and continued to increase throughout the duration of the winter

306   season, with maximums of 28 (26 March), 1,220, 1,220, and 3,220 N for the control, low,

307   medium, and high treatments (on 12 February for all the use treatments).

308

309   *4.5   Experimental Site Time Series*

310   A time series summary of the bulk density (Figure 8a), basal density (Figure 8b), temperature

311   gradient (Figure 8c), and hardness (Figure 8d) illustrates the temporal evolution of the mean

312   properties. The density increase due to snowmobile use is much more at Fraser (Figures 8aii and

313   8bii) and for the start on a low snowpack (30 cm) at Rabbit Ears initiation for the basal density

314   (Figure 8bi), with density for the low use snowpack at FEF approaching the values measured for

315   no use (Figure 8bii). Temperature gradients were not very different (Figure 8c) and not found to

316   be significant (Table 1b). Increased hardness due to snowmobile use showed similar temporal

317   patterns to densification (Figure 8d).

318

319   *4.6   Operational Sites*

320   As illustrated by SWE (Figure 9d) and depth (Figure 9a), the amount of snow was similar for the

321   snowpits dug at the three operational sites, but not the same since they were up to 6km apart

322   (Figure 1). Also these were operational sites, i.e., the amount of treatment was not controlled and

323   was based solely on permitted use. Patterns of increased density (Figure 9a), hardness (Figure

324   9b) and ram resistance (Figure 9c) were similar to the previous presented experiments (Figures 4,

325   6, and 7) with the non-snowmobile snowpits being less dense (Figure 9a) and having layers that

326   were less hard (Figure 9b). For visual inspection, Muddy Creek had the most snowmobile use

327 and thus had the highest density throughout the winter, and the hardest snowpack for mid-winter

328 (Figure 9bii to 9biv) but at times was similar to Dumont Lakes.

329

330 **5. Discussion**

331

332   The increase in density and hardness is greatest compared to an untreated snowpack in

333 early to mid-season (January) for a deeper snowpack (REP in Figures 4a, and 6a), and later into

334 the snow season for the shallower snowpack (FEF in Figures 4c, and 6c). Similar differences

335 were found due to ski run grooming in an Australia snowpack with a 400% increase in hardness

336 early in the snow season but only about a 40% increase later in the winter (Fahey et al., 1999).

337 Snow grooming increased the average density by up to 36% compared to non-groomed ski

338 slopes (Fahey et al., 1999, Rixen et al., 2001).

339   Compaction of the snowpack changes in density, hardness and ram resistance (Figures 4,

340 6, 7, and 9), and results in deformation of snow through 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 4a, 6a, 7a versus Figures 4b, 6b, 7b) and for two

347 different snow covered environments (Figures 4c, 6c, 7c).

348 For a deep snow cover environment (REP), compaction treatments beginning on a shallow

349 snowpack (30 cm) resulted in a 15% and 33% increase in density for low and high use

350   treatments, respectively (Figure 4a), observed mid-winter (early February), similar to maximum

351   late season natural snowpack densities. Density differences were greatest for a shallow snow

352   cover environment (FEF), with high use resulting in 78% greater density (Figure 4c).

353   Conversely, no significant differences in density were observed when snowmobile use began on

354   a deep snowpack (120 cm) (Figures 4b, Table 1). The snowpack density varies spatial and

355   temporally, such as between 40 to 200 kg/m^3 for fresh snow (Fassnacht and Soulis, 2002), but

356   this can double with just one pass of a snowmobile on a very shallow snowpack (Keddy et al.,

357   1979), and even with more accumulation, density will increase, but the underlying snow

358   increases in density (Figures 4 and 9a).

359   Increased densification of the snowpack due to snowmobile use influences snow hardness

360   (Figure 6) and ram resistance (Figure 7). In this study, snow-hardness gauges and circular metal

361   plates of known area were used (McClung and Schaerer, 2006), rather than the more simplistic in

362   situ hand hardness test (American Avalanche Association, 2016). Snowmobile use beginning on

363   a shallow snowpack (30 cm) for a deep snowpack (REP) resulted in a 2- and 6-fold increase in

364   maximum snow hardness for low and high use compared to no use, whereas at a shallow snow

365   study site (FEF), a 15-, 30- and nearly 200-fold increase in maximum snow hardness for low,

366   medium, and high use was observed. A shallow snow environment is more susceptible to large

367   changes in snow hardness due to varying snowmobile use.

