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How mounds are made matters: Seismic line restoration techniques affect peat physical and chemical properties throughout the peat profile

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1 **How mounds are made matters: Seismic line restoration techniques affect peat**

2 **physical and chemical properties throughout the peat profile**

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Abstract

18   Seismic lines are prominent linear disturbances across boreal Canada with large-scale

19   consequences to wildlife and ecosystem function. Although seismic line restoration has been observed

20   to improve tree growth and survival, application in peatlands has been shown to alter ecosystem

21   functions such as hydrology and carbon storage. The most common active restoration method is called

22   mechanical mounding where the classic technique inverts the peat profile. New mounding methods that

23   maintain the peat profile may provide benefits by preserving existing vegetation and reducing

24   disturbance. To determine the effects of different mounding methods on soil quality, peat cores were

25   collected and analyzed from two different sites for various soil properties (C/N ratios, $\delta^{13}C$, $\delta^{15}N$, Fourier

26   transform infrared (FTIR) spectroscopy humification indices). Vegetation surveys were also conducted.

27   The two sites are both a collection of seismic lines crossing poor fens in Alberta. One site was treated

28   with the classic method while the other was treated with two new mounding methods. Classic

29   mechanical mounding significantly increased the degree of decomposition, indicative of lower substrate

30   quality. Mechanical mounding also greatly reduced moss cover and introduced large amounts of bare

31   ground cover. The two newer mounding methods did not result in these changes and were largely

32   comparable to natural peat properties and vegetation communities. Preserving the peat profile in new

33   mounding methods may support faster return of ecosystem function.

34   **Keywords:** organic soil, bulk density, mechanical mounding, C/N ratio, stable isotopes

35

36 **Introduction**

37   An estimated 345,000 km of seismic lines covering 1910 km^2 have been created in all types of

38 peatlands in the province of Alberta, Canada for oil and gas exploration (Strack et al., 2019). Seismic line

39 disturbance has many negative impacts in peatlands such as causing a shift from a C sink to a C source

40 and increasing line of sight and mobility of wolves resulting in declining caribou populations (Dabros et

41 al., 2018). These long, linear disturbances have not returned to tree cover as initially expected and are

42 now being restored through a site preparation method called mechanical mounding (Lee & Boutin,

43 2006) followed by tree planting. Mounding in peatlands is the process of digging, inverting, and placing

44 mounds of peat on the lines to recreate microtopography (Filicetti et al., 2019). Mounding treatments

45 are widely used to promote tree growth (Sutton 1993; Smolander & Heiskanen, 2007; Bilodeau-

46 Gauthier et al., 2011; Lafleur et al., 2011; Bilodeau-Gauthier et al., 2013; Lieffers, Caners, & Ge, 2017;

47 Filicetti et al., 2019) and this technique has been observed to increase tree growth and survival by

48 providing drier microsites (Filicetti et al., 2019). Yet, little is known about how mounding alters the

49 properties of the soil profile, particularly in peatlands where shifts in physical properties following

50 disturbance and restoration have been shown to alter ecohydrological function (McCarter and Price,

51 2015). Important soil properties that indicate decomposition and substrate quality include the ratio of

52 carbon and nitrogen (C/N), stable isotopic composition (δ^{13}C, δ^{15}N), humification indices (HI), bulk

53 density, and organic matter content (OM) (Broder et al., 2012; Biester et al., 2014; Krüger et al., 2015;

54 Drollinger et al., 2020). These decomposition indicators have known responses to aerobic and anaerobic

55 decomposition throughout the peat profile due to preferential loss of certain compounds. This study

56 aims to investigate how various mounding techniques alter the physical and chemical properties of the

57 soil profile in peatlands.

58   While often successful for promoting tree growth, mechanical mounding (hereafter referred to

59 as inverted mounding) methods have drawbacks, especially in peatlands. Mounding has been observed

3

60 to shift vegetation succession trajectories away from the surrounding natural areas (Echiverri,

61 Macdonald, & Nielsen, 2020). Unlike mounded lines, untreated seismic lines often have recovering

62 vegetation on the trajectory of restoring natural peatland plant communities (Echiverri, Macdonald, &

63 Nielsen, 2020). Keeping the peat profile intact during mounding instead of inverting the soil and burying

64 recovering vegetation could provide benefits to both understory vegetation and tree recovery.

65 Removing vegetation decreases evapotranspiration, increases soil moisture and soil bulk density, and

66 changes water storage and flow (Dabros et al., 2018). By exposing bare peat and burying vegetation,

67 inverted mounding may slow and alter vegetation recovery by resetting succession.

68   New mounding treatments have been developed to improve upon the classic inverted

69 mounding (Xu, 2019). The main difference between the new and classic treatments is that the new

70 treatments do not invert the peat profile. The first new method, upright mounding, follows the same

71 procedure of digging and placing the mound on the line but without inversion. The second method,

72 hummock transfer, moves a natural hummock from the adjacent peatland onto the seismic line (Xu,

73 2019). Hummock transfer does not involve digging or inverting the peat but often leaves a small

74 depression where the hummock was removed. The level of disturbance in the adjacent natural area

75 from hummock transfer has not been evaluated but is predicted to be small. Preserving the peat profile

76 may prevent or reduce changes in soil properties and allow for recovering vegetation to survive the

77 mounding treatment, while hummock transfer moves woody vegetation onto the line. New mounding

78 treatments dig to 50 cm depths while classic mounding may dig to 50-100 cm depths.

79   Inverted mounding greatly alters surface peat properties with unknown implications for

80 vegetation recovery (Davidson et al., 2020). The driving factors of changes in soil properties from

81 mounding are not well understood. Inverted mounding exposes deeper peat that has different

82 properties from surface peat but the creation of mounds, inverted or intact, could also alter soil

83 processes. Small degrees of disturbance have been found to increase decomposition rates in peatlands

4

84   (Krüger et al., 2015). Inverted mounds are made of more decomposed peat, but it is not well

85   understood if decomposition is increased on mounds or if changes in properties simply arise from the

86   exposure of deeper peat that was already more highly decomposed (Davidson et al., 2020).

87   Additionally, while tree recovery may benefit from inverted mounding, general vegetation

88   communities are shifted from surrounding natural conditions (Echiverri et al., 2020). Changing inverted

89   mounding methods to keep the peat profile intact and preserve recovering vegetation may maintain

90   peat properties more similar to undisturbed conditions and improve restoration success, but this has

91   not yet been quantified. Therefore, the specific objectives of this study were to:

92   1.   Compare how two different mounding techniques applied to seismic lines in fen peatlands alter

93   physical and chemical soil properties and plant communities

94   2.   Determine if changes in soil properties are driven by changes in soil processes (e.g., enhanced

95   decomposition, compaction) or from the exposure of deep peat during the mounding process

96   **Materials and methods**

97   *Study sites*

98   Two study sites, both wooded poor fens, were selected to compare the different mounding

99   techniques. At both sites, peat depth was at least 100 cm. Sampled seismic lines were explorative only

100   and did not contain pipelines. The first site, South Clyde 3rd year post mounding (SC3), is an east-west

101   seismic line running through a collection of poor fens located north of Cold Lake, Alberta (55° 04'49" N,

102   111° 11'39" W) (Figure 1). SC3 is not accessible to the public and is expected to not be impacted by

103   human use. The line was treated in 2017 by Cenovus Energy using inverted mounding techniques.

104   Samples were collected in two sections on the lines, approximately 200 m long each, during September

105   2020. Dominant vegetation at SC3 includes *Betula pumila* L., *Carex* spp*., Equisetum* sp*., Larix laricina* (Du

106   Roi) K. Koch, *Oxycoccus microcarpus* Turcz. ex Rupr., *Picea mariana* (Mill.) Britton, Sterns & Poggenb.,

107   *Polytrichum strictum* Menzies ex Brid., *Rhododendron groenlandicum* (Oeder) Kron & Judd, and

108   *Sphagnum* spp.

