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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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Abstract

Seismic lines are prominent linear disturbances across boreal Canada with large-scale consequences to wildlife and ecosystem function. Although seismic line restoration has been observed to improve tree growth and survival, application in peatlands has been shown to alter ecosystem functions such as hydrology and carbon storage. The most common active restoration method is called mechanical mounding where the classic technique inverts the peat profile. New mounding methods that maintain the peat profile may provide benefits by preserving existing vegetation and reducing disturbance. To determine the effects of different mounding methods on soil quality, peat cores were collected and analyzed from two different sites for various soil properties (C/N ratios, $\delta^{13}C$, $\delta^{15}N$, Fourier transform infrared (FTIR) spectroscopy humification indices). Vegetation surveys were also conducted. The two sites are both a collection of seismic lines crossing poor fens in Alberta. One site was treated with the classic method while the other was treated with two new mounding methods. Classic mechanical mounding significantly increased the degree of decomposition, indicative of lower substrate quality. Mechanical mounding also greatly reduced moss cover and introduced large amounts of bare ground cover. The two newer mounding methods did not result in these changes and were largely comparable to natural peat properties and vegetation communities. Preserving the peat profile in new mounding methods may support faster return of ecosystem function.

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

Introduction

An estimated 345,000 km of seismic lines covering 1910 km^2 have been created in all types of peatlands in the province of Alberta, Canada for oil and gas exploration (Strack et al., 2019). Seismic line disturbance has many negative impacts in peatlands such as causing a shift from a C sink to a C source and increasing line of sight and mobility of wolves resulting in declining caribou populations (Dabros et al., 2018). These long, linear disturbances have not returned to tree cover as initially expected and are now being restored through a site preparation method called mechanical mounding (Lee & Boutin, 2006) followed by tree planting. Mounding in peatlands is the process of digging, inverting, and placing mounds of peat on the lines to recreate microtopography (Filicetti et al., 2019). Mounding treatments are widely used to promote tree growth (Sutton 1993; Smolander & Heiskanen, 2007; Bilodeau-Gauthier et al., 2011; Lafleur et al., 2011; Bilodeau-Gauthier et al., 2013; Lieffers, Caners, & Ge, 2017; Filicetti et al., 2019) and this technique has been observed to increase tree growth and survival by providing drier microsites (Filicetti et al., 2019). Yet, little is known about how mounding alters the properties of the soil profile, particularly in peatlands where shifts in physical properties following disturbance and restoration have been shown to alter ecohydrological function (McCarter and Price, 2015). Important soil properties that indicate decomposition and substrate quality include the ratio of carbon and nitrogen (C/N), stable isotopic composition ($\delta^{13}C$, $\delta^{15}N$), humification indices (HI), bulk density, and organic matter content (OM) (Broder et al., 2012; Biester et al., 2014; Krüger et al., 2015; Drollinger et al., 2020). These decomposition indicators have known responses to aerobic and anaerobic decomposition throughout the peat profile due to preferential loss of certain compounds. This study aims to investigate how various mounding techniques alter the physical and chemical properties of the soil profile in peatlands.

While often successful for promoting tree growth, mechanical mounding (hereafter referred to as inverted mounding) methods have drawbacks, especially in peatlands. Mounding has been observed to shift vegetation succession trajectories away from the surrounding natural areas (Echiverri, Macdonald, & Nielsen, 2020). Unlike mounded lines, untreated seismic lines often have recovering vegetation on the trajectory of restoring natural peatland plant communities (Echiverri, Macdonald, & Nielsen, 2020). Keeping the peat profile intact during mounding instead of inverting the soil and burying recovering vegetation could provide benefits to both understory vegetation and tree recovery. Removing vegetation decreases evapotranspiration, increases soil moisture and soil bulk density, and changes water storage and flow (Dabros et al., 2018). By exposing bare peat and burying vegetation, inverted mounding may slow and alter vegetation recovery by resetting succession.

