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

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

14   **Abstract**

15   Snowmobile use is a popular form of winter recreation in Colorado, particularly on public

16   lands. To examine the effects of differing levels of use on snowpack properties, experiments

17   were performed at two different areas, Rabbit Ears Pass near Steamboat Springs and at Fraser

18   Experimental Forest near Fraser, Colorado USA. Differences between no use and varying

19   degrees of snowmobile use (low, medium and high) on shallow (the operational standard of 30

20   cm) and deeper snowpacks (120 cm) were quantified and statistically assessed using

21   measurements of snow density, temperature, stratigraphy, hardness, and ram resistance from

22   snow pit profiles. A simple model was explored that estimated snow density changes from

23   snowmobile use based on experimental results. Snowpack property changes were more

24   pronounced for thinner snow accumulations. When snowmobile use started in deeper snow

25   conditions, there was less difference in density, hardness, and ram resistance compared to the

26   control case of no snowmobile use. These results have implications for management of

27   snowmobile use in times and places of shallower snow conditions where underlying natural

28   resources could be affected by denser and harder snowpacks.

1. Introduction

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

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

53   stresses through the snowpack due to type of loading, depth and snowpack stratigraphy

54   (Thumlert et al., 2013).

55   Changing snowpack conditions from snowmobile use will have other impacts. Aside

56   from the work done by Keddy et al. (1979), there is limited research on how snowmobile activity

57   influences underlying vegetation. The addition of snow due to snowmaking provides an

58   indication of possible changes. Changes from snowmaking include a greater occurrence of soil

59   frost, ice layers may form at the base of the snowpack, and there is often a delay in vegetative

60   growth due to extended snow cover (Rixen et al., 2003). Snowmelt can occur later due to

61   compaction and there is greater heat loss from the densified snowpack and underlying soil,

62   keeping soil temperatures colder longer (Fassnacht and Soulis, 2002; Rixen et al., 2003).

63   In our research, we specifically examined the effect of snowmobile use on the physical

64   and material properties of the snowpack. The objectives were to: (1) quantify changes to physical

65   snowpack properties due to compaction by snowmobiles; (2) evaluate these changes based on the

66   amount of use, depth of snow when snowmobile use begins, and the snowfall environment where

67   snowmobiles operate; and (3) create a simple model to estimate the change in snowpack density

68   due to snowmobile use. This work examines not only changes to the basal snowpack layer, but

69   also to the entire snowpack. The positive economic impact of snowmobiling and increasing

70   winter recreation use from non-motorized activities (such as backcountry skiers, snowshoers, and

71   those on fat bikes) dictates a need to better understand impacts to snow and underlying natural

72   resources in multi-use areas, especially when the information may be used by managers to

73   reduce conflict among recreationists and protect the resource.

74

75   **2. Study Sites**

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

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

78   Steamboat Springs. REP is within the Medicine Bow-Routt National Forest (NF) (Figure 1)

79   along the Continental Divide encompassing over 9,400 km^2 of land in Colorado and Wyoming.

80   Rabbit Ears Pass is especially popular during the winter season and is heavily used by

81   snowmobilers and other winter recreationalists due to the ease of access to backcountry terrain

82   from Colorado Highway 40. Due to heavy use and conflict among users during the winter

83   season, the Forest Service manages Rabbit Ears Pass for both non-motorized and motorized uses.

84   The west side of the pass is designated for non-motorized use and prohibits motorized winter

85   recreation while the east side of the pass is a mixed-use area and is open to motorized use (Figure

86   1). This study area was selected to determine if differences in snowpack properties will be

87   observed between the non-motorized and motorized use areas (e.g., Walton Creek versus

88   Dumont Lakes and Muddy Pass in Figure 1).

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

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

91   3,059 m (Figure 1). The snow compaction sites were established within an area that prohibits

92   motorized use to protect the study sites from unintended impacts of snowmobilers. Data from the

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

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

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

96   Conservation Service to monitor snowpack properties. Initially snow water equivalent and

97   precipitation were monitored, temperature and snow depth were added in the 1990s-2000s to aid

98   in operational runoff volume forecasting (see <wcc.nrcs.usda.gov>).

99   Three sites were not experimentally manipulated, i.e. the specific amount of snowmobile

100   use was unknown, and were identified as operational sites along Colorado Highway 40 on REP

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

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

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

104   access backcountry terrain. Two sites, Dumont Lakes and Muddy Creek, were located east of

105   REP at an elevation of about 2,900 m within an area managed for motorized and mixed uses; the

106   sites were located in open meadows near their respective trailheads (Figure 1). These trailheads

107   provide backcountry access to snowmobilers. Snowmobile use in the meadows near the

108   trailheads is medium to high, especially on weekends and over holidays (Skorkowsky, 2010).

109   The meadow near the Muddy Creek trailhead is more heavily used by snowmobiles than the

110   meadow near the Dumont Lakes trailhead.

111   Another experimental snow compaction plot was established during the same winter

112   snow season of 2009-2010 at the Fraser Experimental Forest (FEF) near the town of Fraser,

113   Colorado in the Rocky Mountains of Central Colorado (Figure 1). The 93 km^2 experimental

114   forest is a research unit of the United States Forest Service (USFS) Rocky Mountain Research

115   Station (RMRS) located within the Arapaho NF. The FEF snow compaction site was located in a

116   small meadow at an elevation of 2,851 m surrounded by lodgepole pine (*Pinus contorta*) forest.

117   The Fraser Experimental Forest is closed to snowmobile use, but is used to access backcountry

118   terrain by snowshoers, skiers, and snowboarders. The Middle Fork Camp SNOTEL station,

119   located at an elevation of 2,725 m, was used to characterize the 2009-2010 winter at FEF.

120

121   **3. Methods**

3.1   *Experimental snow compaction plots*

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

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

3.2   *Snow pit analyses and data collection*

144   Snow pit profiles were used to examine the physical properties of the snowpack at both

145   the experimental and at the operational sites. A vertical snow face was excavated by digging a pit

146   from the snow surface to the ground. Measurements of snow density, temperature, stratigraphy,

147   hardness and ram resistance were taken vertically along the snowpack profile. Total snow depth

148   was measured from the ground up, and combined with density to yield snow water equivalent

149   (SWE). Physical snowpack properties were compared between non-snowmobile (control) and

150   varying degrees (low, medium (FEF), and high) of snowmobile use (treatment).

151   Density was measured at 10 cm intervals, from the surface of the snowpack to the ground, by

152   extracting a 250 mL or 1000 mL snow sample using a stainless-steel wedge cutter

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

154   least two samples were taken per 10 cm interval. With the 1000 mL wedge cutter, the density of

155   the snow (ρ_s in kg/m^3) was read directly from the scale as the volume of the cutter is 1/1000 of a

156   cubic meter and a gram is 1/1000 of a kilogram. For the 250 mL cutter, the mass measurement

157   results were multiplied by 4 to obtain density. Snowpack density profiles were created from

158   samples extracted at discrete 10 cm intervals vertically along the working face of the snowpit.

