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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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## 17 **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,  $\delta^{13}\text{C}$ ,  $\delta^{15}\text{N}$ , 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<sup>2</sup> 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 ( $\delta^{13}\text{C}$ ,  $\delta^{15}\text{N}$ ), 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

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

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<sup>3</sup> 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<sup>3</sup>. 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,  $\delta^{13}\text{C}$ ,  $\delta^{15}\text{N}$ , 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  $\delta^{13}\text{C}$ ,  $\delta^{15}\text{N}$ . TC, TN,  $\delta^{13}\text{C}$ , and  $\delta^{15}\text{N}$  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  $\delta^{13}\text{C}$  and 0.3‰ for  $\delta^{15}\text{N}$  (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  $\text{cm}^{-1}$  (wavenumber) at a resolution of

177 4 cm<sup>-1</sup> 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<sup>-1</sup> bands representing aromatics or deprotonated COO<sup>-</sup> such as lignin and aliphatic or aromatic  
181 carboxylates over 1090 cm<sup>-1</sup> bands representing carbohydrates (Hodgkins, 2016).

## 182 *Statistics*

183 The statistical program R (R Core Team, 2017) was used for statistical analysis. A value of  $\alpha =$   
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<sup>3</sup> 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,  $\delta^{15}\text{N}$  was found to range from -5.94 to 3.22‰ (Figure 5). When comparing  
239 across core types, at 0–10 cm,  $\delta^{15}\text{N}$  varied significantly between cores ( $F_{6,28} = 30.62$ ,  $p < 0.001$ ). SC3  
240 natural hummocks had the most negative (lightest)  $\delta^{15}\text{N}$  while inverted mounds had the most  
241 positive (heaviest)  $\delta^{15}\text{N}$  followed by SC3 low-lying areas. Transferred hummocks, upright mounds,  
242 and BR1 natural hummocks and low-lying areas were all similar.  $\delta^{15}\text{N}$  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  $\delta^{15}\text{N}$  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,  $\delta^{15}\text{N}$  became  
249 heavier rapidly until 20–30 cm. At SC3,  $\delta^{15}\text{N}$  remained constant at lower depths while at BR1,  $\delta^{15}\text{N}$   
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  $\delta^{13}\text{C}$  of  $-34.26$  to  $-26.29\text{‰}$  (Figure 5). At 0–10 cm, the  $\delta^{13}\text{C}$  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  $\delta^{13}\text{C}$  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,  $\delta^{13}\text{C}$  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  $\text{COO}^-$  aromatic/aliphatic carboxylates. The small peak on the right of the  
275 middle peak represents the organic acids (protonated  $\text{COOH}$ ) 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<sup>3</sup> 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 (Kozłowski, 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  $\text{NH}_4^+$  (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.  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  can be  
369 used as decomposition indicators as lighter isotopes are preferentially lost during decomposition  
370 (Broder et al., 2012; Biester et al., 2014).  $\delta^{13}\text{C}$  in the inverted mound cores was heavier in the top 30  
371 cm but the difference was not statistically significant.  $\delta^{15}\text{N}$  was also constant with depth for the  
372 inverted mounds. Constant  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  at depth can result from moderate disturbance while  
373 intensive disturbance has been shown to cause surface  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  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  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  became constant. This is consistent with other studies as  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  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,  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  show an aerobic zone in the top