New mounding treatments have been developed to improve upon the classic inverted mounding (Xu, 2019). The main difference between the new and classic treatments is that the new treatments do not invert the peat profile. The first new method, upright mounding, follows the same procedure of digging and placing the mound on the line but without inversion. The second method, hummock transfer, moves a natural hummock from the adjacent peatland onto the seismic line (Xu, 2019). Hummock transfer does not involve digging or inverting the peat but often leaves a small depression where the hummock was removed. The level of disturbance in the adjacent natural area from hummock transfer has not been evaluated but is predicted to be small. Preserving the peat profile may prevent or reduce changes in soil properties and allow for recovering vegetation to survive the mounding treatment, while hummock transfer moves woody vegetation onto the line. New mounding treatments dig to 50 cm depths while classic mounding may dig to 50-100 cm depths.

Inverted mounding greatly alters surface peat properties with unknown implications for vegetation recovery (Davidson et al., 2020). The driving factors of changes in soil properties from mounding are not well understood. Inverted mounding exposes deeper peat that has different properties from surface peat but the creation of mounds, inverted or intact, could also alter soil processes. Small degrees of disturbance have been found to increase decomposition rates in peatlands

(Krüger et al., 2015). Inverted mounds are made of more decomposed peat, but it is not well understood if decomposition is increased on mounds or if changes in properties simply arise from the exposure of deeper peat that was already more highly decomposed (Davidson et al., 2020).

Additionally, while tree recovery may benefit from inverted mounding, general vegetation communities are shifted from surrounding natural conditions (Echiverri et al., 2020). Changing inverted mounding methods to keep the peat profile intact and preserve recovering vegetation may maintain peat properties more similar to undisturbed conditions and improve restoration success, but this has not yet been quantified. Therefore, the specific objectives of this study were to:

1. Compare how two different mounding techniques applied to seismic lines in fen peatlands alter physical and chemical soil properties and plant communities
2. Determine if changes in soil properties are driven by changes in soil processes (e.g., enhanced decomposition, compaction) or from the exposure of deep peat during the mounding process

Materials and methods

Study sites

Two study sites, both wooded poor fens, were selected to compare the different mounding techniques. At both sites, peat depth was at least 100 cm. Sampled seismic lines were explorative only and did not contain pipelines. The first site, South Clyde 3rd year post mounding (SC3), is an east-west seismic line running through a collection of poor fens located north of Cold Lake, Alberta (55° 04’49" N, 111° 11’39” W) (Figure 1). SC3 is not accessible to the public and is expected to not be impacted by human use. The line was treated in 2017 by Cenovus Energy using inverted mounding techniques. Samples were collected in two sections on the lines, approximately 200 m long each, during September 2020. Dominant vegetation at SC3 includes *Betula pumila* L., *Carex* spp., *Equisetum* sp., *Larix laricina* (Du Roi) K. Koch, *Oxycoccus microcarpus* Turcz. ex Rupr., *Picea mariana* (Mill.) Britton, Sterns & Poggenb., *Polytrichum strictum* Menzies ex Brid., *Rhododendron groenlandicum* (Oeder) Kron & Judd, and *Sphagnum* spp.

The second site, Brazeau, was restored using two new methods of mounding, upright mounding and hummock transfer as described below. Brazeau 1st year post mounding (BR1) is an east-west seismic line crossing a poor fen near Brazeau Reservoir, Alberta (52° 53’ 21" N, 115° 32’ 57” W) (Figure 1). BR1 is easily accessible by road and is situated on crown land. However, no evidence of recreational activity was observed on-site during year-round monitoring. Samples were collected over a 600 m long section of the line. The line was restored in March 2019 and sampled during August 2020. The dominant vegetation at BR1 consists of *P. mariana*, *L. laricina*, *R. groenlandicum*, *Salix* spp., *Menyanthes trifoliata*, *Vaccinium oxycoccos*, *Sphagnum fuscum*, and *Sphagnum magellanicum*.