109   The second site, Brazeau, was restored using two new methods of mounding, upright mounding

110   and hummock transfer as described below. Brazeau 1st year post mounding (BR1) is an east-west

111   seismic line crossing a poor fen near Brazeau Reservoir, Alberta (52° 53' 21" N, 115° 32' 57" W) (Figure

112   1). BR1 is easily accessible by road and is situated on crown land. However, no evidence of recreational

113   activity was observed on-site during year-round monitoring. Samples were collected over a 600 m long

114   section of the line. The line was restored in March 2019 and sampled during August 2020. The dominant

115   vegetation at BR1 consists of *P. mariana*, *L. laricina*, *R. groenlandicum*, *Salix* spp*.*, *Menyanthes trifoliata*,

116   *Vaccinium oxycoccos*, *Sphagnum fuscum*, and *Sphagnum magellanicum*.

117   As described in Filicetti et al. (2019), an excavator with a 1 m^3 bucket was used to create

118   mounds at SC3 by digging to a depth of 50–100 cm and inverting the peat onto the line. The resulting

119   mound buried established vegetation and exposed deeper, more decomposed peat or mineral soils

120   (Figure 2a). New mounding methods were used at BR1. The first, upright mounding, is similar to inverted

121   mounding but preserves the soil profile by not inverting the peat. This method does not expose

122   deeper peat and keeps established vegetation intact (Figure 2b). The second method, hummock

123   transfer, does not involve further disturbance on the line. Hummock transfer refers to the transfer of

124   natural hummocks, located off the line in the adjacent peatland, onto the line (Figure 2c). This aims

125   to introduce desired vegetation to the line and does not result in created hollows on the lines (Xu,

126   2019). Both methods of mounding were done while the ground was frozen, and operators did not dig

127   below the rooting depth of around 50 cm to allow regrowth in created hollows.

128   Since the new mounding techniques tested here have not been applied widely, we were limited

129   in study site selection and had to compare to inverted hummocks at another study site. The comparison

130   of the two study sites may be influenced by time since mounding as BR1 was sampled 1 year after

131   restoration while SC3 was sampled 3 years after restoration. In the comparison, BR1 may be at a

132   disadvantage as the highest degree of disturbance would be expected to occur right after mounding

133   treatments. However, a comparison of surface soil properties 2 and 3 years after mounding at SC

134   showed minimal changes in soil properties over the year (see Supplemental Material). Differences over

135   time should not be substantial enough to prevent the comparison of the two mounding techniques. To

136   limit study site impacts on interpretation, mounding techniques were primarily compared to their

137   corresponding surrounding natural conditions.

138   *Sampling Methods*

139   At SC3, six cores were collected from each of 1) inverted mounds, 2) adjacent low-lying areas on

140   the lines, and 3) hummocks in the surrounding natural areas for a total of 18 cores. At BR1, four cores

141   each were collected from 1) mounds on hummock transfer, 2) mounds on upright mounding, 3) adjacent

142   low-lying areas, and 4) hummocks in surrounding natural areas for a total of 16 cores. Peat was sampled

143   to 100 cm in depth with a Russian auger with a diameter of 8.3 cm from the natural hummocks and low-

144   lying areas at BR1. Peat was sampled up to 150 cm in depth or until reaching clay from the hummock

145   transfer and upright mounds and for all cores at SC3. All cores were cut into 10 cm intervals in the field

146   and then frozen and shipped to Waterloo, Ontario for processing. Due to the compressibility of moss,

147   the top moss layer samples (up to 30 cm in depth) were collected with a knife and metal can with a

148   known volume of 562.70 cm^3. Additionally, vegetation and ground cover surveys (i.e., percent cover) to

149   the functional group level (graminoids, forbs, mosses, shrubs, trees, bare ground, and open water) were

150   conducted in a 100 x 100 cm square where each core was sampled. Percent cover was determined

151   visually to the nearest 5% above 10% cover and to the nearest 1% below 10% cover.

152   *Sample Processing*

153   Samples were thawed, weighed, dried at 80 °C for 48 hours or until dry (based on reaching a

154   constant weight), and weighed again. Bulk density was calculated using known volumes of peat and dry

155   weights. At SC3, bulk densities were analyzed for every 10 cm depth interval collected. At BR1, peat

156   volumes were not measured, and bulk density could not be calculated from cores samples. Instead, bulk

157   density was calculated from other cores that were taken at the same time and site but only up to 50 cm

158   in depth. These 50 cm cores were only taken from upright mounds, low-lying areas, and natural

159   hummocks; no samples from hummock transfer could be used to calculate bulk densities. Subsamples of

160   2 g of dried peat for every sample were further burned in a muffle furnace at 550 °C for 4 hours and

161   then weighed the following day to calculate organic matter (OM) content.

162   We measured several peat parameters, including C/N ratios, $\delta^{13}C$, $\delta^{15}N$, and humification

163   indices, that have been previously used to investigate changes in peat quality and decomposition status

164   (Broder et al., 2012; Biester et al., 2014; Krüger et al., 2015; Drollinger et al., 2020). The rest of the dried

165   peat for depth intervals 0-40 cm, the interface of the mound and underlying line (between 50-80 cm),

166   70-80 cm, 90-100 cm, and the deepest depth interval collected up 150 cm were ground into a fine

167   powder using a ball mill. One milligram of the ground peat samples was used to determine total carbon

168   (TC), total nitrogen (TN), and $\delta^{13}C$, $\delta^{15}N$. TC, TN, $\delta^{13}C$, and $\delta^{15}N$ through combustion conversion of

169   sample material to gas through a 4010 Elemental Analyzer (EA) (Costech Instruments, Italy) coupled to a

170   Delta Plus XL (Thermo-Finnigan, Germany) continuous flow isotope ratio mass spectrometer (CFIRMS) at

171   the Environmental Isotope Lab (EIL) at University of Waterloo. Standard quality control methods were

172   applied by the Environmental Isotope Lab, resulting in errors of 0.2‰ for $\delta^{13}C$ and 0.3‰ for $\delta^{15}N$ (see

173   Supplemental material for details)

174   Lastly, further subsamples of the ground peat were used in Fourier Transform Infrared (FTIR)

175   analysis conducted in the Waterloo Advanced Technology Laboratory (WATLab). For FTIR analysis,

176   spectra were acquired in absorbance mode between 4500 and 300 cm^{-1} (wavenumber) at a resolution of

177   4 cm^{-1} and 128 scans were averaged for each spectrum. A script was used to find the exact wavenumber

178   locations of specific peaks and convert them into relative abundances

179   (https://github.com/shodgkins/FTIRbaselines). Humification indices (HI) were calculated using 1630

180   cm^{-1} bands representing aromatics or deprotonated COO$^-$ such as lignin and aliphatic or aromatic

181   carboxylates over 1090 cm^{-1} bands representing carbohydrates (Hodgkins, 2016).

182   *Statistics*

183   The statistical program R (R Core Team, 2017) was used for statistical analysis. A value of α =

184   0.05 was used to determine statistical significant for all tests. Shapiro-Wilk tests and Q-Q normality plots

185   were used to assess the normality of soil properties. Although overall samples were found to not be

186   normal, groups of samples (I.e., all inverted mound cores) were normal. With the normality of groups

187   confirmed, ANOVAs were used to test differences in peat properties between different groups

188   (treatments) at each depth as well as between depths within a core type. ANOVAs were also used to test

189   differences between the cover of vegetation functional groups between treatments. When differences

190   were significant, Tukey post hoc tests were used to determine which means differed from each other.

191   **Results**

192   *Bulk density and organic matter content*

193   Bulk densities of peat samples varied greatly between treatments and depths with a range

194   of 0.015 to 0.86 g/cm^3 across all samples (Figure 3). The most compacted samples were either at the

195   greatest depths or from the inverted mounds. At 0-10 cm and 10-20 cm depths, the inverted mounds

196   were found to be significantly more compacted than all other cores (0-10 cm: $F_{5,22}$ = 17.38, p < 0.001)

197   (10-20 cm: $F_{5,22}$ = 11.6, p < 0.001). Natural hummocks, low-lying areas, and upright mounds had similar

198   bulk densities to each other at all depths. Changes in bulk densities of inverted and upright mounds at

199   depth were not statistically significant. Low-lying areas and natural hummocks at the sites had

200   significantly higher bulk density with increasing depths (Supplemental material, Tables S1-4).