159   The bulk snowpack density was determined by averaging density measurements over the entire

160   depth of the snowpack. A mean of the density measurements for the bottom 10 cm of the

161   snowpack was used to evaluate changes near the snow and ground interface (basal layer).

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

163   the snowpack using a dial stem thermometer with $\pm 1^{\circ}$C accuracy. Temperature gradients are well

164   represented by this instrument, and the repeatability of temperature measurements are better than

165    $\pm 1^{\circ}$C (Elder et al., 2009; American Avalanche Association, 2016). Snowpack temperature

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

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

168 distance (d in m) over which the change in temperature occurred. The snowpack temperature

169 gradient was approximated as linear from an upper boundary that was 25-30 cm below the

170 surface to the lower boundary at 0 cm. For this study, the depth below the snow surface where

171 temperature did not fluctuate diurnally was used as the upper boundary to remove bias from

172 diurnal fluctuations (Pomeroy and Brun, 2001). Basal layer temperatures taken at 0 cm were

173 used to compare temperature changes near the snow and ground interface.

174   Stratigraphic measurements were used to illustrate the evolution of the snowpack over

175 time through characterization of the shape, size, and layering of snow crystals within the

176 snowpack. Classification of grain morphology was based on *The International Classification for*

177 *Seasonal Snow on the Ground* (Fierz et al., 2009) and mean grain size was measured and

178 recorded to the nearest 0.5 mm using a hand lens and a crystal card. The crystal forms were

179 identified as precipitation particles, rounded grains, faceted grains, and ice layers.

180   Hardness is the penetration resistance of the snowpack (Fierz et al., 2009), and is reported

181 as the force per unit area required to penetrate the structure of the snowpack (McClung and

182 Schaerer, 2006). It is affected by snowpack microstructure and bonding characteristics of the

183 snow grains (Shapiro et al., 1997). Hardness measurements were taken horizontally with a force

184 gauge in each stratigraphic layer using a Wagner Instruments Force Dial gauge

185 (<http://wagnerinstruments.com>) with maximum force measurements of 25 N and 100 N, and

186 fabricated circular metal plate attachments of 20 cm^2 in area. For each measurement, the circular

187 metal plate was pushed into the snow and the force required to penetrate the snow was recorded.

188 The snow hardness (h_i in N/m^2) for each stratigraphic layer was calculated as the force required

189 to penetrate the snow (F in N) per unit area of the circular metal plate (A in m^2). All layers

190   thicker than 5 cm were identified using the 5-cm diameter of the plate. The bulk snowpack

191   hardness (H_B in N/m^2) was determined by weighting each stratigraphic layer hardness

192   measurement by the stratigraphic layer thickness. The hardness associated with the bottom

193   stratigraphic layer for each transect was used to describe hardness changes in the basal layer of

194   the snowpack.

195   The standard ram penetrometer is an instrument with a cone on the end of a rod onto

196   which a hammer of defined weight is dropped from a given height and the depth of penetration is

197   recorded; it was used here to vertically measure the resistance of snow layers to assess the

198   change in ram resistance due to compaction (American Avalanche Association, 2016). A ram

199   profile measurement was taken 0.5 meters from the edge of the snow pit wall subsequent to snow

200   pit profile measurements. The mean ram resistance (S_B in N) was determined by weighting each

201   ram resistance value obtained from the standard ram penetrometer measurement with the depth

202   sampled. The ram resistance value associated with the bottom layer was measured to describe

203   changes in ram resistance in the basal layer of the snowpack.

204

205   *3.3   Statistical analyses*

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

207   Mann and Whitney, 1947). This statistical test is non-parametric and determines whether two

208   independent samples were selected from populations having the same distribution. For this work,

209   the sets of samples compared were density, temperature, hardness, and ram resistance profiles for

210   the five different monthly measurements and the controls (Table 1). A statistical significance

211   was determined for the 95% (significant) and 99% (highly significant) confidence interval

212   ($p < 0.05$, and $p < 0.01$) and noted with an asterisk in Table 1.

213

3.4   Bulk Snowpack Density Change Model

A multi-variate non-linear model was created to estimate the change in bulk snowpack density for various treatments compared to the control (no use) using the following snowpack properties: depth, bulk density, and the number of passes (Figure 8). The cross-correlation between variables was considered to reduce model over-fitting. The model was calibrated with the experimental data from REP and FEF, and evaluated using data from the operational sites with Walton Creek as the control, Dumont Lakes as medium use, and Muddy Creek as high use. The Nash Sutcliffe Coefficient of Efficiency (NSCE, Nash and Sutcliffe, 1970) was used to evaluate the fit of the model.

4. Results

4.1   The Measurement Winter

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

4.2   Snowpack Properties

236

4.2.1   Density

238   The natural variability in density was small at the test sites (Figure 4). At REP, deep

239   snow (120 cm) compaction treatments were not initiated until after the second sampling date

240   (Figure 3a), so density for the deep snow low and high use treatments could then be compared to

241   the control; these show minimal difference (Figure 4). At FEF, there were two sets of control

242   snowpits, and sampling occurred before treatment at all plots (Figure 3b). These difference in

243   density were greater than those at REP but were still small (Figure 4).

244   The mean density values at the FEF plots were almost the same at the end of the

245   sampling period in April (Figure 5aii). The mean snowpack density increased over the snow

246   season (Figure 5a), with the exception of the FEF control and at the high use site on 12 Feb 2010

247   due to fresh snow deposition. At the REP snow compaction study site, mean density for high use

248   compaction treatments starting on 30 cm of snow was greater throughout the measurement

249   period than the no use treatment (Figures 5ai, 6ai, and 6aii), while the density from low and high

250   use starting on the deeper snowpack of 120 cm was very similar to that measured for no use. The

251   snowpack was more dense for low use on the shallower snowpack (start at 30 cm) than the

252   control, expect for 13 March (Figure 5ai). Density differences are more pronounced for the basal

253   layer (Figure 5b); for compaction treatments starting at 30 cm, the lowest layers were much more

254   dense than the control (Figure 6a). Densities for the compaction treatments starting at 30 cm

255   were significantly different than the control and compaction treatments beginning at 120 cm of

256   snow (Table 1a). The density differences between the treatments on the deep snow (120 cm) and

257   the control were not significantly different (Table 1a).

258   Density increases due to snowmobile use were much greater at Fraser (Figures 5ai and

259   5bii) than Rabbit Ears. All treatments at FEF were significantly different than the control, but the

260   difference among treatments was not significant (Table 1a). The density differences among

261   treatments are highlighted in the 10-cm individual density measurements (Figure 6a) and in the

262   basal layer (Figure 5bii).

263

264   *4.2.2   Temperature*

265   Low and high use compaction treatments at the REP snow compaction study site that

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

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

268   on the earliest sampling date (12 December, Figure 5c), while they were almost the same for the

269   control, low use, and high use compaction treatments that began on a deep snowpack.