As described in Filicetti et al. (2019), an excavator with a 1 m^3 bucket was used to create mounds at SC3 by digging to a depth of 50–100 cm and inverting the peat onto the line. The resulting mound buried established vegetation and exposed deeper, more decomposed peat or mineral soils (Figure 2a). New mounding methods were used at BR1. The first, upright mounding, is similar to inverted mounding but preserves the soil profile by not inverting the peat. This method does not expose deeper peat and keeps established vegetation intact (Figure 2b). The second method, hummock transfer, does not involve further disturbance on the line. Hummock transfer refers to the transfer of natural hummocks, located off the line in the adjacent peatland, onto the line (Figure 2c). This aims to introduce desired vegetation to the line and does not result in created hollows on the lines (Xu, 2019). Both methods of mounding were done while the ground was frozen, and operators did not dig below the rooting depth of around 50 cm to allow regrowth in created hollows.

Since the new mounding techniques tested here have not been applied widely, we were limited in study site selection and had to compare to inverted hummocks at another study site. The comparison of the two study sites may be influenced by time since mounding as BR1 was sampled 1 year after restoration while SC3 was sampled 3 years after restoration. In the comparison, BR1 may be at a disadvantage as the highest degree of disturbance would be expected to occur right after mounding treatments. However, a comparison of surface soil properties 2 and 3 years after mounding at SC showed minimal changes in soil properties over the year (see Supplemental Material). Differences over time should not be substantial enough to prevent the comparison of the two mounding techniques. To limit study site impacts on interpretation, mounding techniques were primarily compared to their corresponding surrounding natural conditions.

Sampling Methods

At SC3, six cores were collected from each of 1) inverted mounds, 2) adjacent low-lying areas on the lines, and 3) hummocks in the surrounding natural areas for a total of 18 cores. At BR1, four cores each were collected from 1) mounds on hummock transfer, 2) mounds on upright mounding, 3) adjacent low-lying areas, and 4) hummocks in surrounding natural areas for a total of 16 cores. Peat was sampled to 100 cm in depth with a Russian auger with a diameter of 8.3 cm from the natural hummocks and low-lying areas at BR1. Peat was sampled up to 150 cm in depth or until reaching clay from the hummock transfer and upright mounds and for all cores at SC3. All cores were cut into 10 cm intervals in the field and then frozen and shipped to Waterloo, Ontario for processing. Due to the compressibility of moss, the top moss layer samples (up to 30 cm in depth) were collected with a knife and metal can with a known volume of 562.70 cm^3. Additionally, vegetation and ground cover surveys (i.e., percent cover) to the functional group level (graminoids, forbs, mosses, shrubs, trees, bare ground, and open water) were conducted in a 100 x 100 cm square where each core was sampled. Percent cover was determined visually to the nearest 5% above 10% cover and to the nearest 1% below 10% cover.

Sample Processing

Samples were thawed, weighed, dried at 80 °C for 48 hours or until dry (based on reaching a constant weight), and weighed again. Bulk density was calculated using known volumes of peat and dry weights. At SC3, bulk densities were analyzed for every 10 cm depth interval collected. At BR1, peat volumes were not measured, and bulk density could not be calculated from cores samples. Instead, bulk density was calculated from other cores that were taken at the same time and site but only up to 50 cm in depth. These 50 cm cores were only taken from upright mounds, low-lying areas, and natural hummocks; no samples from hummock transfer could be used to calculate bulk densities. Subsamples of 2 g of dried peat for every sample were further burned in a muffle furnace at 550 °C for 4 hours and then weighed the following day to calculate organic matter (OM) content.