368   Ram resistance values ranged from 0 N to just below 1000 N, which is a normal range for

369   snowpack strength measurements (Colbeck et al., 1990). The precision of the ram penetrometer

370   used in this study was 10N, so the ram resistance of a fresh snow and layers of the snowpack

371   with limited metamorphism could not be measured as it is typically in the range of 0.5N (Pruitt,

372   2005). These values can increase to as much as 70N as a result of two passes with one person on

373   a snowmobile (Pruitt, 2005). Similar to hardness observations, snowmobile use beginning on a

374   shallow snowpack yielded ram resistance 1.5- and 4-fold greater than the natural snowpack

375   (Figure 7). The impact of snowmobile use on a snowpack ram resistance (Figures 7 and 9c) has

376   only been observed by Pruitt (2005).More frequent fresh snowfall events (REP, Figure 7a) with

377   compaction treatments can produce a snowpack of stratified strong and weak layers, and a

378   deeper snowpack is capable of lessening the effect of compaction from snowmobile use (Figure

379   7b).

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°C m^{-1} at the beginning of the season, and approached 0°C m^{-1} as the

383   snowpack became isotherm at the end of the winter season. The temperature gradient was

384   sufficient for kinetic growth metamorphism for most of the winter season ($T_G > 10^{\circ}$C m^{-1}), as

385   seen by less dense lower snowpack layers for the controls (Figures 4a, 4c, 9a) and the deep

386   snowpack where snowmobile use started at 120 cm (Figure 4b).

387   At rest, a snowmobile and its rider exert 4 to 10 kPa of pressure to the underlying

388   snowpack (assuming a track length from 0.9 to 1.4 m, width of 0.50 m, a snowmobile weight of

389   200 to 350 kg, and a rider weight of about 100 kg, data from <polarisindustries.com>). There is

390   an increase of less than an order of magnitude due to snowmobile movement (Thumlert et al.,

391   2013 measured stresses of about 10 to 20 kPa at a depth of 30 cm below the surface of a deep

392   snowpack). In comparison, fresh snow with a density of 100 kg/m^3 exerts a pressure of 0.003

393   kPa on the underlying snowpack (Moynier, 2006). Snowpack loading by wheeled vehicles on a

394   shallow snowpack was much greater, peaking at about 350 kPa (Pytka, 2010). Grooming

395   vehicles added a load similar to snowmobiles (Pytka, 2010), due to the larger track size and

396   results may be transferrable.

397   A decrease in crystal size was observed for both the deep and shallow snowpacks

398   subjected to snowmobile use (Table 2). Specifically, depth hoar crystals for the controls at FEF

399   reached a maximum average size of 9.0 mm, while low, medium, and high use resulted in

400   average crystal sizes of 1.3 mm, 2.5 mm and 1.5 mm, respectively (Table 2). While the

401   temperature profile differences between control and snowmobile use were not significant,

402   temperature gradients, and thus vapour pressure gradients, were still less decreasing depth hoar

403   growth (Table 2). This trend was also observed on REP, but the difference in depth hoar crystal

404   sizes between control and treatments was less (Table 2).

405   The overall increase in density, hardness and ram resistance (Figure 7) was statistically

406   significant between the control (no snowmobile use) and all treatments, except when treatments

407   were initiated on a deep snowpack (Figures 4b, 6b, and 7b, Table 1). The measured depth of

408   influence for a snowmobile is about 90 cm (Thumlert et al., 2013). At 20 cm below the snow

409   surface, the induced stress is already much less than 10 cm below the surface from a snowmobile

410   (Thumlert et al., 2013) or a grooming machine (Pytka, 2010). Most ski resorts in the French Alps

411   required a minimum snow depth of 40 cm to offer skiing, with a range from 60 cm in February to

412   40 cm in April (Spandre et al., 2016b). The US Forest Service (2013b) recommends a minimum

413   of 30 cm before the use of snowmobiles. Increasing the minimum snow depth before allowing

414   snowmobile traffic will reduce changes to the snowpack due to snowmobiles (Table 1). Where

415   the experiments were undertaken, i.e., Colorado, there are 1.1 to 1.6 million annual snowmobile

416   visits, with an increase from 580 thousand to 690 thousand between 2010 to 2013 in northern

417   Colorado (Routt NF and Arapaho-Roosevelt NF) and southern Wyoming (Medicine Bow NF)

418   (US Forest Service, 2010 and 2013a), with an annual economic impact of more than $100

419   million to each state (Nagler et al., 2012; Colorado Off-Highway Vehicle Coalition, 2016). Thus

420   snowmobile use will continue to change to the snowpack, and the impacts are expected to

421   become greater with the anticipated increases in snowmobile activity.

422   Snowmobile use, starting with a shallow or thin (30 cm) snowpack, resulted in a denser

423   and harder snowpack (Figure 8) with smaller basal grains (Table 2). This is expected, yet this

424   paper does not suggest that snowmobiles can be used to strengthen the snowpack and prevent

425   avalanches that fail on basal facets, similar to a boot packing program (e.g. Sahn, 2010). While

426   this may be useful in very limited and small areas, it is very difficult to properly align the

427   creation of repetitive tracks, as done here (Figure 2), nor to the same intensity. Do not try

428   snowmobile use in the backcountry to reduce avalanche hazard.