385 0–20 cm where decomposition rates could be increased by shifting from slower anaerobic to aerobic  
386 decomposition. In water-saturated peatlands,  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  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  $^{13}\text{C}$  enriched lignin can result in lighter  $\delta^{13}\text{C}$ , but  
389 decomposition rates are often too slow to show changes in  $\delta^{13}\text{C}$  (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 ( $\text{R-COO}^-$ ) 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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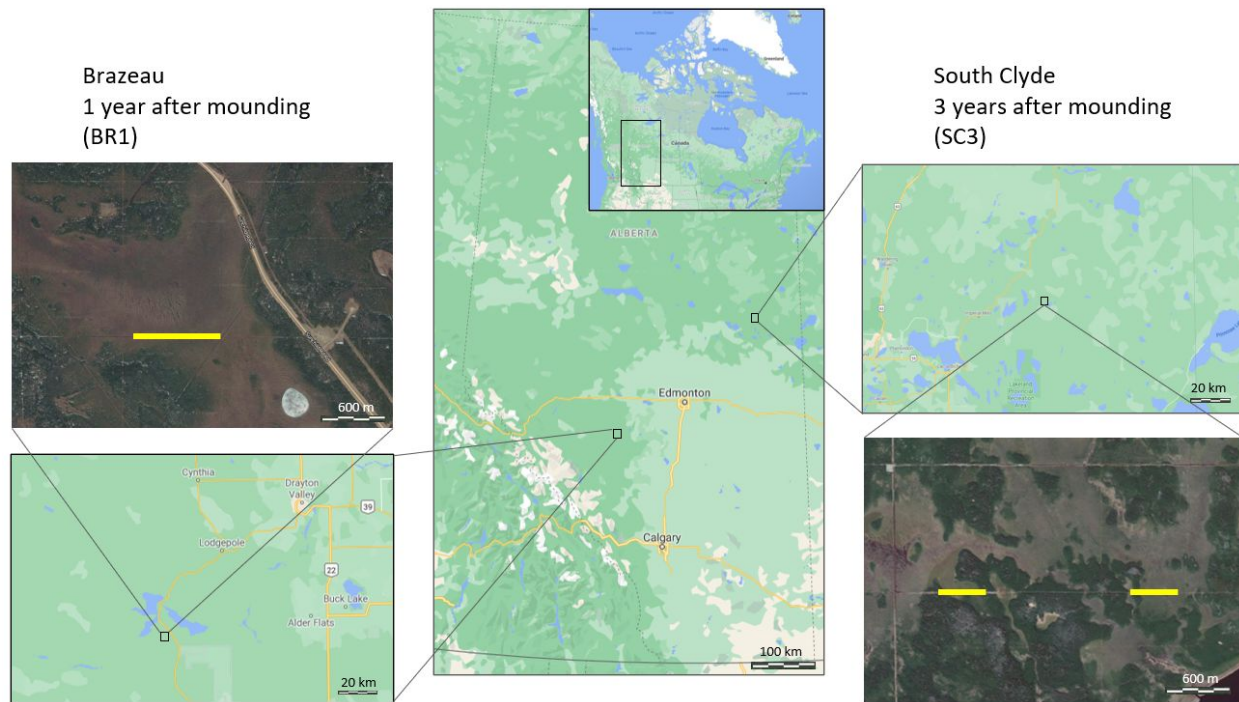
748 **Tables**

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

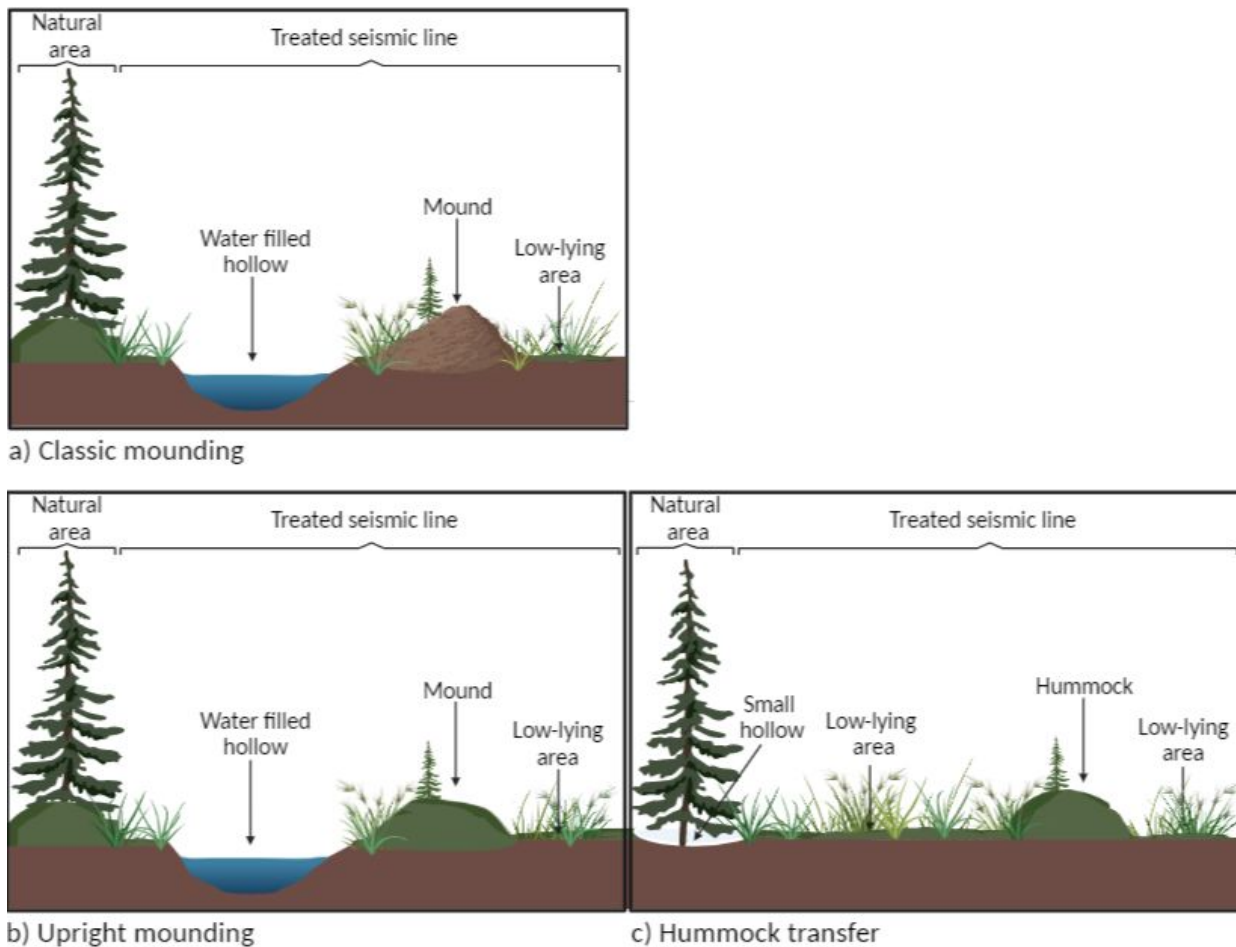
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753 **Figures**