We measured several peat parameters, including C/N ratios, $\delta^{13}C$, $\delta^{15}N$, and humification indices, that have been previously used to investigate changes in peat quality and decomposition status (Broder et al., 2012; Biester et al., 2014; Krüger et al., 2015; Drollinger et al., 2020). The rest of the dried peat for depth intervals 0-40 cm, the interface of the mound and underlying line (between 50-80 cm), 70-80 cm, 90-100 cm, and the deepest depth interval collected up 150 cm were ground into a fine powder using a ball mill. One milligram of the ground peat samples was used to determine total carbon (TC), total nitrogen (TN), and $\delta^{13}C$, $\delta^{15}N$. TC, TN, $\delta^{13}C$, and $\delta^{15}N$ through combustion conversion of sample material to gas through a 4010 Elemental Analyzer (EA) (Costech Instruments, Italy) coupled to a Delta Plus XL (Thermo-Finnigan, Germany) continuous flow isotope ratio mass spectrometer (CFIRMS) at the Environmental Isotope Lab (EIL) at University of Waterloo. Standard quality control methods were applied by the Environmental Isotope Lab, resulting in errors of 0.2‰ for $\delta^{13}C$ and 0.3‰ for $\delta^{15}N$ (see Supplemental material for details)

Lastly, further subsamples of the ground peat were used in Fourier Transform Infrared (FTIR) analysis conducted in the Waterloo Advanced Technology Laboratory (WATLab). For FTIR analysis, spectra were acquired in absorbance mode between 4500 and 300 cm^{-1} (wavenumber) at a resolution of

4 cm^{-1} and 128 scans were averaged for each spectrum. A script was used to find the exact wavenumber locations of specific peaks and convert them into relative abundances (https://github.com/shodgkins/FTIRbaselines). Humification indices (HI) were calculated using 1630 cm^{-1} bands representing aromatics or deprotonated COO^- such as lignin and aliphatic or aromatic carboxylates over 1090 cm^{-1} bands representing carbohydrates (Hodgkins, 2016).

Statistics

The statistical program R (R Core Team, 2017) was used for statistical analysis. A value of α = 0.05 was used to determine statistical significant for all tests. Shapiro-Wilk tests and Q-Q normality plots were used to assess the normality of soil properties. Although overall samples were found to not be normal, groups of samples (I.e., all inverted mound cores) were normal. With the normality of groups confirmed, ANOVAs were used to test differences in peat properties between different groups (treatments) at each depth as well as between depths within a core type. ANOVAs were also used to test differences between the cover of vegetation functional groups between treatments. When differences were significant, Tukey post hoc tests were used to determine which means differed from each other.

Results

Bulk density and organic matter content

Bulk densities of peat samples varied greatly between treatments and depths with a range of 0.015 to 0.86 g/cm^3 across all samples (Figure 3). The most compacted samples were either at the greatest depths or from the inverted mounds. At 0-10 cm and 10-20 cm depths, the inverted mounds were found to be significantly more compacted than all other cores (0-10 cm: $F_{5,22}$ = 17.38, p < 0.001) (10-20 cm: $F_{5,22}$ = 11.6, p < 0.001). Natural hummocks, low-lying areas, and upright mounds had similar bulk densities to each other at all depths. Changes in bulk densities of inverted and upright mounds at depth were not statistically significant. Low-lying areas and natural hummocks at the sites had significantly higher bulk density with increasing depths (Supplemental material, Tables S1-4).

There was a large range of OM content across all samples from 27.1 to 98.1% (Figure 3). However, the range was greatly skewed with only 13 out of 384 samples having an OM content below 80%. These 13 samples were all either below 100 cm deep or from the inverted mounds and had the highest bulk densities. With many samples consisting of high OM, there was no significant difference between the treatments. Similarly, SC3 cores had no significant trends in OM content down the peat profile. The inverted mounds had lower OM content at 0–30 cm than deeper depths, but the difference to other cores was not significant. At BR1 only, the natural hummocks, low-lying areas, and transferred hummocks had higher OM content at shallower depths (0–30 cm) than all deeper depths (Supplemental material, Tables S5–S7).

Total C and N content

TC content of all samples ranged from 12.17 to 54.99%. However, averages between cores were similar and there was no significant difference between the treatments except for the low TC of natural samples at 110–120 cm ($F_{3,4}$ = 144.7, p = 0.00016). Within cores, TC also was largely uniform.