429   Snowmobile use was found to have a highly significant effect upon natural vegetation

430   below the snow (Keddy et al., 1979), with grooming shown to delay the blooming of alpine

431   plants (Rixen et al., 2001) due to a later snowmelt and a significantly cooler soil (Fassnacht and

432   Soulis, 2002). Deeper snowpack were found to not have a cooler soil temperature under the

433   snowpack (Keller et al., 2004), but did melt out four weeks later (Keller et al., 2004). Since the

434   snowpack changes due to snowmobile traffic on a shallow snowpack were significant (Table 1),

435   the effects of snowmobile use on the soil and vegetation underlying a shallow snowpack should

436   be further investigated.

437   Without wind, snow depth will be less for areas with snowmobile traffic (Figures 2d, 2e,

438   and 4; Rixen et al., 2001; Spandre et al., 2016a). However, wind is often present in open areas

439   where snowmobiling occurs. The local terrain features and position and extent of canopy

440   influence how the wind interacts with the snowpack (Pomeroy and Brun, 2001). In an Australia

441 case study, SWE increased by 45% in groomed areas (Fahey et al., 1999); at the Rabbit Ears Pass

442 recreational use areas, SWE also increased (Figure 9d) likely due to snow blowing into the

443 depressions created by snowmobile tracks (Figure 2d). The increased load could further impact

444 the underlying snowpack properties. Further, snowmaking (Spandre et al., 2016a) to supplement

445 natural snow conditions and/or grooming (Fahey et al., 1999; Rixen et al., 2001; Spandre et al.,

446 2016a) compacts the snowpack below it, and alters the underlying snowpack properties (Howard

447 and Stull, 2014; Spandre et al., 2016a; Spandre et al., 2016b). Also, a changing climate will

448 likely reduce the extent of terrain and decrease the length of the winter recreation season (Laxar

449 and Williams, 2008; Steiger, 2010; Dawson and Scott, 2013; Marke et al., 2015; Tercek and

450 Rodman, 2016).

451

452 **6. Conclusion**

453 This study examined the effect of compaction from snowmobile use on snowpack properties. It

454 showed that snowpack properties change with varying use of snowmobile use, annual snowfall

455 (REP versus FEF), and the depth at which snowmobile use was initiation. Snowmobile use

456 creates compaction that influences the physical and mechanical properties of the snowpack. In

457 particular, this increases snowpack density, hardness, and ram resistance when winter

458 recreational use occurs. The largest differences in snowpack properties are snowmobile use

459 beginning on a shallow snowpack (30 cm) compared to no use, which increases snowpack

460 density, hardness, and ram resistance. These increases are directly related to increasing

461 snowmobile use (from low to medium to high). Conversely, snowmobile use that begins on a

462 deep snowpack (120 cm) has a limited effect on snowpack properties as seen by density,

463 temperature, hardness, and ram resistance measurements comparable to an undisturbed

464 snowpack.

465

466

467 **Author contribution**

468 The experiment were designed by J.T. Heath and S.R. Fassnacht with input from K.J. Elder. J.T.

469 Heath performed the experiments with assistance from K.J. Elder at the Fraser site. All authors

470 contributed to the writing of the manuscript. S.R. Fassnacht generated the figures.

471

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480 creation of new figures. TC editor Dr. Guillaume Chambon provided additional comments and

481 an important citation that helped reformulate the discussion.

482

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

a) Density

				Shallow initiation depth (30 cm)		
			control	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

				Shallow initiation depth (30 cm)		
			No use	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

				Shallow initiation depth (30 cm)		
			No use	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

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

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

		date	Basal layer grain size [mm]			
			control	Low	Medium	High
REP	Shallow initiation depth (30 cm)	12/12/2009	3.0	1.0		<0.5
		01/09/2010	2.0	3.0		1.0
		02/06/2010	3.0	1.5		1.0
		03/13/2010	3.0	3.0		1.0
		04/17/2010	1.5	1.5		1.0
	Deep initiation depth (120 cm)	12/12/2009	3.0	3.0		3.0
		01/09/2010	2.0	3.0		1.5
		02/06/2010	3.0	3.5		3.0
		03/13/2010	3.0	3.0		3.5
		04/17/2010	1.5	1.5		1.5
FEF	Shallow initiation depth (30 cm)	12/27/2009	4.0	3.0	1.0	1.0
		01/22/2010	3.0	1.0	2.0	1.5
		02/12/2010	4.5	2.0	2.0	1.5
		03/26/2010	9.0	1.0	2.5	1.5
		04/26/2010	5.0	1.5	3.0	3.0

List of Figures

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

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

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

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

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

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

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

8. Time series for the different sampling dates of a) mean snowpack density, b) basal snowpack density, c) snowpack temperature gradient, and d) mean snowpack hardness for i. Rabbit Ear Pass and ii. Fraser Experimental Forest. Note that the snow at the low and high use start at 30 cm could not be adequately tested for hardness on the first sampling date at the REP treatment plots.