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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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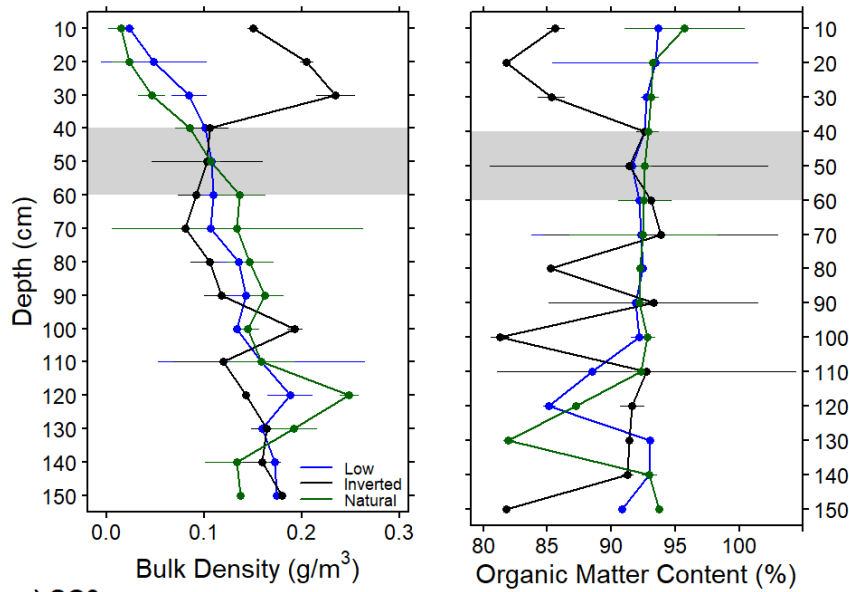
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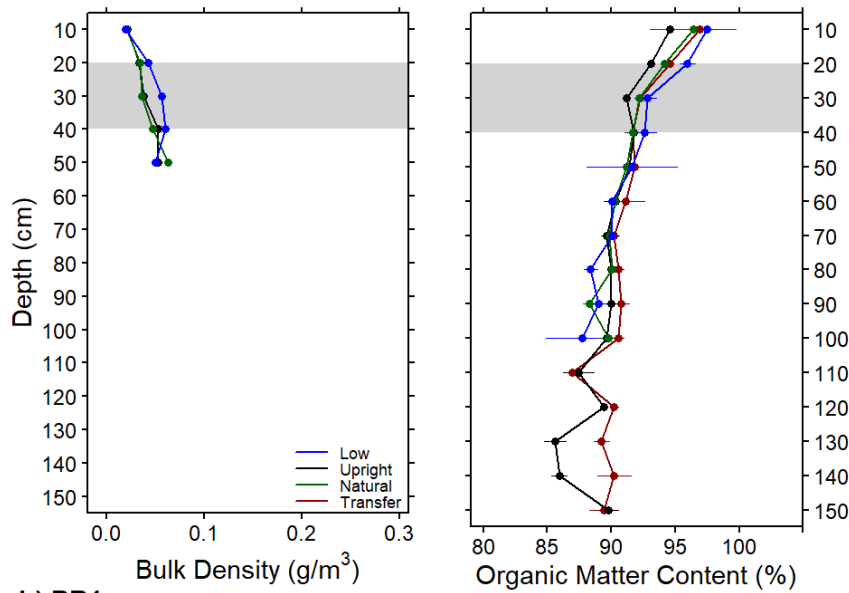
b) Upright mounding

c) Hummock transfer

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.