201   There was a large range of OM content across all samples from 27.1 to 98.1% (Figure 3).

202   However, the range was greatly skewed with only 13 out of 384 samples having an OM content below

203   80%. These 13 samples were all either below 100 cm deep or from the inverted mounds and had the

204   highest bulk densities. With many samples consisting of high OM, there was no significant difference

205   between the treatments. Similarly, SC3 cores had no significant trends in OM content down the peat

206   profile. The inverted mounds had lower OM content at 0–30 cm than deeper depths, but the difference

207   to other cores was not significant. At BR1 only, the natural hummocks, low-lying areas, and transferred

208   hummocks had higher OM content at shallower depths (0–30 cm) than all deeper depths (Supplemental

209   material, Tables S5–S7).

210   *Total C and N content*

211   TC content of all samples ranged from 12.17 to 54.99%. However, averages between cores were

212   similar and there was no significant difference between the treatments except for the low TC of natural

213   samples at 110–120 cm ($F_{3,4}$ = 144.7, *p* = 0.00016). Within cores, TC also was largely uniform.

214   TN was more variable between samples and depths than TC with a smaller range of 0.50 to

215   3.04%. At 0–10 cm and 10–20 cm depths, the inverted mounds were found to have higher TN than the

216   transferred hummocks, low-lying areas, and natural hummocks at both sites (0–10 cm: $F_{6,28}$ = 6.65, *p* =

217   0.00019; 10–20 cm: $F_{6,25}$ = 7.27, *p* = 0.00014). Additionally, at the 10–20 cm depth, SC3 low-lying areas

218   also had greater TN than the natural hummocks and BR1 low-lying areas. Transferred hummocks had

219   more TN than the upright mounding at the 50–60 cm depth interval ($F_{2,2}$ = 29.13, *p* = 0.033). The

220   decrease in TN at 110–120 cm depth for the SC3 natural samples was only significantly lower than the

221   inverted mounds ($F_{3,4}$ = 8.02, *p* = 0.036). For all cores except inverted mounds, TN increased with depth

222   until 30–40 cm. Below 40 cm, SC3 cores had constant TN while BR1 cores decreased with

223   depth (Supplemental material, Tables S8–S13).

224   Between all samples, C/N ratios ranged from 14.4 to 119.6 (Figure 4). At 0–10 cm, SC3 low-lying

225   areas and inverted mounds had lower C/N ratios than both natural hummocks, BR1 low-lying areas,

226   and transferred hummocks ($F_{6,28}$ = 12.29, p < 0.001). Similarly, SC3 low-lying areas and inverted mounds

227   had lower C/N ratios at 10–20 cm than SC3 natural hummocks and BR1 low-lying areas ($F_{6,25}$ = 5.18, p =

228   0.0014). Inverted mounds' C/N ratios at 10–20 cm were also lower than SC3 low-lying areas. Although

229   the upright mounding had a lower C/N than the other BR1 cores at 0–10 and 10–20 cm, this difference

230   was not significant. At 50–60 cm depth, the transferred hummocks had lower C/N ratios than upright

231   mounding and inverted mounding ($F_{9,17}$ = 12.1, p < 0.001).

232   Hummock transfer, upright mounding, low-lying areas, and natural hummocks all had

233   decreasing C/N ratios at depth while inverted mounding did not significantly change along the

234   profile (Supplemental material, Tables S14–S19). The decrease at depth was rapid until 20–30 cm

235   for BR1 and 30–40 cm for SC3. SC3 cores were then mostly uniform at greater depths while

236   the BR1 cores increased slightly although this was only significant for the upright mounds.

237   *Stable isotope signatures and humification indices*

238   Across all samples, $\delta^{15}N$ was found to range from -5.94 to 3.22‰ (Figure 5). When comparing

239   across core types, at 0–10 cm, $\delta^{15}N$ varied significantly between cores ($F_{6,28}$ = 30.62, p < 0.001). SC3

240   natural hummocks had the most negative (lightest) $\delta^{15}N$ while inverted mounds had the most

241   positive (heaviest) $\delta^{15}N$ followed by SC3 low-lying areas. Transferred hummocks, upright mounds,

242   and BR1 natural hummocks and low-lying areas were all similar. $\delta^{15}N$ of SC3 natural hummocks were

243   still the lightest at 10–20 cm but the difference was only significant compared to SC3 low-lying areas,

244   inverted mounds, and upright mounds. The inverted mounds at 10–20 cm were also still

245 the heaviest but the difference was only significant when compared to the natural hummocks and BR1

246 low-lying areas and transferred hummocks ($F_{6,25}$ = 10.05, p < 0.001). At the 30–40 cm and 140–150 cm

247 depths, the $\delta^{15}N$ of the SC3 natural hummocks was lighter than the low-lying areas at both sites ($F_{6,24}$ =

248 3.765, p = 0.0088; $F_{4,7}$ = 10.82, p = 0.0040). For all cores except for inverted mounding, $\delta^{15}N$ became

249 heavier rapidly until 20–30 cm. At SC3, $\delta^{15}N$ remained constant at lower depths while at BR1, $\delta^{15}N$

250 became lighter again. The inverted mounding cores did not vary at depth (Supplemental material,

251 Tables S20–S25).

252   There was a small range for $\delta^{13}C$ of -34.26 to -26.29‰ (Figure 5). At 0–10 cm, the $\delta^{13}C$ of

253 inverted mounds was significantly heavier than SC3 low-lying areas ($F_{6,28}$ = 3.38, p = 0.012). At 10–20

254 cm, the $\delta^{13}C$ of inverted mounds was heavier than the BR1 low-lying areas and SC3 natural hummocks.

255 The SC3 natural hummocks were also lighter than the BR1 natural hummocks and low-lying areas ($F_{6,25}$ =

256 6.21, p = 0.00043). For all cores except for inverted mounding, $\delta^{13}C$ becomes heavier rapidly until 20–30

257 cm and then remains constant (Supplemental material, Tables S26-30).

258   The HI of all samples fell within the range from 0.026 to 0.56 (Figure 6). There was a large

259 variation in HI at depth below 50 cm, so we focused comparisons here on peat shallower than this depth

260 as this is also the part of the profile most affected by mounding activities. Core profiles showed different

261 patterns across sites and treatments (Supplemental material, Tables S31-36). At SC3, low-lying areas and

262 natural hummocks increased slightly with depth until 40 cm where greater depths had variable HI. HI for

263 inverted mounds were higher than other cores and did not change throughout 0–40 cm depths. BR1

264 cores showed a sharp increase in HI from 0–10 cm to 10–20 cm depths. Natural and low-lying cores then

265 sharply decreased back to 0–10 cm values at 20–30 cm while intact mounds and transferred hummocks

266 did not change or slightly increased. At 0–10 cm, the HI of the inverted mounds was higher than

267 the transferred hummocks, and both natural hummocks and low-lying areas ($F_{6,28}$ = 4.21, p = 0.0039). At

268　10–20 cm, the upright mounds had a higher HI than the natural hummocks and low-lying areas at SC3.

269　SC3 cores had a lower HI than the natural hummocks and BR1 low-lying areas and transferred

270　hummocks ($F_{6,25}$ = 9.46, p < 0.001). At 20-30 cm, the transferred hummocks and upright mounds had a

271　higher HI than the low-lying areas and BR1 natural hummocks ($F_{6,19}$ = 4.76, p = 0.0040).

272　　　　Figure 7 shows the shape of the aromatic compounds' absorbance peak from FTIR analysis. The

273　middle large peak was used in the calculation of HI and represents the absorbance of lignin, other

274　aromatics, and deprotonated COO^- aromatic/aliphatic carboxylates. The small peak on the right of the

275　middle peak represents the organic acids (protonated COOH) such as carboxylic acids and aromatic

276　esters. As shown in the first two panel columns of Figure 7, this acid peak was reduced or not present

277　for inverted mounds and SC3 low-lying areas for depth intervals 0–10 and 10–20 cm. The acids peak

278　disappears for all depth intervals below 20 cm. The last two panel columns show that the peaks do not

279　change with depth below 20 cm.