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

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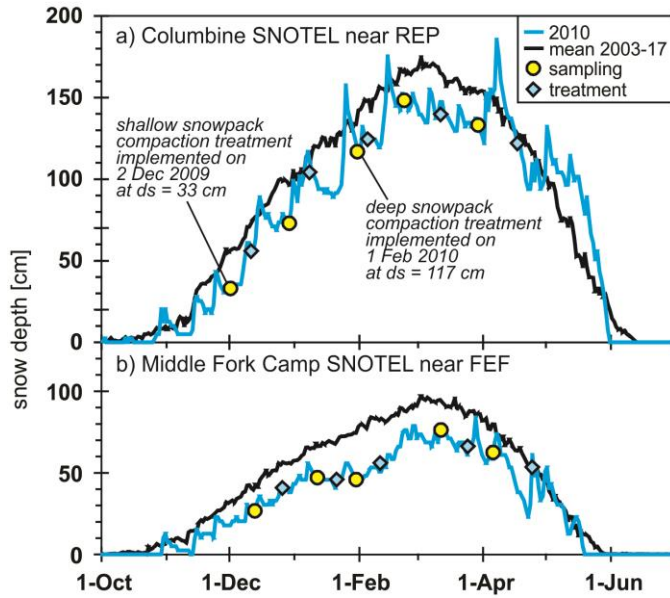
Figure 3. Mean snow depth from 2003-2017, and for the 2010 water year (WY2010) measured at a) the Columbine SNOTEL site near Rabbit Ears Pass (REP), Colorado and b) the Middle Fork Camp SNOTEL near Fraser Experimental Forest (FEF). Data were obtained online from the Natural Resource Conservation Service (NRCS) National Water and Climate Center (http://www.wcc.nrcs.usda.gov/).