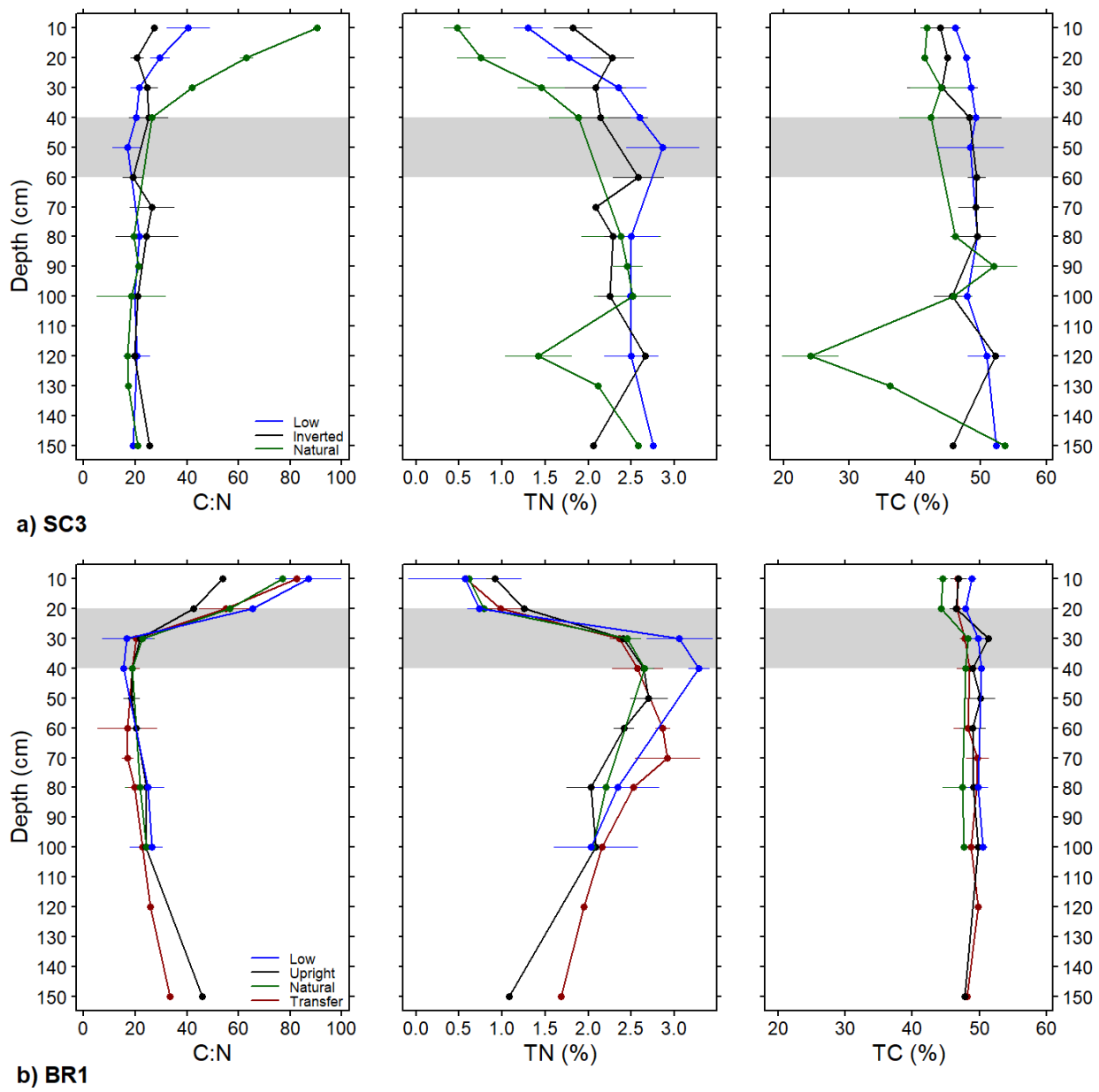
a) SC3



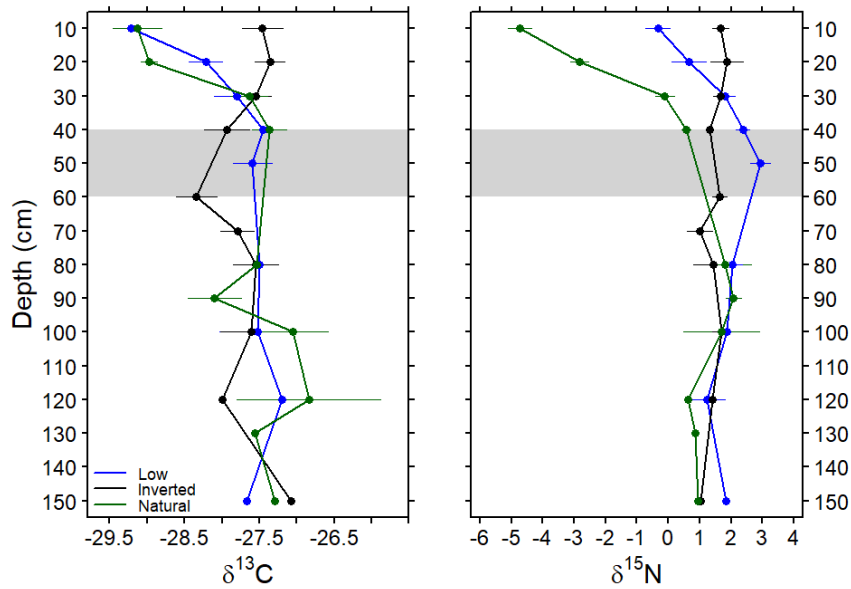
b) BR1

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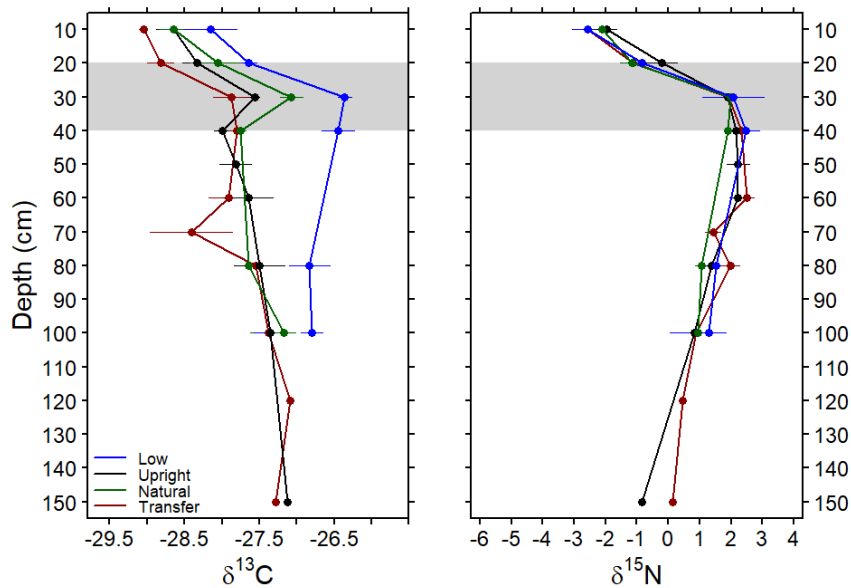
763 Figure 3: Profiles of bulk density and organic matter content for a) SC3 and b) BR1. When present, error  
 764 bars represent one standard error. Points without errors bars did not have a large enough sample size to  
 765 calculate the standard error. Grey bars show the range depth of the interface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