270   Temperature gradients for all treatments decreased throughout the winter season, and were

271   isothermal at 0°C/m by mid to late April (Figures 5ci and 5cii), since the snow had stared to melt

272   (Figure 3). Overall, temperature gradients were not very different (Figure 5c) and the variations

273   among treatments were not found to be significant (Table 1b). At FEF, gradients in the high use

274   were greatest after the first treatment and the temperature gradients were essentially the same by

275   March (Figure 5cii).

276

277   *4.2.3   Hardness*

278   The snowpack was harder for snowmobile use starting on 30cm than the control (no use)

279   for both sites (Figures 5d and 5e). Mean snowpack hardness did not change much over time

280   (Figure 5d), except once high use treatments started (06 Feb) on a deeper snowpack. However,

281   basal layer hardness did decline at REP for both high and low use starting on 30 cm (Figure 5ei).

282   With treatments at FEF, the hardness was always much higher than the control (Figure 5dii).

283   Hardness initially increased at the REP snow compaction study site following low and high use

284   compaction treatments that began on 30 cm of snow (Figure 5di), but these were about the same

285   as the control by 17 Apr, when melt had started. Significant increases in hardness were observed

286   between treatments that began on 30 cm of snow and the control (Table 1c). There was also a

287   significant difference in hardness for deep and shallow initiation depths (Table 1c). In contrast,

288   mean snowpack hardness was not significantly impacted by snow compaction treatments that

289   began on 120 cm of snow (Table 1c). Mean snowpack hardness increased following the initial

290   snow compaction treatments for low starting on 30 cm and high use for both starting on 30 and

291   120 cm (Figure 5di). Subsequent compaction treatments did not appear to have a large effect

292   (Figure 5dii). There were minimal differences by the last sampling date (Figure 5ei).

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

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

295   (Figure 5ei). For both controls and all treatments that began on 120 cm of snow (Figure 5ei), the

296   maximum basal layer hardness was about 6 kPa. Increased hardness due to snowmobile use

297   showed similar temporal patterns to densification (Figures 5a and 5d). At REP, snowmobile use

298   compacted the second layer below the surface, and high use (50 passes) made that layer about 10

299   times harder than the low use (5 passes) snowpack (Figures 6bi and 6bii).

300   There was more spatial variability in snowpack hardness (NSCE of 0.50; results not

301   shown graphically) than differences in density (NSCE of 0.93 in Figure 4) for low and high use

302   compaction treatments versus the control on the first two sampling dates at REP and for the

303   control snowpits at FEF on the pre-treatment date. These larger differences are attributed both to

304   spatial variability, but most to the low range of non-treatment hardness values from 0.4 to 5.8

305   kPa compared to the range of treatment hardness values from 30 to 1157 kPa (Figure 5d and 5e).

306

307   *4.2.4   Ram resistance*

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

309   ram resistance, but the difference was not significant for treatments that began on deep snow

310   (120 cm; Table 1d). After the initial snow compaction treatments mean snowpack ram resistance

311   for low and high use was greater than the control for the entire study period, but by the end of the

312   study period minimal differences were observed between treatments. Basal layer ram resistance

313   increased as a result of low and high use compaction treatments that began on both 30 cm and

314   120 cm of snow. Snow compaction treatments at the FEF snow compaction study site caused a

315   significant increase in mean snowpack ram resistance (Table 1d, e.g. Figure 6ciii for the

316   February sampling dates). Basal layer ram resistance increased following the initial snow

317   compaction treatments and continued to increase throughout the duration of the winter season.

318

319   *4.2.5   Grain Size*

320   Smaller crystals in the basal layer were observed for snowmobile use starting on a

321   shallow snowpack compared to the control or starting on a deeper snowpack (Figure 5f).

322   Rounded grains were observed during the first sampling at REP shallow depth snowmobile start,

323   with faceted grains for the following three sampling dates (Figure 5fi). Rounding facets were

324   observed on the last sampling day at both sites. At FEF, there were 3 to 4 mm faceted crystals

325   prior to the treatments; fragmentation was noted in the faceted crystals found in the basal layer of

326   the treated plots, which began rounding by the last sampling date (Figure 5fii). The shallower

327   snow at FEF enabled large faceted crystals to grow in the basal layer, up to 9 mm in size (Figure

328   5fii).

329

4.3   *Operational Sites*

331   As illustrated by SWE (Figure 7d) and snow depth (Figure 7e), the amount of snow was

332   comparable for the snowpits dug at the three operational sites, even though they were located up

333   to 6 km apart (Figure 1). Also since these were operational sites, the amount of treatment was not

334   controlled and was based solely on permitted snowmobile use. Generally, patterns of increased

335   density (Figure 7a), hardness (Figure 7b) and ram resistance (Figure 7c) seen at the REP

336   operational sites were similar to the overall patterns seen in the previously presented experiments

337   from REP and FEF (Figures 5, and 6) with the non-snowmobile impacted snowpits being less

338   dense (Figure 7a) and having layers that were less hard (Figure 7b). From visual inspection of

339   the sites and the measurement results, Muddy Creek had the most snowmobile use and thus

340   exhibited the highest density throughout the winter, and the hardest snowpack for mid-winter

341   (Figure 7b), but at times the results for Dumont Lakes were similar.

342

4.4   *Bulk Snowpack Density Change Model*

344   A non-linear bulk snowpack density change model was created using data from the

345   experiments prior to onset of melt conditions (Fassnacht et al., 2010); before the last sampling

346   date (Figure 3) and prior to when the difference in density between the control and treatments

347   was small (Figure 5a). Additionally, treatments starting on a deep snowpack at REP were not

348   significantly different than the control (Figure 5a, Table 1) and were not used in fitting the

349   model. The variables of number of passes per treatment, depth, and bulk density were tested for

350   correlation that might result in model over-fitting. Cross-correlation results were small

351   (R^2<0.04), so these variables were used to create the model. Difference in bulk density compared

352   to the control due to snowmobile use is a function of the number of passes per treatment and bulk

353   density, but it is inversely related to snow depth (Figure 8a). The optimal model had a NSCE of

354   0.81 (Figure 8a), which is considered very good (Moriasi et al., 2007). The model was calibrated

355   on the experimental data (Figure 8a) and applied to the operational sites (Figure 8b), with no

356   passes occurring equivalent to a density change of 0 kg/m^3. The evaluation results were less

357   optimal, with a NSCE of -0.79 for the four dates tested in December through March (Figure 8b).

358   The poorer performance of the model at the operational sites is due to an unknown number of

359   snowmobile passes at each site and from limited snowmobile use early in the season

360   (December), resulting in minimal differences between compaction levels at that time (Figures 7

361   and 8b). Removal of the December data points and using only the January through March dates

362   improved the model fit to a NSCE of 0.34 (Figure 8b).

363

364   **5.   Discussion**

365   *5.1   Observed Changes to Snowpack Properties*

366   Snowpack changes were observed for varying snowmobile use beginning with two

367   different snow depths (REP only in Figure 5 or 6i and 6ii) and for two different snow-covered

368   environments (Figures 5 and 6). A total of 101 snowpits (50 at REP, 15 at the operational sites,

369   and 36 at FEF) were dug and sampled for this work. The increase in density and hardness from

370   snowmobile use is greatest compared to an untreated snowpack in early to mid-season (January)

371   for a deeper snowpack at REP, with density increases of 7-33% and hardness 4 to 13 times

372   greater than the control (Figures 5ia and 5id). For a shallower snowpack at FEF, density

373 increased by 64-76% and hardness was 500-2000 times greater than the control (Figures 5iia and

374 5iid).