TN was more variable between samples and depths than TC with a smaller range of 0.50 to 3.04%. At 0–10 cm and 10–20 cm depths, the inverted mounds were found to have higher TN than the transferred hummocks, low-lying areas, and natural hummocks at both sites (0–10 cm: $F_{6,28}$ = 6.65, p = 0.00019; 10–20 cm: $F_{6,25}$ = 7.27, p = 0.00014). Additionally, at the 10–20 cm depth, SC3 low-lying areas also had greater TN than the natural hummocks and BR1 low-lying areas. Transferred hummocks had more TN than the upright mounding at the 50–60 cm depth interval ($F_{2,2}$ = 29.13, p = 0.033). The decrease in TN at 110–120 cm depth for the SC3 natural samples was only significantly lower than the inverted mounds ($F_{3,4}$ = 8.02, p = 0.036). For all cores except inverted mounds, TN increased with depth until 30–40 cm. Below 40 cm, SC3 cores had constant TN while BR1 cores decreased with depth (Supplemental material, Tables S8–S13).

Between all samples, C/N ratios ranged from 14.4 to 119.6 (Figure 4). At 0–10 cm, SC3 low-lying areas and inverted mounds had lower C/N ratios than both natural hummocks, BR1 low-lying areas, and transferred hummocks ($F_{6,28}$ = 12.29, p < 0.001). Similarly, SC3 low-lying areas and inverted mounds had lower C/N ratios at 10–20 cm than SC3 natural hummocks and BR1 low-lying areas ($F_{6,25}$ = 5.18, p = 0.0014). Inverted mounds' C/N ratios at 10–20 cm were also lower than SC3 low-lying areas. Although the upright mounding had a lower C/N than the other BR1 cores at 0–10 and 10–20 cm, this difference was not significant. At 50–60 cm depth, the transferred hummocks had lower C/N ratios than upright mounding and inverted mounding ($F_{9,17}$ = 12.1, p < 0.001).

Hummock transfer, upright mounding, low-lying areas, and natural hummocks all had decreasing C/N ratios at depth while inverted mounding did not significantly change along the profile (Supplemental material, Tables S14–S19). The decrease at depth was rapid until 20–30 cm for BR1 and 30–40 cm for SC3. SC3 cores were then mostly uniform at greater depths while the BR1 cores increased slightly although this was only significant for the upright mounds.

Stable isotope signatures and humification indices

Across all samples, $\delta^{15}N$ was found to range from -5.94 to 3.22‰ (Figure 5). When comparing across core types, at 0–10 cm, $\delta^{15}N$ varied significantly between cores ($F_{6,28}$ = 30.62, p < 0.001). SC3 natural hummocks had the most negative (lightest) $\delta^{15}N$ while inverted mounds had the most positive (heaviest) $\delta^{15}N$ followed by SC3 low-lying areas. Transferred hummocks, upright mounds, and BR1 natural hummocks and low-lying areas were all similar. $\delta^{15}N$ of SC3 natural hummocks were still the lightest at 10–20 cm but the difference was only significant compared to SC3 low-lying areas, inverted mounds, and upright mounds. The inverted mounds at 10–20 cm were also still the heaviest but the difference was only significant when compared to the natural hummocks and BR1 low-lying areas and transferred hummocks ($F_{6,25}$ = 10.05, p < 0.001). At the 30–40 cm and 140–150 cm depths, the $\delta^{15}N$ of the SC3 natural hummocks was lighter than the low-lying areas at both sites ($F_{6,24}$ = 3.765, p = 0.0088; $F_{4,7}$ = 10.82, p = 0.0040). For all cores except for inverted mounding, $\delta^{15}N$ became heavier rapidly until 20–30 cm. At SC3, $\delta^{15}N$ remained constant at lower depths while at BR1, $\delta^{15}N$ became lighter again. The inverted mounding cores did not vary at depth (Supplemental material, Tables S20–S25).

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 inverted mounds was significantly heavier than SC3 low-lying areas ($F_{6,28}$ = 3.38, p = 0.012). At 10–20 cm, the $\delta^{13}C$ of inverted mounds was heavier than the BR1 low-lying areas and SC3 natural hummocks. The SC3 natural hummocks were also lighter than the BR1 natural hummocks and low-lying areas ($F_{6,25}$ = 6.21, p = 0.00043). For all cores except for inverted mounding, $\delta^{13}C$ becomes heavier rapidly until 20–30 cm and then remains constant (Supplemental material, Tables S26-30).