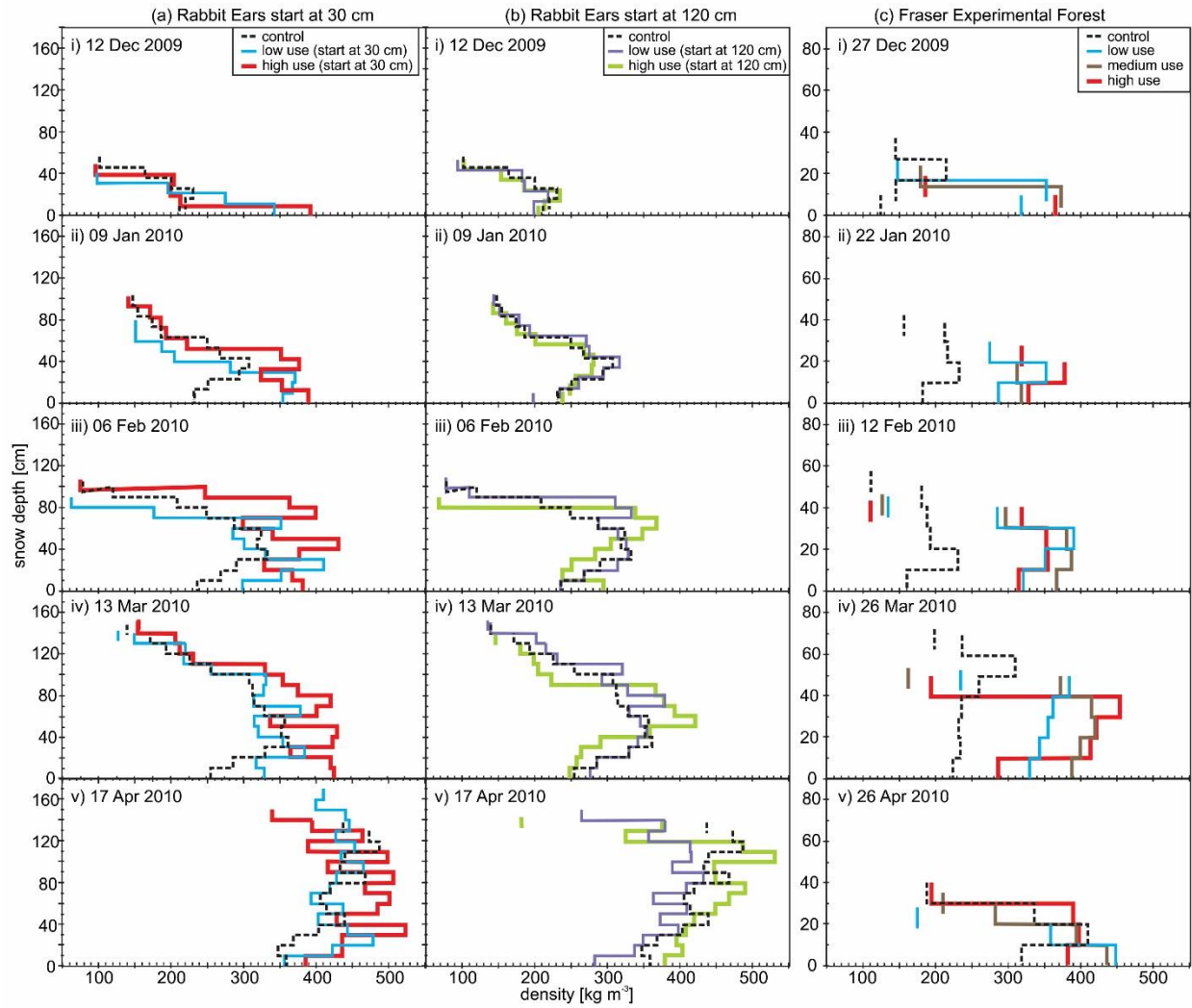
Figure 4. Density profiles for five dates (i to v) measured at the REP snow compaction study plot for no (control), low, and high use treatments beginning on a) 30 cm and b) 120 cm of snow, and c) the FEF snow compaction study plot for no (control), low, medium, and high use treatments beginning on 30 cm of snow. Note that free floating measurements represent overlapping density measurements.
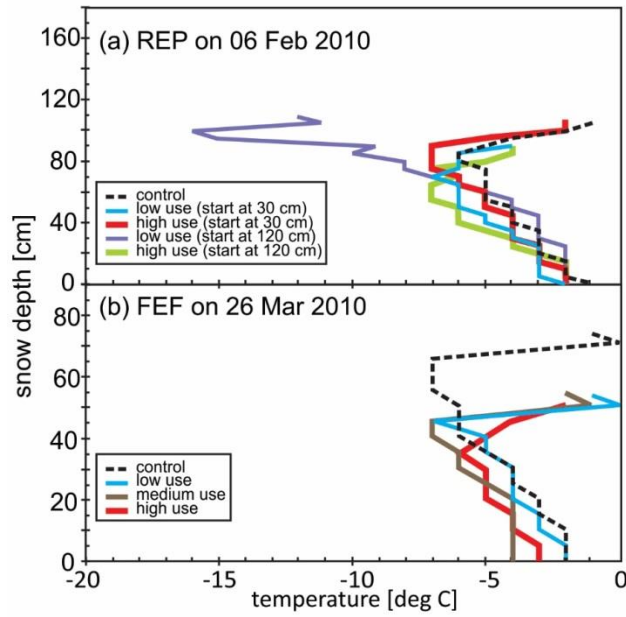
Figure 5. Temperature profiles measured at a) the REP snow compaction study plot on