280　*Vegetation surveys*

281　　　　Mounding generally increased the cover of bare ground with a significant increase to 48% on

282　inverted mounds (Table 1; $F_{6,65}$ = 13.66, p < 0.001). The inverted mounds also had the lowest moss

283　cover. SC3 low-lying areas had lower moss cover than natural hummocks, BR1 mounding treatments,

284　and low-lying areas ($F_{6,65}$ = 37.97, p < 0.001). Transferred hummocks and natural hummocks

285　had a significantly higher shrub cover than SC3 ($F_{6,65}$ = 5.81, p < 0.001). SC3 low-lying areas had higher

286　graminoid cover than all mounding treatments and natural hummocks at SC3 ($F_{6,65}$ = 3.84, p =

287　0.0025). For forbs, all types within a site were similar, while SC3 had lower forb cover than BR1 ($F_{6,65}$ =

288　10.09, p < 0.001). BR1 low-lying areas had higher open water cover than all other cores ($F_{6,65}$ = 5.63, p <

289　0.001).

290   **Discussion**

291   *Substrate Quality*

292   Bulk densities and OM were similar across low-lying areas and natural hummocks. This suggests

293   the soil properties on low-lying areas were able to recover from the disturbance of seismic line creation

294   and that mounding likely resulted in a very localized disturbance on the mounds. A lack of compaction

295   and no loss of OM content on seismic lines conflicts with previous research (Lee & Boutin, 2006; Dabros

296   et al., 2018; Lovitt et al., 2018; Davidson et al., 2020) but matches the previous sampling at the study

297   sites (Kleinke, 2021). Although the heavy machinery used in seismic line creation can cause compaction,

298   boreal seismic lines are constructed in the winter when the ground is frozen to facilitate equipment

299   access and reduce compaction. A common cause of seismic line disturbance after the initial creation is

300   human use for recreational activities (Dabros et al., 2018). Without further disturbance, compacted

301   peat has been shown to recover naturally within 15 years after disturbance (Lepilin et al., 2019). SC3

302   and BR1 seismic lines are all at least 34 years old at the time of sampling, allowing for many years of

303   peat volume recovery.

304   Recently made mounds would not have recovered from the disturbance caused during the

305   restoration treatment. Inverted mounding had significantly higher bulk density than all other cores at

306   the 0–10 and 10–20 depth intervals. Although bulk densities could not be calculated for the hummock

307   transfer treatment, their bulk density would be expected to be similar or slightly lower than natural

308   hummocks due to the mechanism of how the hummocks are collected and transferred. The higher bulk

309   densities of the inverted mounds would have various impacts linked to hydrology, gas exchange, soil

310   stability, and microbial communities. The major structural impact of higher bulk densities is a decrease

311   in macroporosity. Lower macroporosity results in increased water retention and unsaturated hydraulic

312   conductivity and decreased gas exchange (Frey et al., 2009; Gauthier, McCarter, & Price, 2018). A bulk

313   density of 0.2 g/cm^3 has been presented as a critical threshold for identifying degraded peat (Liu &

314   Lennartz, 2018). Additionally, starting at a 15% increase, higher bulk density has been found to

315   negatively impact soil microbes, increase water retention, and decrease gas exchange (Frey et al., 2009).

316   At SC3, inverted mounding increased bulk density by an average of 541% and 324% for 0–10 cm and 10–

317   20 cm depths, respectively. These changes may cause the peat to become waterlogged and

318   anoxic, which would inhibit the growth and survival of both microbial and vegetation communities

319   (Kozlowski, 1999; Frey et al., 2009). These structural changes are also linked to peat collapsing, which is

320   a common issue with mounding in peatlands (Kool, Buurman, & Hoekman, 2006; Lieffers, Caners, & Ge,

321   2017; Filicetti et al., 2019). While inverted mounds were heavily compacted, upright mounding bulk

322   densities were comparable to natural conditions. The unaffected bulk densities of the upright mounding

323   may provide an advantage in vegetation recovery and mound persistence over the inverted mounding.

324   The inverted mounding method also resulted in significantly lower OM content, while upright

325   mounding and hummock transfer had similar OM to natural hummocks and low-lying areas. The

326   preservation of OM and moss cover on upright mounds and transferred hummocks may also be

327   advantageous as it reflects the preservation of the moss layer and less decomposed peat. Moss cover

328   on inverted mounds was 16 ± 7% compared to 96 ± 2% on upright mounds and 92 ± 5% on transferred

329   hummocks. While the exposure of mineral soil and removal of the moss layer has been found to

330   increase seedling growth (Lafleur et al., 2011b), small disturbances of the moss layer without exposing

331   mineral soil have also been found to increase seedling growth (Lafleur et al., 2011a). Seedling growth

332   was increased after gently disturbing the moss layer as a result of increased nutrient availability and

333   reduced competitive shrub cover (Lafleur et al., 2011a). In both papers, 2-year-old black spruce

334   seedlings were used. Upright mounding may result in a similar disturbance as in Lafleur et al. (2011a) as

335   the shrub and graminoid cover decreased slightly (Table 1). Transferred hummocks did not show a

336   decrease in shrub cover but did show a reduction in the graminoid cover. Decreasing the shrub and

337   graminoid cover can promote tree survival and growth by removing competition (Nelson & Jobidon,

338   2011; Bilodeau-Gauthier et al., 2011). The disturbance of upright mounding may be sufficient in

339   promoting tree growth without large changes in substrate quality from the exposure of mineral soils

340   and deeper peat and with preservation of much of the ground layer plant community, but further

341   research on the growth of trees on the mounds is needed to evaluate this.

342   In Lafleur et al. (2011a) and Lafleur et al. (2011b), the increases in seedling growth were

343   attributed to comparably lower C/N ratios due to an increase in N, specifically NH_4^+ (Lafleur et al.,

344   2011a; Lafleur et al., 2011b). While available and foliar nutrients were not measured in this study, lower

345   C/N ratios driven by increases in TN were observed for both inverted and upright mounds at 0–20 cm

346   depth (Figure 4) with only changes at the inverted mounds being statistically significantly lower than

347   low-lying areas. Lower C/N ratios are associated with N availability and can promote tree growth, but

348   too low C/N ratios indicating C limitations negatively affect vegetation growth and survival, availability

349   of nutrients, and microbial activity (Asada, Warner, & Schiff, 2005). More in-depth research on available

350   nutrients and limitations would be required to determine how lower C/N affects vegetation recovery on

351   seismic lines.

352   Previous studies on logged peatlands would suggest that seismic lines may have lower C/N

353   ratios from loss of dissolved organic carbon due to flooded conditions and leaching (Trettin et al., 2011;

354   Kim et al., 2014). The similar TC among treatments and depths suggests this did not occur (Figure 4), yet

355   the quality of the carbon present was likely affected. FTIR analysis of peat showed how the abundance

356   of different C compounds changed between and within cores. A higher HI represents a higher degree of

357   decomposition as carbohydrates are preferentially lost (Cocozza, et al., 2003; Broder et al., 2012;

358   Biester et al., 2014; Hodgkins, 2016). The HI for the top 40 cm of peat was highest for inverted

359   mounds. Upright mounds and transferred hummocks only had elevated HI for the 20–30 cm depths,

360   otherwise, BR1 cores were comparable at shallower depths. In addition to HI, the shape of the FTIR

361 absorbance can be used to assess substrate quality. The merging of aromatic peaks seen for

362 the inverted mounds and low-lying areas is indicative of the loss of easily decomposed compounds

363 during aerobic decomposition (Cocozza, et al., 2003). Although inverted mounds did not lose TC,

364 inverting the peat profile likely increased the amount of recalcitrant C compounds and decreased labile

365 C compounds. This may negatively impact restoration efforts as increases in recalcitrant C compounds

366 have been observed to lower substrate quality by limiting microbial and plant growth and survival

367 (Asada, Warner, & Aravena, 2005).

368 Isotopic data indicate reduced substrate quality on the inverted mounds. $\delta^{13}C$ and $\delta^{15}N$ can be

369 used as decomposition indicators as lighter isotopes are preferentially lost during decomposition

370 (Broder et al., 2012; Biester et al., 2014). $\delta^{13}C$ in the inverted mound cores was heavier in the top 30

371 cm but the difference was not statistically significant. $\delta^{15}N$ was also constant with depth for the

372 inverted mounds. Constant $\delta^{13}C$ and $\delta^{15}N$ at depth can result from moderate disturbance while

373 intensive disturbance has been shown to cause surface $\delta^{13}C$ and $\delta^{15}N$ to be heavier than greater depths

374 (Krüger et al., 2015). All other cores became heavier with depth until around 30 cm, below which

375 $\delta^{13}C$ and $\delta^{15}N$ became constant. This is consistent with other studies as $\delta^{13}C$ and $\delta^{15}N$ should become

376 heavier as decomposition proceeds through the peat profile until lower depths where decomposition

377 stops or is greatly reduced (Broder et al., 2012; Biester et al., 2014; Krüger et al., 2015). As with bulk

378 density and OM, stable isotopes were only impacted by inverted mounding while upright mounding and

379 hummock transfer maintained patterns observed in undisturbed hummocks.