375   Similar differences were found from ski run grooming in an Australia snowpack with a

376 400% increase in hardness early in the snow season but only about a 40% increase later in the

377 winter (Fahey et al., 1999). Snow grooming increased the average density by up to 36%

378 compared to non-groomed ski slopes (Fahey et al., 1999, Rixen et al., 2001).

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

380 snowpack. This assumes a track length from 0.9 to 1.4 m, width of 0.50 m, a snowmobile weight

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

382 is an increase of less than an order of magnitude due to snowmobile movement. Thumlert et al.

383 (2013), measured stresses of about 10 to 20 kPa at a depth of 30 cm below the surface of a deep

384 snowpack. At 20 cm below the snow surface, the induced stress from a snowmobile is already

385 much less than 10 cm below the surface (Thumlert et al., 2013). Grooming vehicles add a force

386 similar to snowmobiles (Pytka, 2010) based on mass and track size. The snowpack property

387 changes we observed could therefore also be representative of impacts from both types of

388 vehicles. Snowpack loading by wheeled vehicles on a shallow snowpack was much greater than

389 that of a snowmobile, peaking at about 350 kPa (Pytka, 2010). In comparison, fresh snow with a

390 density of 100 kg/m^3 exerts a pressure of 0.003 kPa on the underlying snowpack (Moynier,

391 2006).

392   Compaction due to snowmobile use increased density of the snowpack which influences

393 snow hardness (Figure 5d and 5e) and ram resistance (Figure 6c). Compaction altered snow

394 characteristics (Figures 5, 6, and 7), fragmented faceted grains (Figure 5fii), and reduced the

395 growth of faceted grains (Figure 5f). Density measurements for fresh snow (Fassnacht and

396   Soulis, 2002) and/or uncompacted snow (López-Moreno et al., 2013) vary spatially and

397   temporally (Figure 4) , these values can double with just one pass of a snowmobile on a very

398   shallow snowpack (Keddy et al., 1979). The snowpack properties of a shallow snow environment

399   can be more greatly affected by compaction from snowmobile use than those for an area that

400   receives more snow (e.g., Figure 3b versus Figure 3a). With more snow accumulation, density

401   also increases, but high levels of snowmobile use will tend to increase the density above what is

402   observed with non-snowmobile impacted snow (Figures 5, 6, and 7).

403

404   *5.2   Limitations of the Measurements*
405

406   Although snowpack variability over space was limited (Figure 4), the properties of the

407   snowpack change from site to site and through time. For example, the mean snowpack density

408   was less in February (Figure 6) than January at FEF (Figure 5ii). From the operational sites,

409   specific hard layers and high values of ram resistance were measured that did not persist until the

410   next monthly sampling (observed in the experimental treatments- not shown graphically). These

411   variations were possibly a combination of naturally occurring spatio-temporal snowpack

412   variability and sampling errors; it can be difficult to obtain reliable hardness measurements in

413   snow disturbed by snowmobiles. Future investigations could focus on specific aspects of this

414   study, such as using a finer temporal resolution, but with fewer treatments.

415   Another source of variability or bias is the type of equipment used for sampling. Density

416   and temperature were measured at 10-cm intervals using the Snowmetrics wedge cutter and dial

417   gauge thermometers. A different sampler could be used to measure the density over each layer

418   and other types of thermometers could be used. Snow-hardness gauges and circular metal plates

419   of known area were used for hardness testing (McClung and Schaerer, 2006), rather than the

420   more simplistic in situ hand hardness test (American Avalanche Association, 2016). However,

421   the hardness of thin layers could not be measured as the circular metal plate used for

422   measurements had a diameter of 5 cm, omitting the possible measurement of these thin layers.

423   Thus, bulk hardness was possibly under-estimated. Also, due to compaction of the snow grains

424   by the high use 30-cm start treatment at REP the hardness could not be measured (Figure 5ii).

425   Different equipment may resolve this issue.

426

427   *5.3   Significance of the Changes to Snowpack Properties from Snowmobile Use*

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

429   below the snow (Keddy et al., 1979), and by extension from snowmaking as well (Rixen et al.,

430   2003). Ski grooming has been shown to delay the blooming of alpine plants (Rixen et al., 2001)

431   due to later snowmelt and significantly cooler soil temperatures (Fassnacht and Soulis, 2002).

432   Deeper snowpacks were found to not have cooler soil temperatures under the snowpack (Keller

433   et al., 2004), but melted out four weeks later than thinner snowpacks (Keller et al., 2004). Since

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

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

436   further investigated.

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

438   and harder snowpack with a decrease in grain size throughout the season, and rounded crystals or

439   facets observed with the last measurements (Figure 5f). If compaction penetrates deep enough

440   into the snowpack, it could affect weak layers that cause avalanches (Saly et al., 2016), which are

441   typically composed of soft layers consisting of large facetted grains (e.g. Schweizer and

442   Jamieson, 2003; van Herwijnen and Jamieson, 2007). While this may be useful in very limited

443   and small areas, such as that performed in boot packing programs (e.g. Sahn, 2010) to strengthen

444 snowpacks likely to fail on basal facets, it is very difficult to properly align and reproduce the

445 intensity of repetitive tracks, as done experimentally here (Figure 2). The effects of snowmobile

446 use for avalanche hazard reduction through changing snow stability properties requires more

447 investigation.

448   Other factors acting in concert with snowmobile traffic to affect snowpack properties

449 include wind, snowmaking/grooming, and a changing climate. Without the effects of wind, snow

450 depth will generally be lower for areas with snowmobile traffic (Figures 2d, 2e, and 7; Rixen et

451 al., 2001; Spandre et al., 2016a). However, wind is often present in open areas where

452 snowmobiling occurs. Local terrain features and position and extent of canopy cover influence

453 how the wind interacts with the snowpack (Pomeroy and Brun, 2001). In an Australian case

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

455 recreational use areas, SWE also increased through time (Figure 7d) likely due to snow blowing

456 into the depressions created by snowmobile tracks (Figure 2d). The increased load could further

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

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

459 Spandre et al., 2016a) compacts the snowpack below it, and alters the underlying snowpack

460 properties (Howard and Stull, 2014; Spandre et al., 2016a; Spandre et al., 2016b). Also, a

461 changing climate will likely reduce the extent of snow-covered terrain and decrease the length of

462 the winter recreation season (Lazar and Williams, 2008; Steiger, 2010; Dawson and Scott, 2013;

463 Marke et al., 2015; Schmucki et al., 2015; Tercek and Rodman, 2016; Marty et al., 2017). In

464 addition to possible effects from a changing climate, inter-annual variability of snowpack

465 patterns can be large in Colorado (Fassnacht and Hultstrand, 2015; Fassnacht and Records, 2015;

466   Fassnacht et al., 2017). The effects of this variability should be included in long term motorized

467   use land management considerations.