February 06, 2010 for no, low, and high use treatments beginning on 30 cm and 120 cm of snow and b) the FEF snow compaction study plot on March 26, 2010 for no, low, medium, and high use treatments beginning on 30 cm of snow.
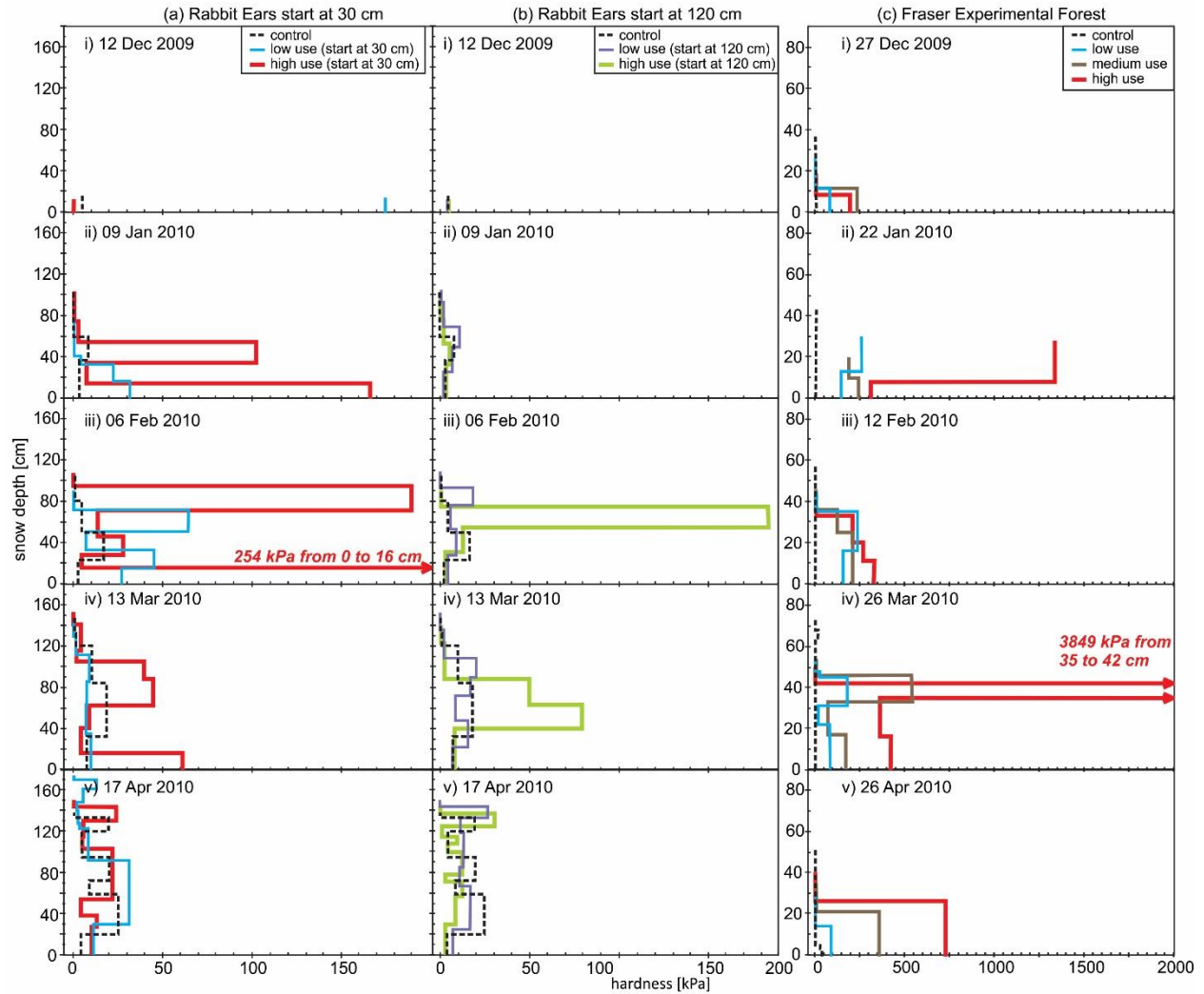
Figure 6. Hardness profiles for five dates (i to v) measured at the REP snow compaction study plot for no, low, and high use treatments beginning on a) 30 cm and b) 120 cm of snow, and c) the FEF snow compaction study plot for no, low, medium, and high use treatments beginning on 30 cm of snow.