380 *Decomposition*

381 The shift of labile to recalcitrant OM and lighter to heavier stable isotopes on mounds could be

382 from the exposure of deeper, more decomposed peat or because of increased decomposition rates

383 following mounding. Peatlands are characterized by low decomposition rates under anoxic

384 conditions (Limpens et al., 2008). At both BR1 and SC3, $\delta^{13}C$ and $\delta^{15}N$ show an aerobic zone in the top

17

385　0–20 cm where decomposition rates could be increased by shifting from slower anaerobic to aerobic

386　decomposition. In water-saturated peatlands, $\delta^{13}C$ and $\delta^{15}N$ would be expected to be constant at depth

387　with little decomposition and fractionation occurring (Krüger et al., 2015; Drollinger, Kuzyakov, &

388　Glatzel, 2019). Anaerobic decomposition of ^{13}C enriched lignin can result in lighter $\delta^{13}C$, but

389　decomposition rates are often too slow to show changes in $\delta^{13}C$ (Drollinger, Kuzyakov, & Glatzel,

390　2019). Stable isotopes vary with depth within the cores. In the top layers of peat, isotopes become

391　steadily heavier then remain constant at depths below 20–30 cm. This suggests aerobic decomposition

392　is occurring in the top 0–20 cm.

393　　　　Trends in TN with depth also support a zone of aerobic decomposition in the top 0–20 cm. As

394　with the stable isotopes, TN is normally constant in peatlands due to anoxic conditions from

395　waterlogged peat (Kuhry & Vitt, 1996). However, TN can increase during decomposition due to inputs

396　from microbe biomass after microbial N immobilization (Malmer & Holm, 1984; Damman, 1988). The

397　inverted mounds and low-lying areas had higher TN than the natural hummocks up to 60 cm but the

398　increase in TN was only significant in the top 20 cm. Upright mounding also had slightly higher TN than

399　other cores in the top 20 cm. Consistent with the stable isotope data, the increase in TN suggests

400　aerobic decomposition is occurring in at least the top 20 cm.

401　　　　In addition to water-saturated conditions, decomposition in peatlands is slowed by its inhibition

402　by organic acids (R-COO⁻) produced by *Sphagnum* (Mellegård et al., 2009). FTIR analysis showed

403　a decrease in organic acids for the top 20 cm of inverted mounds. The disappearance or decrease in the

404　acids peak is representative of deep peat samples or a higher pH closer to neutral (Hodgkins et al.,

405　2018). This decrease in organic acids may support higher rates of decomposition in the surface of

406　inverted mounds.

407   Mounds may be able to support higher rates of decomposition with aerobic conditions and

408   decreases in organic acids. To determine if decomposition rates were increased on mounds,

409   decomposition indicators of the mound peat were compared to deeper peat. If peat on the mounds

410   matches conditions in deeper peat, changes in soil properties would be from the exposure of deeper

411   peat and not increased decomposition rates. Bulk density and OM content showed a clear threshold for

412   inverted mounding. At the beginning of the mound interface, 40 cm below the surface, both bulk

413   density and OM content were similar to surrounding natural values. As the highest bulk density for

414   inverted mounds was at 0–30 cm depths, further compaction would have occurred on mounds beyond

415   that caused by exposure of deep peat alone. Further compaction may occur during mounding as

416   operators use the backhoe bucket to push down onto the mounds with the aim of increasing mound

417   persistence. Despite not being statistically significant due to high variability between cores, there was

418   also a potential loss of OM content on the mounds. The average OM content for the top 30 cm of the

419   inverted mounds was 84.2% while the 30 cm below the mounds had an average of 90.6%. This suggests

420   a loss of OM to decomposition in addition to mechanical compaction of the mounds.

421   Unlike bulk density and OM, C/N ratios were lower on both mounds and low-lying areas. The

422   lower C/N ratios at low-lying areas at SC3 and on upright mounds indicate further changes to peat

423   properties past the exposure of deeper peat and mineral soils. The top layers of peat in low-lying areas

424   and upright mounds should consist of younger peat that should reflect high C/N ratio litter inputs from

425   vegetation (Malmer & Holm, 1984; Biester et al., 2014). C/N ratios decrease as decomposition occurs

426   (Malmer & Holm, 1984), which suggests that decomposition rates may be increased above natural

427   conditions for both mounds and low-lying areas. Direct measurements of litter decomposition, litter

428   inputs, and soil respiration are needed to better quantify changes in C cycling and decomposition rates

429   following seismic line disturbance and restoration by mounding.

430   *Implications of restoration*

431   Out of the three mounding treatments evaluated, the classic method of inverted mounds

432   showed the most differences in peat properties to the natural hummocks. The inversion of the peat

433   profile introduced significant bare ground cover and greatly reduced moss cover. Inverted mounds had

434   higher bulk densities, lower OM, heavier stable isotopes, more recalcitrant C compounds, and lower C/N

435   ratios. The degree of these changes combined with the evidence of increased decomposition indicates

436   lower substrate quality on the inverted mounds. The high bulk densities of the inverted mounds may

437   have further implications for hydrological conditions resulting in more waterlogged and anoxic

438   microsites instead of the desired drier and aerated microsites that are beneficial for tree establishment

439   and growth.

440   Disturbance during mounding and subsequent oxic conditions in mounds may be able to

441   support higher rates of decomposition indicated by trends in stable isotopes and TN. Inverted mounds

442   specifically also showed decreases in decomposition-inhibiting organic acids. Changes in peat properties

443   along depth profiles of inverted mounds that were greater than those expected from the inversion of

444   the peat profile alone, which suggests an increase in decomposition in response to mounding. At SC3,

445   C/N ratios were lower for both mounds and low-lying areas where there was no exposure of deeper

446   peat, which indicates increased decomposition may not be isolated to mounds but occurring throughout

447   the line.

448   Newly tested upright mounding and hummock transfer techniques were found to not add costs

449   or time to the classic mounding. The same equipment and operators, with minimal, in-field instruction,

450   were able to employ new mounding techniques in comparable time to the classic mounding. The newer

451   treatments also showed minimal changes to peat properties on both mounds and low-lying areas.

452   Transferred hummocks showed no differences from natural hummocks while upright mounding had

453   slightly lower C/N ratios. While lower C/N ratios are indicative of disturbance and lower substrate

454   quality, lower C/N may be beneficial for tree growth with potentially higher N availability. Vegetation

455   communities that were similar to natural conditions on the two upright mounding techniques reflected

456   the lack of changes in soil properties and the preservation of plants during mounding. Additionally, the

457   upright mounds did have a decrease in graminoid and shrub cover that may be important in promoting

458   tree growth by lessening competition. The soil properties and vegetation communities of the different

459   mounding treatments suggest that upright mounds and hummock transfer may provide additional

460   benefits to the whole ecosystem recovery over the inverted mounds, while likely still supporting a

461   return to tree cover. Although more research will be required on long-term effects of restoration such as

462   tree growth and survival, upright mounding and hummock transfer techniques showed advantages over

463   inverted mounding.