468   The significant change to snowpack properties by snowmobiles, except when treatments/use

469   were initiated on a deep snowpack (Table 1), could impact land management decisions for multi-

470   use public lands. The measured depth of influence for a snowmobile is about 90 cm according to

471   work done by Thumlert et al. (2013), but additional work could test starting depths such as 30,

472   60 and 90 cm in differing snow conditions to identify the depth when snowmobile use has no

473   significant impact. Most ski resorts in the French Alps required a minimum snow depth of 40 cm

474   to offer skiing, with a range from 60 cm in February to 40 cm in April (Spandre et al., 2016b).

475   The US Forest Service (2013b) recommends a minimum of 30 cm before the use of

476   snowmobiles. Increasing the minimum snow depth before allowing snowmobile traffic will

477   reduce changes to the snowpack due to snowmobile traffic (Table 1). Additionally, the non-

478   linear bulk density change model developed here and applied to operational sites could be used

479   predictively for management needs. This model may be useful in terms of estimating when to

480   limit snowmobile use given changes in specific snow depth and density conditions.

481   Where the experiments for this study were undertaken, on public lands in Colorado, there

482   are 1.1 to 1.6 million annual snowmobile visits, with an increase from 580 thousand to 690

483   thousand between 2010 to 2013 in northern Colorado (Routt NF and Arapaho-Roosevelt NF) and

484   southern Wyoming (Medicine Bow NF) (US Forest Service, 2010 and 2013a) alone. The annual

485   economic impact of snowmobile use is more than $125 million to each state (Nagler et al., 2012;

486   Colorado Off-Highway Vehicle Coalition, 2016). Snowmobile use is likely to continue to

487   increase, and economic gains need to be balanced with potential impacts to the landscape,

488   particularly in those times and places where snowpacks are shallow.

489

6. Conclusion

491   Snowmobiling is a multimillion dollar industry that impacts local and regional economies

492   and public recreation lands. There have been limited studies regarding the influence of

493   snowmobile use on snowpack properties. We examined the effect of snowmobile use on the

494   physical and material properties of the snowpack at sites with varying snowmobile use and

495   seasonal snow conditions. Low, medium, and high snowmobile use was simulated on

496   experimental transects and snowpack sampling results from the treated sites were compared to

497   the snowpack properties observed at undisturbed control sites, and at operational sites with

498   varying levels of use. A non-linear bulk snowpack density change model was developed relating

499   changes in bulk density to snowmobile use as a function of the number of passes, snow depth

500   (inverse relation) and bulk density. The largest differences in snowpack properties occur with

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

502   snowpack density, hardness, and ram resistance. These increases are directly related to

503   increasing snowmobile use (from low to medium to high). Conversely, snowmobile use that

504   begins on a deep snowpack (120 cm) has a limited effect on the snowpack properties of density,

505   temperature, hardness, and ram resistance as compared to an undisturbed snowpack. These

506   results suggest that from a management standpoint, it may be desirable to limit snowmobile use

507   in shallower snow conditions to avoid increases in density, hardness, and ram resistance that

508   could possibly impact land resources below the snowpack.

509

510   **Author contribution**

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

512   Heath performed the experiments with assistance from K.J. Elder at the Fraser site. The initial

513   manuscript was written by J.T. Heath, S.R. Fassnacht, and K.J. Elder. The final version of the

514   manuscript was written by S.R. Fassnacht and N.B.H Venable. S.R. Fassnacht generated the

515   figures and created the density model.

516

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530

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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*	

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List of Figures

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

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

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

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4. Spatial variability of mean (yellow) and basal (blue) snowpack density. At the Rabbit Ears Pass (REP shown with circles) the deep snow (120 cm) compaction treatments (low and high use) are compared to the control on the first two sampling dates (pre-treatment, Figure 3a). At the Fraser Experiment Forest (FEF shown with triangles) the two sets of control snowpits were compared, and all plots were sampled prior to the initial treatment and are compared (see Figures 5i and 5ii, parts a) and b), respectively).

5. Time series for i. Rabbit Ear Pass (REP) and ii. Fraser Experimental Forest (FEF) at the different sampling dates of a) mean snowpack density, b) basal snowpack density, c) snowpack temperature gradient, d) mean snowpack hardness, e) basal layer hardness, and f) mean basal crystal size and shape. The crystal shape is included as per Fierz et al. (2009), with the exception of faceted crystals that were fragmented. Note that the snowpack at the low and high use start at 30 cm could not be adequately tested for hardness on the first sampling date at the REP treatment plots.

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

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

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8. Bulk snowpack density change model for different amounts of use compared to the control of no use a) calibrated for the two experiment sites (Rabbit Ears Pass, REP and Fraser Experimental Forest, FEF), and b) applied to the operational sites (Dumont Lakes and Muddy Creek), compared to the no use Walton Creek site. The calibrated model is presented in a) with the Nash Sutcliffe Coefficient of Efficiency (NSCE). The NSCE is presented in b) for two different time periods: the four pre-melt dates (December through March- 4 dates) and the later three pre-melt dates (January through March- JFM).

Figure 1. The snow compaction study plots are located in north-central Colorado. The Rabbit Ears Pass (REP) site is within the Routt National Forest near the town of Steamboat Springs, as are the three operational (non-experimentally manipulated) sites (Walton Creek with no use, Dumont Lakes with low to medium use, and Muddy Pass with high use based on field observations). The Columbine snow telemetry (SNOTEL) station was used to identify the amount of annual snowfall in 2009-2010 compared to the long-term average. The Fraser Experimental Forest (FEF) site is within the Arapaho-Roosevelt National Forest near the town of Fraser. The Middle Fork Camp SNOTEL site was used to represent the year's snowfall.