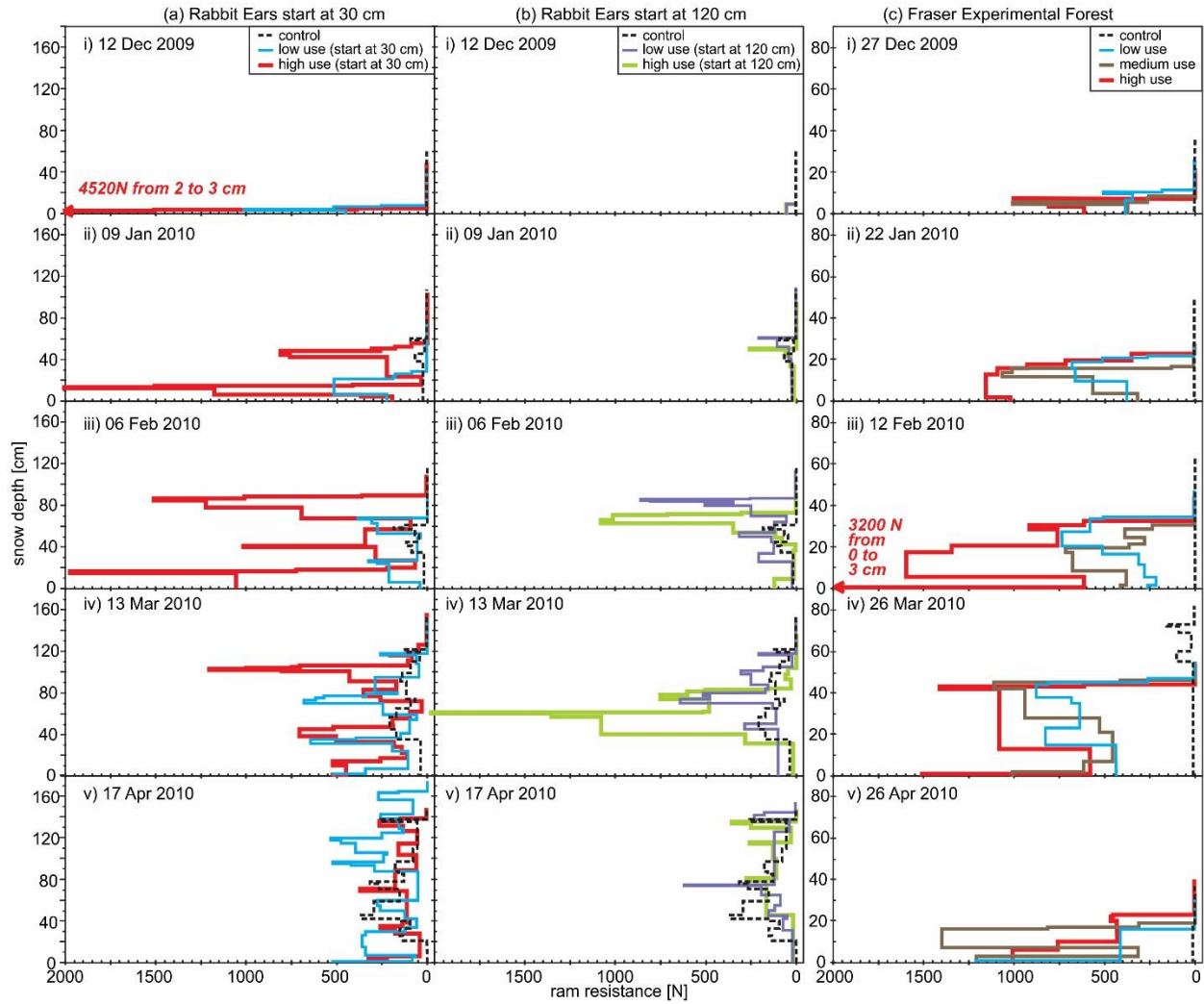
Figure 7. Ram resistance for five dates (i to v) profiles measured at the REP snow compaction study plot for no, low, and high use treatments beginning on a) 30 cm and b) 120 cm of snow, and c) the FEF snow compaction study plot for no, low, medium, and high use treatments beginning on 30 cm of snow.
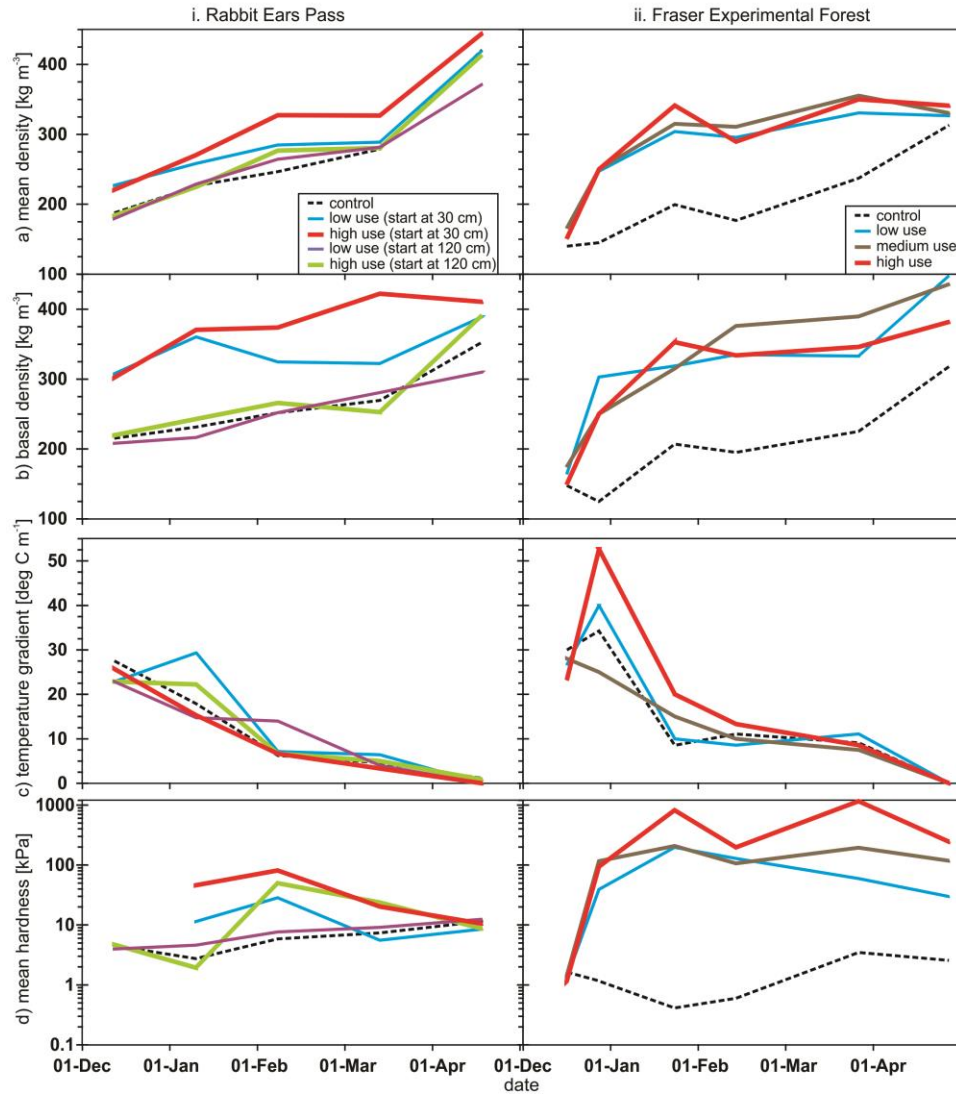
Figure 8. Time series for the different sampling dates of a) mean snowpack density, b) basal snowpack density, c) snowpack temperature gradient, and