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464

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748 **Tables**

749 *Table 1: Average percent cover of vegetation functional groups for different mounding techniques. Different letters indicate*
750 *statistical differences in percent cover of functional groups between treatments. Treatments with the same letter indicate no*
751 *statistical differences.*

	Shrubs	Graminoid	Forbs	Moss	Open water	Bare ground
SC3						
Natural	11.9 ± 2.9[a]	4.4 ± 3.1[a]	2.8 ± 0.8[a]	100 ± 0[a]	0 ± 0[a]	0 ± 0[a]
Low	8.6 ± 2.5[a]	30 ± 12.5[b]	2.5 ± 0.8[a]	46.6 ± 10.6[b]	1.3 ± 1.3[a]	0 ± 0[a]
Inverted	3.8 ± 1.4[a]	7.6 ± 2.7[a]	3.5 ± 0.9[a]	15.9 ± 7.2[c]	0 ± 0[a]	48.1 ± 13.9[b]
BR1						
Natural	26.9 ± 5.9[b]	11.1 ± 4.2[a]	10.6 ± 2.4[b]	100 ± 0[a]	0.6 ± 0.6[a]	1.5 ± 1.0[a]
Low	21.5 ± 3.7[ab]	22 ± 3.6[ab]	19 ± 2.7[b]	96 ± 4.0[a]	23.7 ± 9.8[b]	0.2 ± 0.2[a]
Upright	19.5 ± 2.2[ab]	10.3 ± 2.1[a]	14.1 ± 1.8[b]	96.3 ± 1.9[a]	1.6 ± 0.6[a]	2.9 ± 1.0[a]
Transfer	30.7 ± 5.2[b]	6.3 ± 1.7[a]	15.4 ± 2.3[b]	92 ± 4.8[a]	0 ± 0[a]	0 ± 0[a]

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753 **Figures**
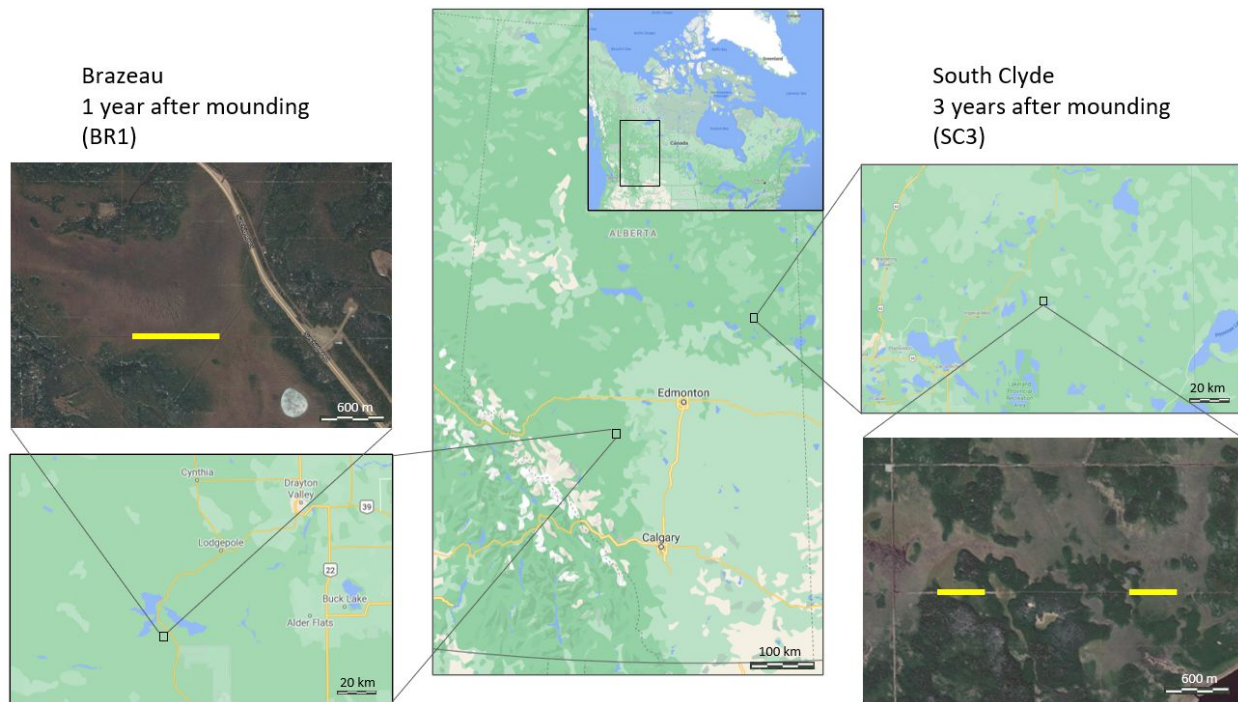
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755 Figure 1: Map of the two study areas in Alberta, Canada. All maps sourced from Google maps available
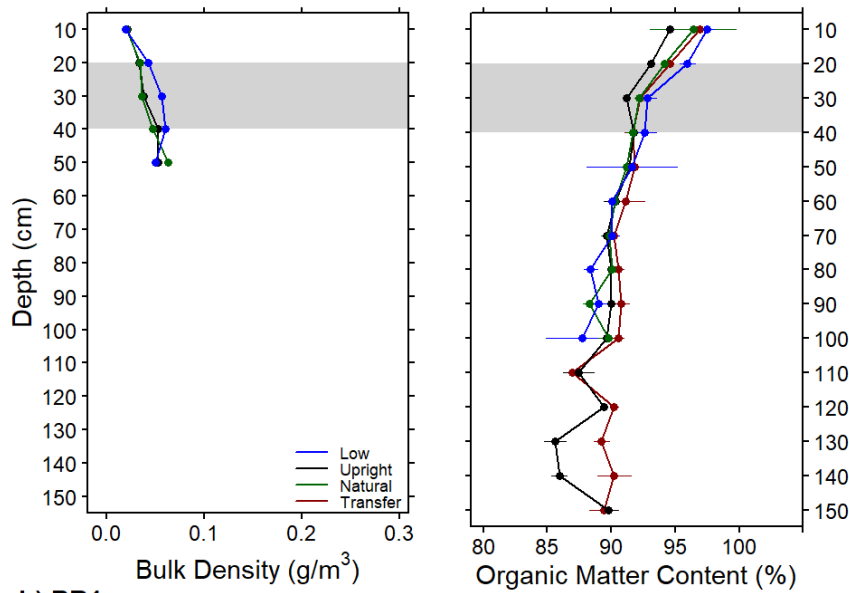756 at http://maps.google.ca