Figure 2. The sampling design for the snow compaction plots at a) Rabbit Ears Pass, b) Fraser Experimental Forest, and photographs of the study plots c) pre-treatment, d) during treatment, and e) after treatment. The colors used for the control and treatment plots are used in Figures 5 through 8.
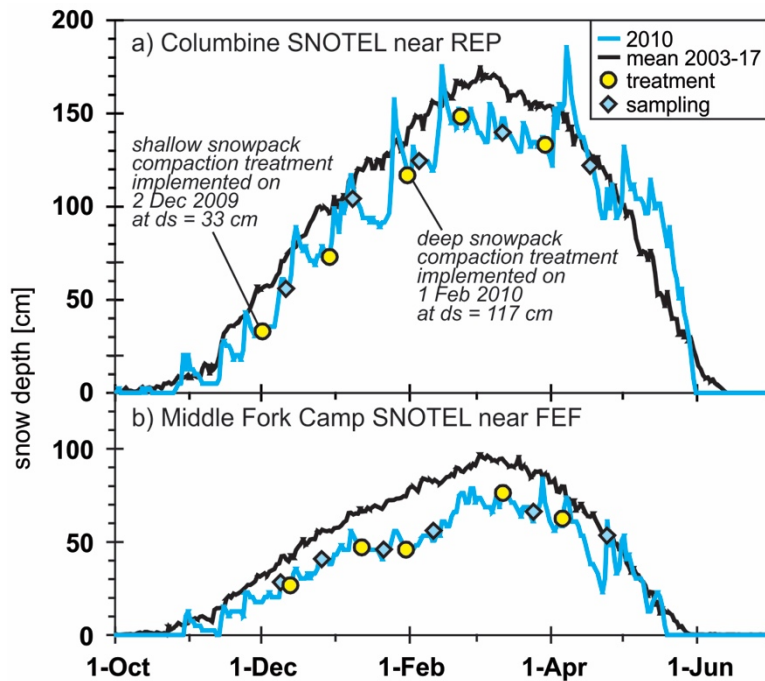
Figure 3. Mean snow depth from 2003-2017, and for the 2010 water year (WY2010) measured at a) the Columbine SNOTEL site near Rabbit Ears Pass (REP), Colorado and b) the Middle Fork Camp SNOTEL near Fraser Experimental Forest (FEF), Colorado, illustrating the dates of treatment and dates of sampling. Data were obtained online from the Natural Resource Conservation Service (NRCS) National Water and Climate Center (http://www.wcc.nrcs.usda.gov/).
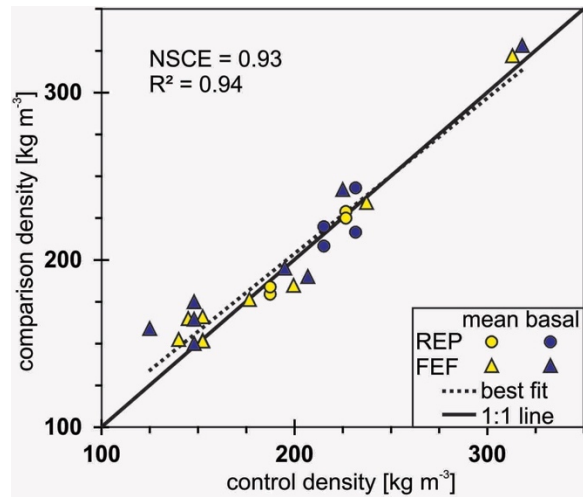
Figure 4. Spatial variability of mean (yellow) and basal (blue) snowpack density. At the Rabbit Ears Pass (REP shown with circles) the deep snow (120 cm) compaction treatments (low and high use) are compared to the control on the first two sampling dates (pre-treatment, Figure 3a). At the Fraser Experiment Forest (FEF shown with triangles) the two sets of control snowpits were compared, and all plots were sampled prior to the initial treatment and are compared (see Figures 5i and 5ii, parts a) and b), respectively).