d) mean snowpack hardness for i. Rabbit Ear Pass (REP) and ii. Fraser Experimental Forest. Note that the snow at the low and high use start at 30 cm could not be adequately tested for hardness on the first sampling date at the REP treatment plots.
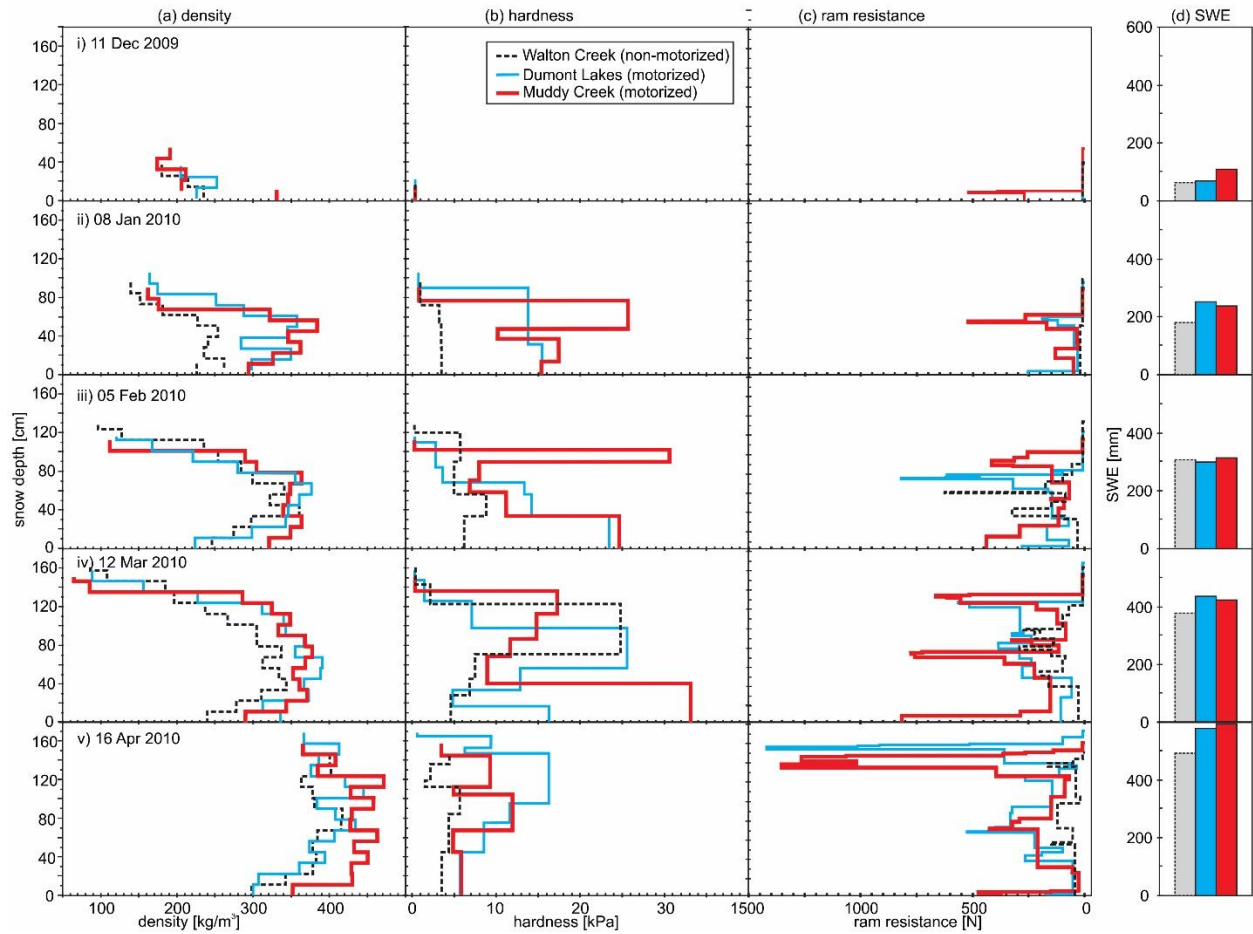
Figure 9. Snowpit data for Walton Creek (no snowmobile use), Dumont Lakes (moderate snowmobile use) and Muddy Creek (high snowmobile use) in the Rabbit Ears Pass recreational use areas illustrating a) density, b) hardness, c) ram resistance, and d) SWE.