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

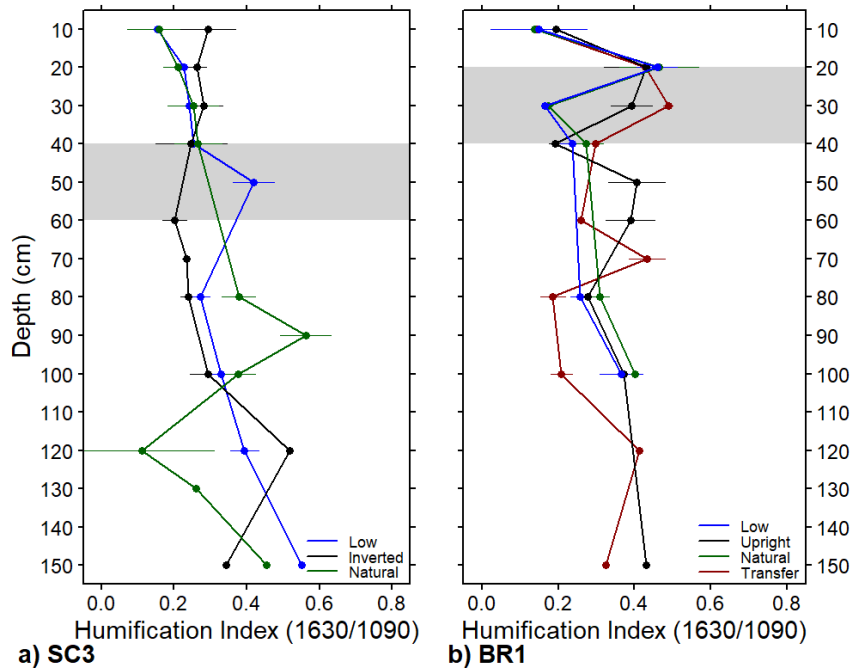


a) SC3



b) BR1

771  
 772 Figure 5: Profiles of  $\delta^{13}\text{C}$  and  $\delta^{15}\text{N}$  at depth for a) SC3, and b) BR1. When present, error bars represent  
 773 one standard error. Points without error bars did not have a large enough sample size to calculate the  
 774 standard error. Grey bars show the range depth of the interface of the mound to the ground surface.



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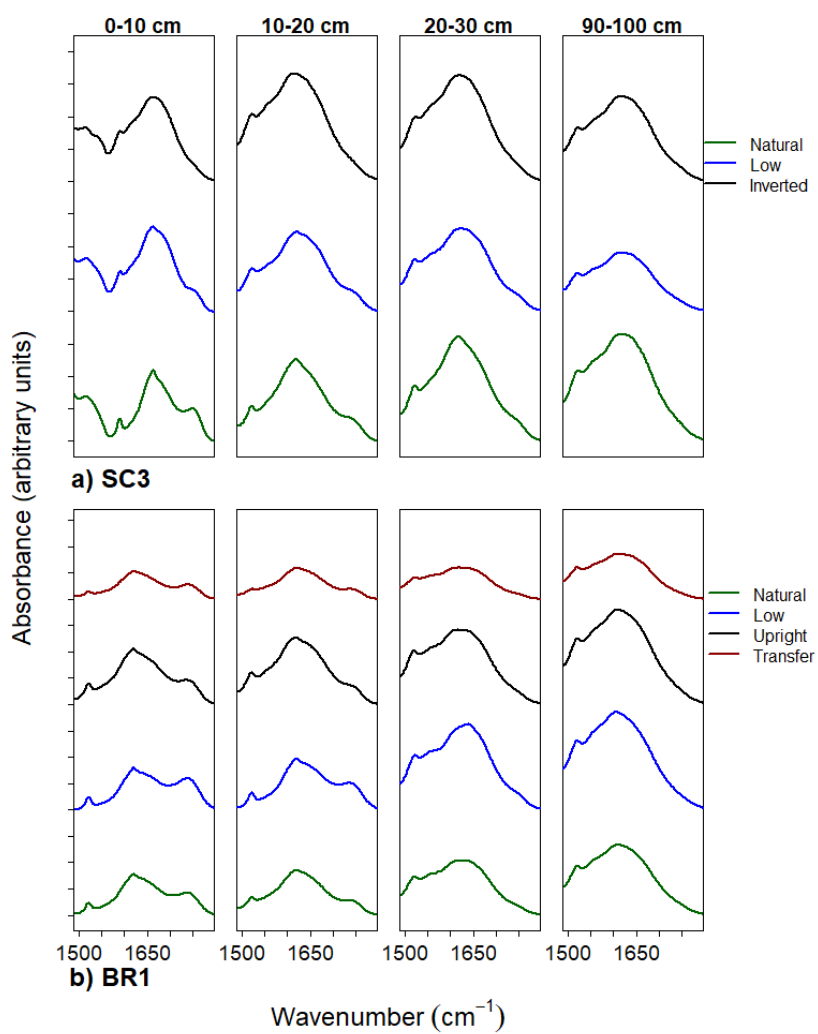
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Figure 6: Profiles of humification indices (absorbance at wavenumbers 1630/1090) for a) SC3, and b) BR1. When present, error bars represent one standard error. Points without errors bars did not have a large enough sample size to calculate the standard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



780

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

782