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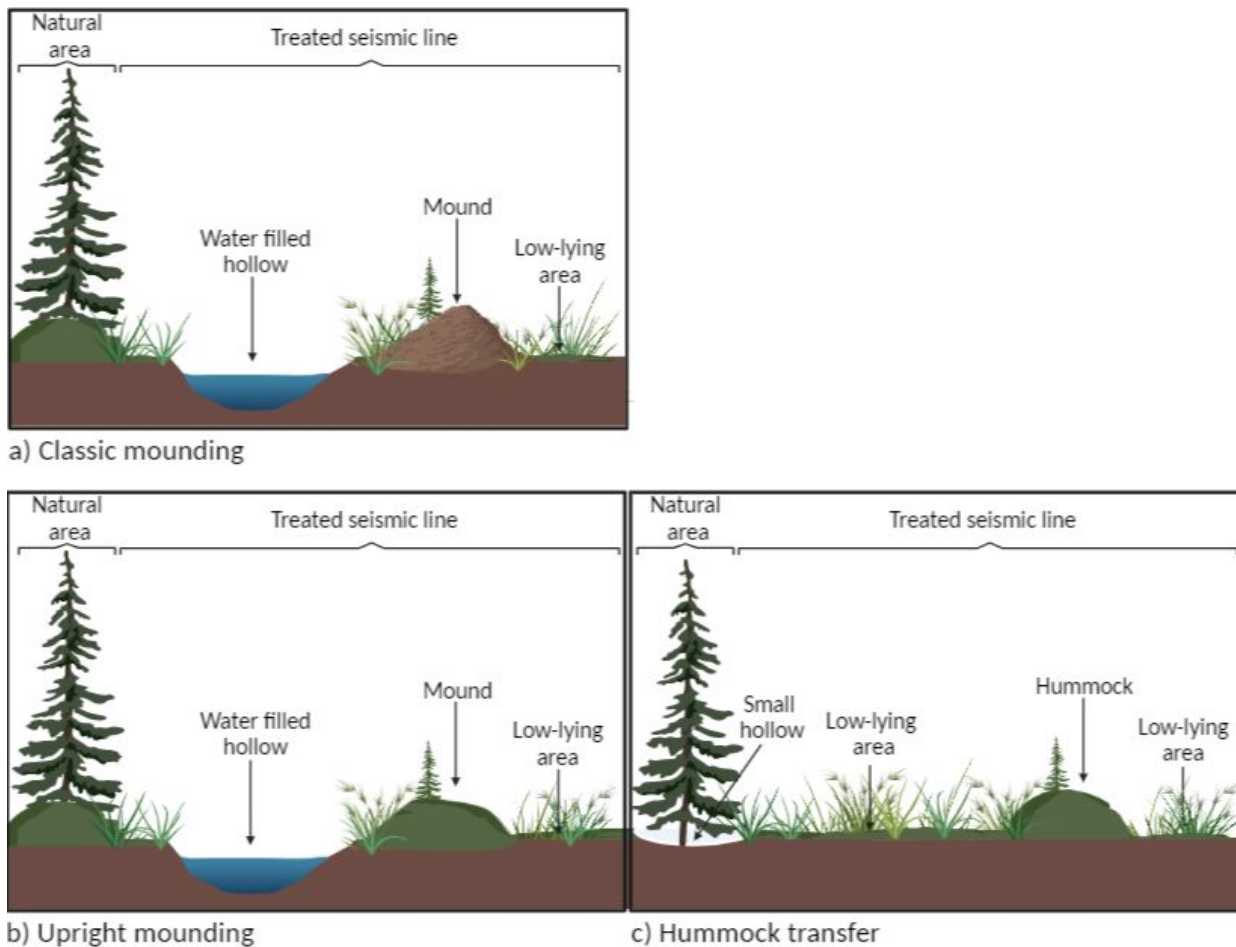
Figure 2: Illustration of different mounding techniques used on seismic lines: a) inverted mounding, b) intact mounding, and c) hummock transfer. Sampled seismic lines were about 6 m wide. Classic mounds were about 50 cm tall while upright mounds and transferred were smaller around 30 cm tall. Created with BioRender.com.
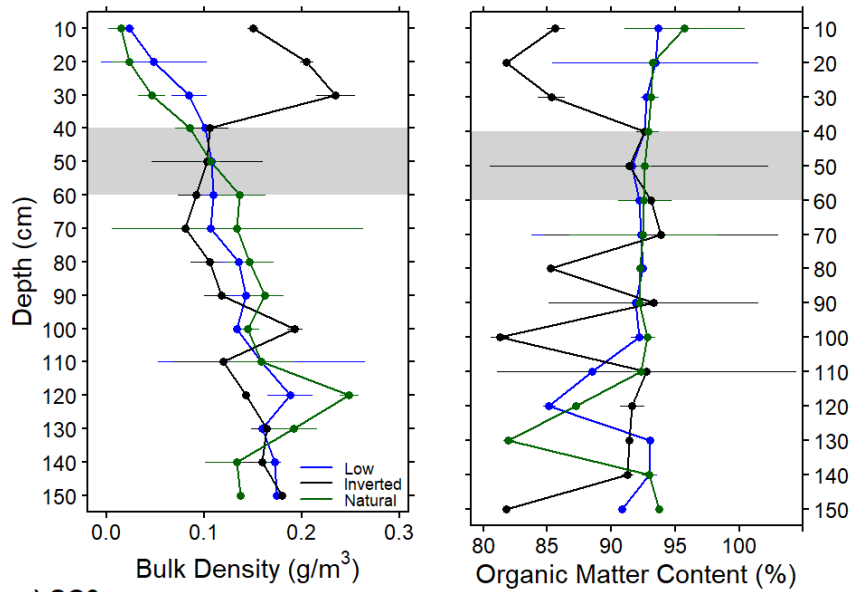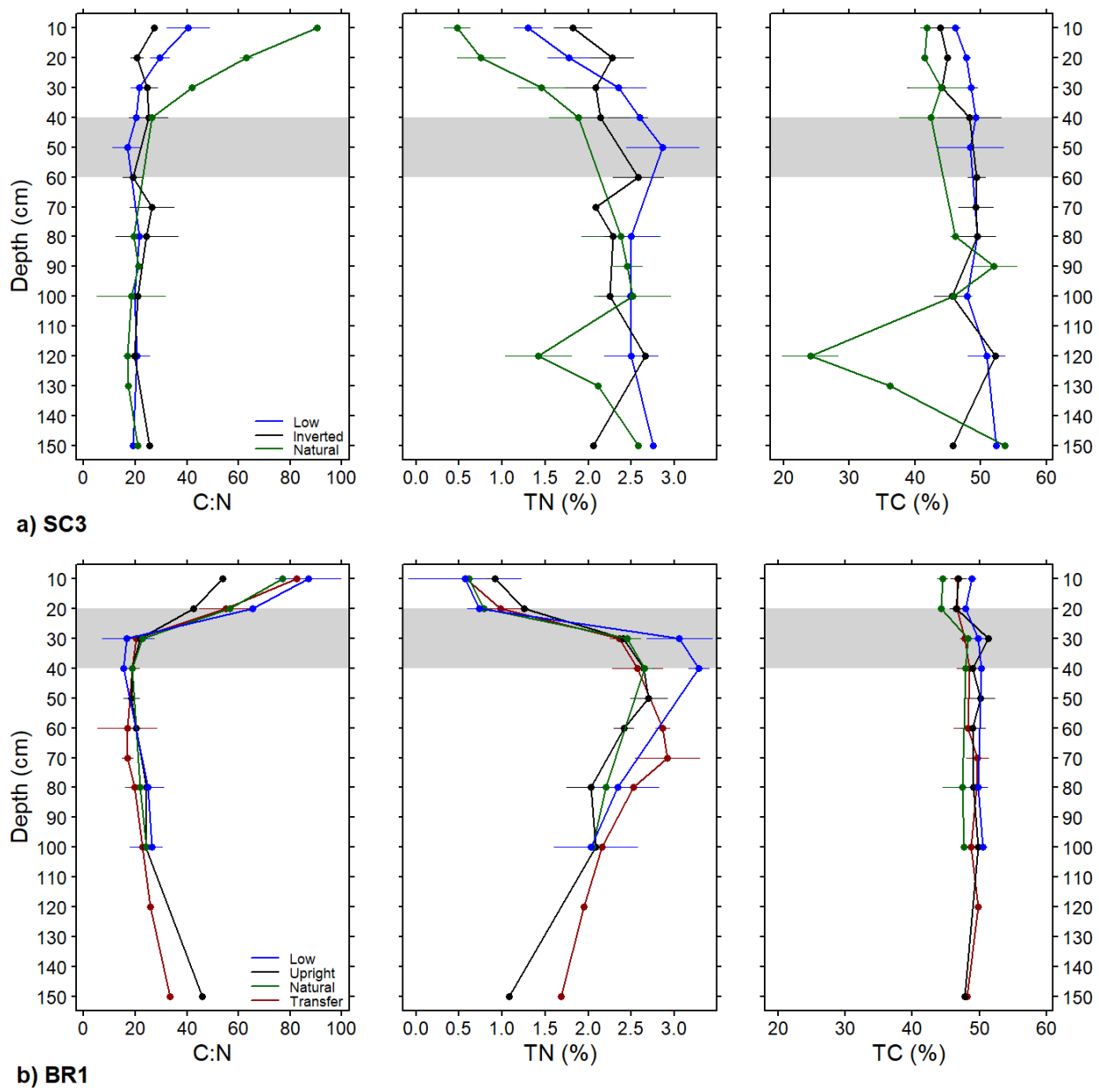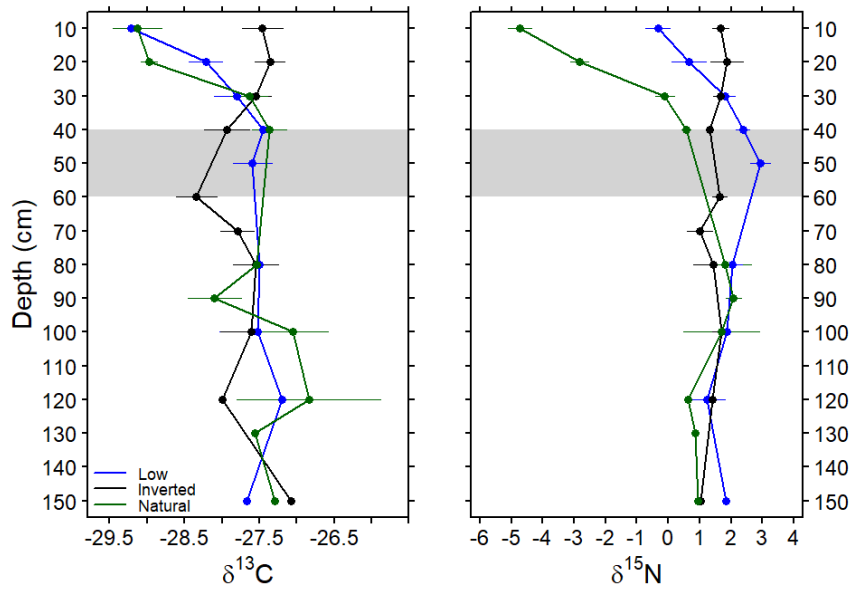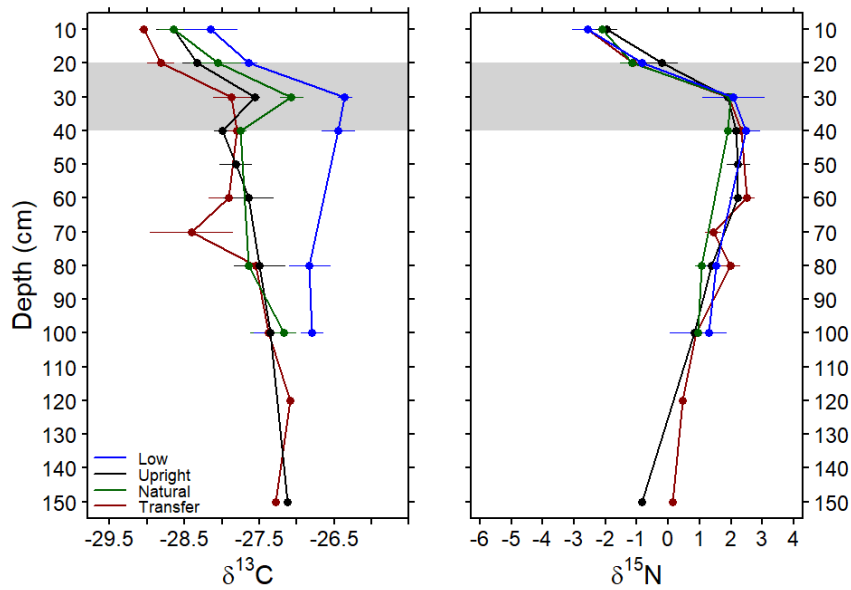
a) SC3