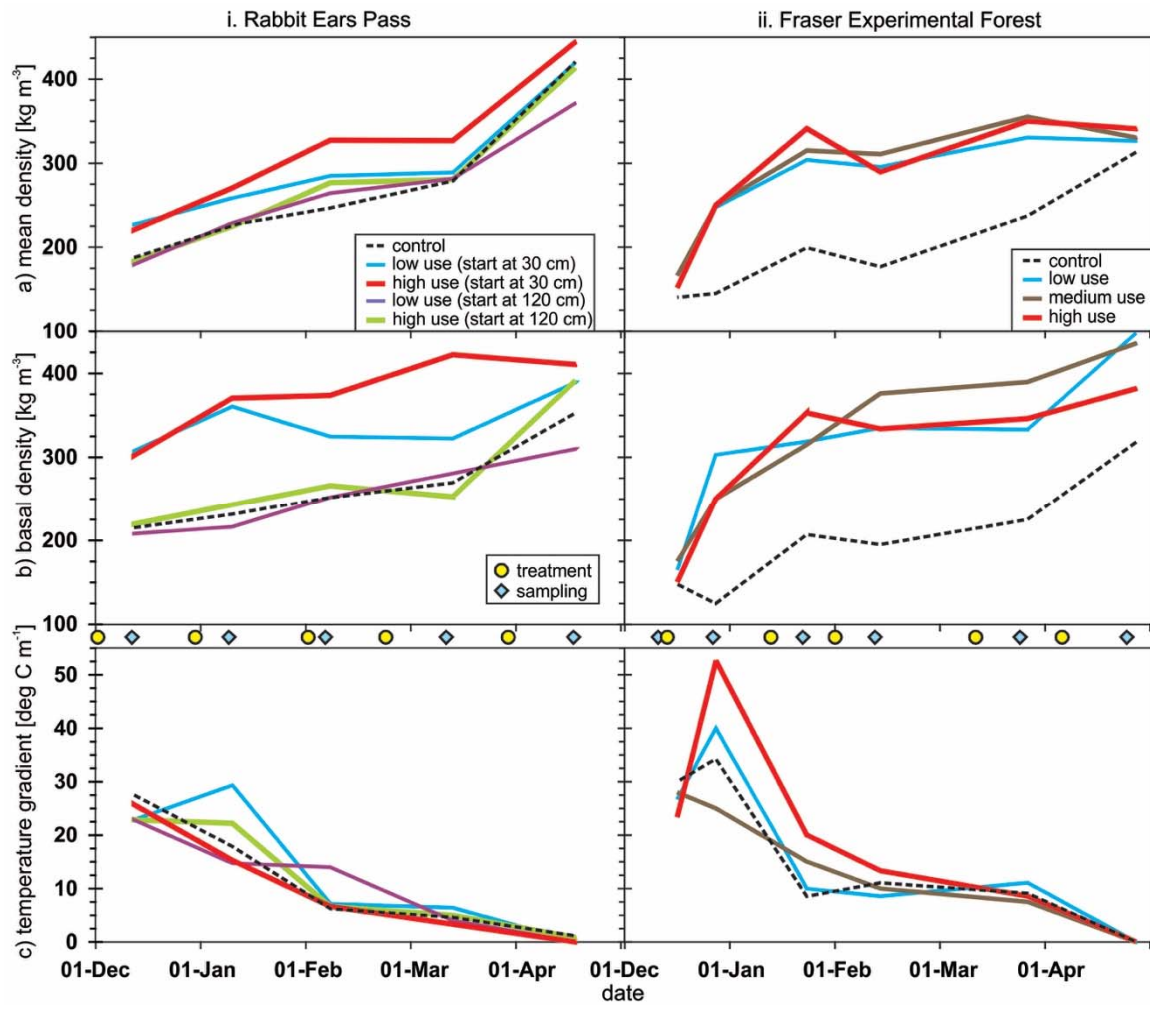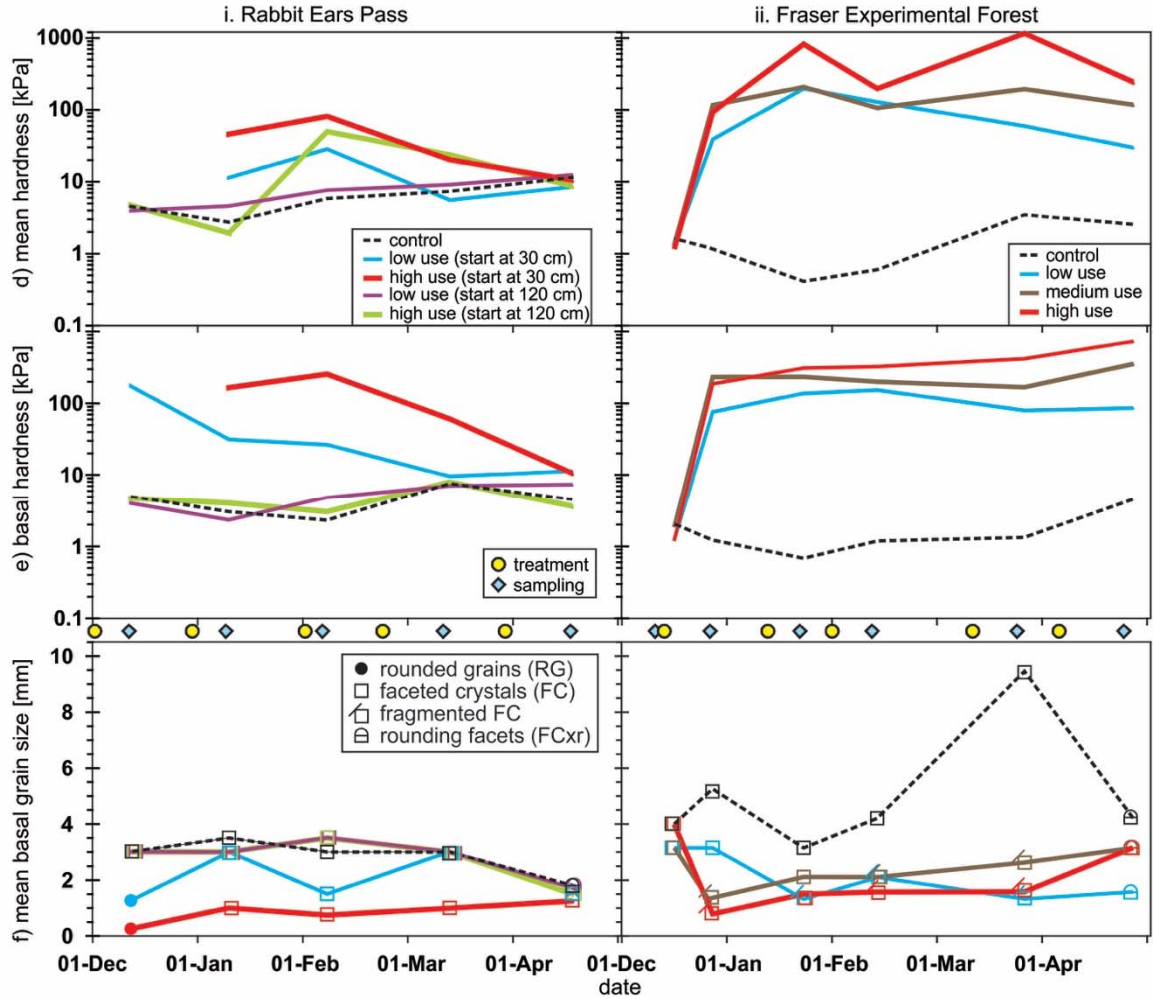
Figure 5. Time series for i. Rabbit Ear Pass (REP) and ii. Fraser Experimental Forest (FEF) at the different sampling dates of a) mean snowpack density, b) basal snowpack density, c) snowpack temperature gradient, d) mean snowpack hardness, e) basal layer hardness, and f) mean basal crystal size and shape. The crystal shape is included as per Fierz et al. (2009), with the exception of faceted crystals that were fragmented. Note that the snowpack at the low and high use start at 30 cm could not be adequately tested for hardness on the first sampling date at the REP treatment plots.
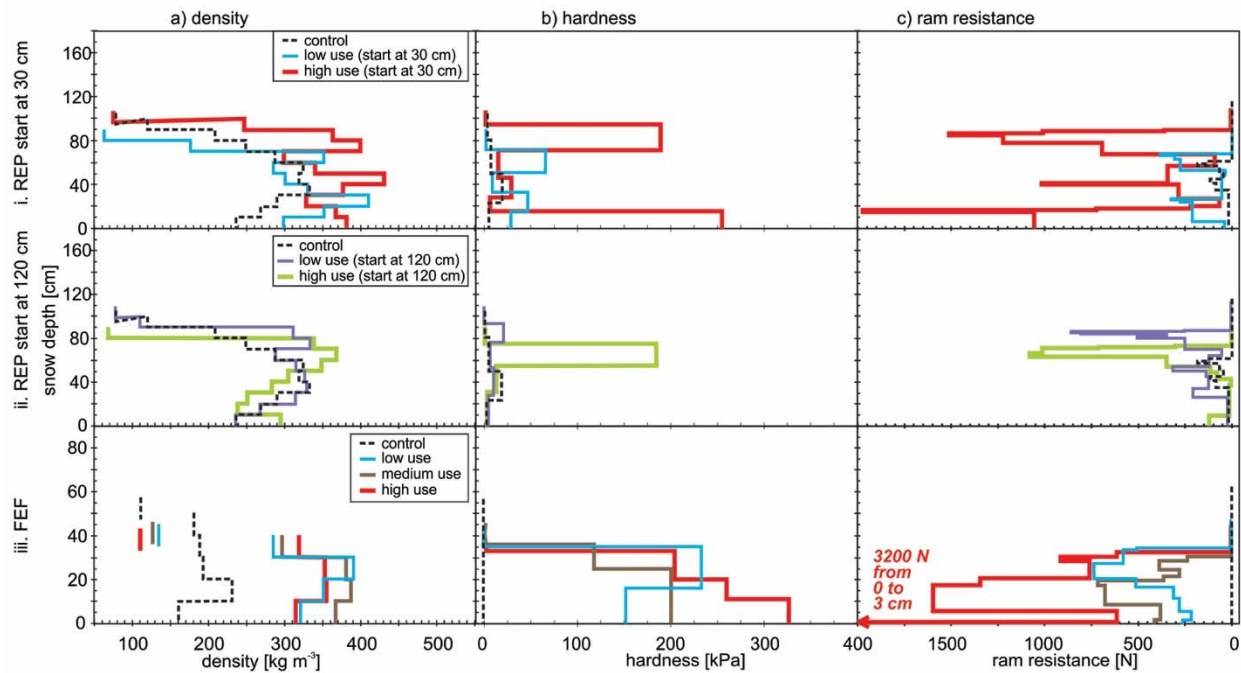
Figure 6. a) Density, b) hardness, and c) ram resistance profiles for the February sampling dates (06 Feb at REP and 12 Feb at FEF) measured at the REP snow compaction study plot for no (control), low, and high use treatments beginning on i) 30 cm and ii) 120 cm of snow, and iii) the FEF snow compaction study plot for no (control), low, medium, and high use treatments beginning on 30 cm of snow. Note that free floating measurements represent overlapping density measurements. The ground is at zero snow depth.