b) BR1

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763 Figure 3: Profiles of bulk density and organic matter content for a) SC3 and b) BR1. When present, error
764 bars represent one standard error. Points without errors bars did not have a large enough sample size to
765 calculate the standard error. Grey bars show the range depth of the interface of the mound to the
766 former ground surface.

a) SC3

b) BR1

Figure 4: Profiles of C/N, TN, and TC at depth for a) SC3, and b) BR1. When present, error bars represent one standard error. Points without errors bars did not have a large enough sample size to calculate the standard error. Grey bars show the range depth of the interface of the mound to the ground surface.
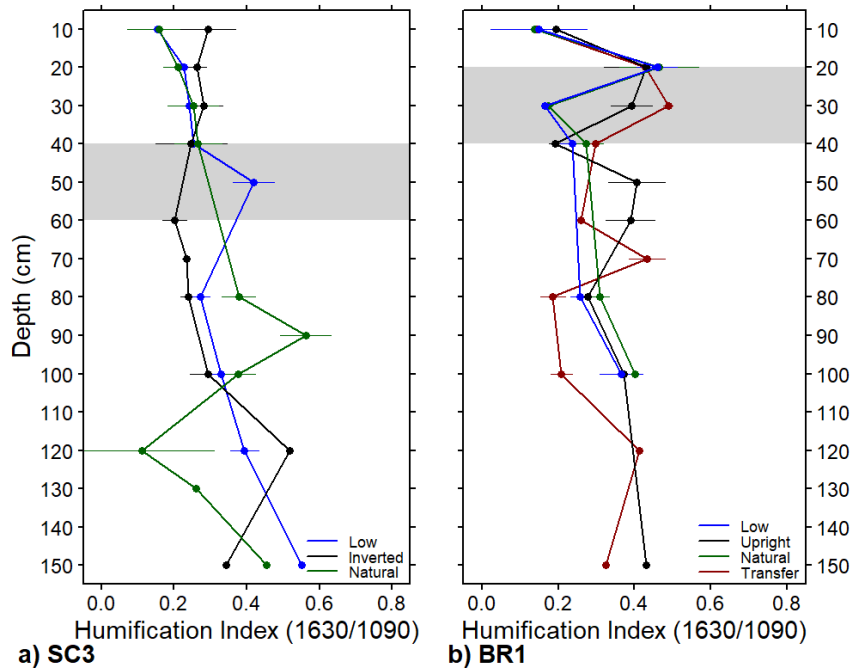
a) SC3

b) BR1

Figure 5: Profiles of δ13C and δ15N at depth for a) SC3, and b) BR1. When present, error bars represent one standard error. Points without errors bars did not have a large enough sample size to calculate the standard error. Grey bars show the range depth of the interface of the mound to the ground surface.
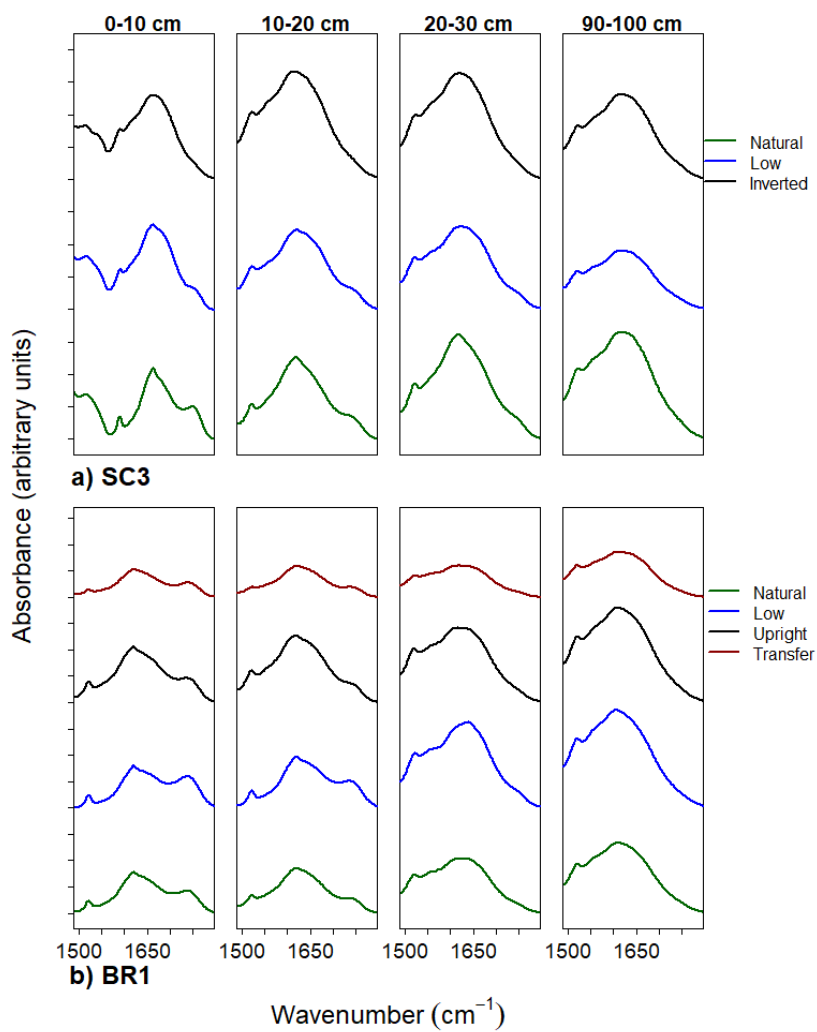
a) SC3   b) BR1

Figure 6: Profiles of humification indices (absorbance at wavenumbers 1630/1090) for a) SC3, and b) BR1. When present, error bars represent one standard error. Points without errors bars did not have a large enough sample size to calculate the standard error. Grey bars show the range depth of the interface of the mound to the ground surface.

Figure 7: FTIR absorbance of aromatics between wavenumbers 1400 and 1650 for a) SC3, and b) BR1.

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