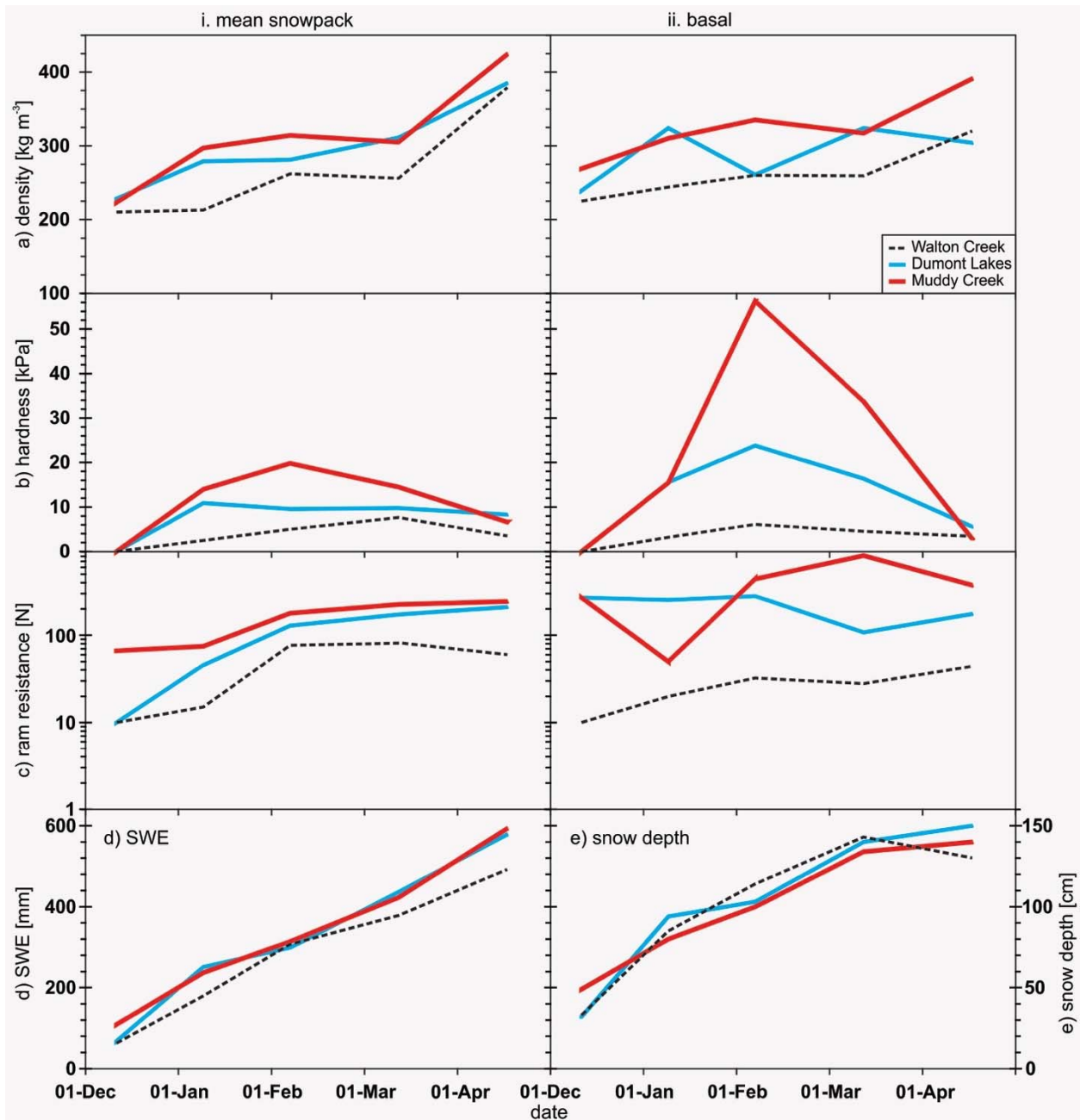
Figure 7. Snowpit data for Walton Creek (no snowmobile use), Dumont Lakes (moderate snowmobile use) and Muddy Creek (high snowmobile use) in the Rabbit Ears Pass recreational use areas illustrating a) density, b) hardness, c) ram resistance, d) SWE, and e) snow depth. For a through c, the left panel (i) is the mean snowpack value and the right panel (ii) is the basal layer value.
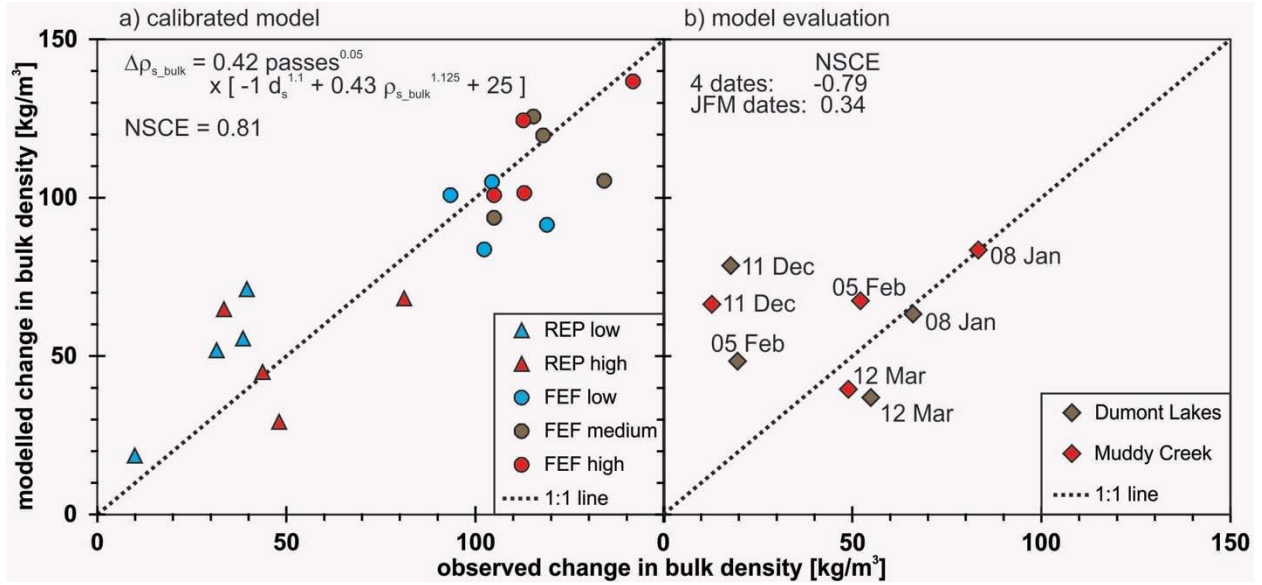
Figure 8. Bulk snowpack density change model for different amounts of use compared to the control of no use a) calibrated for the two experiment sites (Rabbit Ears Pass, REP and Fraser Experimental Forest, FEF), and b) applied to the operational sites (Dumont Lakes and Muddy Creek), compared to the no use Walton Creek site. The calibrated model is presented in a) with the Nash Sutcliffe Coefficient of Efficiency (NSCE). The NSCE is presented in b) for two different time periods: the four pre-melt dates (December through March- 4 dates) and the later three pre-melt dates (January through March- JFM).