The HI of all samples fell within the range from 0.026 to 0.56 (Figure 6). There was a large variation in HI at depth below 50 cm, so we focused comparisons here on peat shallower than this depth as this is also the part of the profile most affected by mounding activities. Core profiles showed different patterns across sites and treatments (Supplemental material, Tables S31-36). At SC3, low-lying areas and natural hummocks increased slightly with depth until 40 cm where greater depths had variable HI. HI for inverted mounds were higher than other cores and did not change throughout 0–40 cm depths. BR1 cores showed a sharp increase in HI from 0–10 cm to 10–20 cm depths. Natural and low-lying cores then sharply decreased back to 0–10 cm values at 20–30 cm while intact mounds and transferred hummocks did not change or slightly increased. At 0–10 cm, the HI of the inverted mounds was higher than the transferred hummocks, and both natural hummocks and low-lying areas ($F_{6,28}$ = 4.21, p = 0.0039). At

10–20 cm, the upright mounds had a higher HI than the natural hummocks and low-lying areas at SC3. SC3 cores had a lower HI than the natural hummocks and BR1 low-lying areas and transferred hummocks ($F_{6,25}$ = 9.46, p < 0.001). At 20-30 cm, the transferred hummocks and upright mounds had a higher HI than the low-lying areas and BR1 natural hummocks ($F_{6,19}$ = 4.76, p = 0.0040).

Figure 7 shows the shape of the aromatic compounds' absorbance peak from FTIR analysis. The middle large peak was used in the calculation of HI and represents the absorbance of lignin, other aromatics, and deprotonated COO^- aromatic/aliphatic carboxylates. The small peak on the right of the middle peak represents the organic acids (protonated COOH) such as carboxylic acids and aromatic esters. As shown in the first two panel columns of Figure 7, this acid peak was reduced or not present for inverted mounds and SC3 low-lying areas for depth intervals 0–10 and 10–20 cm. The acids peak disappears for all depth intervals below 20 cm. The last two panel columns show that the peaks do not change with depth below 20 cm.

Vegetation surveys

Mounding generally increased the cover of bare ground with a significant increase to 48% on inverted mounds (Table 1; $F_{6,65}$ = 13.66, p < 0.001). The inverted mounds also had the lowest moss cover. SC3 low-lying areas had lower moss cover than natural hummocks, BR1 mounding treatments, and low-lying areas ($F_{6,65}$ = 37.97, p < 0.001). Transferred hummocks and natural hummocks had a significantly higher shrub cover than SC3 ($F_{6,65}$ = 5.81, p < 0.001). SC3 low-lying areas had higher graminoid cover than all mounding treatments and natural hummocks at SC3 ($F_{6,65}$ = 3.84, p = 0.0025). For forbs, all types within a site were similar, while SC3 had lower forb cover than BR1 ($F_{6,65}$ = 10.09, p < 0.001). BR1 low-lying areas had higher open water cover than all other cores ($F_{6,65}$ = 5.63, p < 0.001).

Discussion

Substrate Quality

Bulk densities and OM were similar across low-lying areas and natural hummocks. This suggests the soil properties on low-lying areas were able to recover from the disturbance of seismic line creation and that mounding likely resulted in a very localized disturbance on the mounds. A lack of compaction and no loss of OM content on seismic lines conflicts with previous research (Lee & Boutin, 2006; Dabros et al., 2018; Lovitt et al., 2018; Davidson et al., 2020) but matches the previous sampling at the study sites (Kleinke, 2021). Although the heavy machinery used in seismic line creation can cause compaction, boreal seismic lines are constructed in the winter when the ground is frozen to facilitate equipment access and reduce compaction. A common cause of seismic line disturbance after the initial creation is human use for recreational activities (Dabros et al., 2018). Without further disturbance, compacted peat has been shown to recover naturally within 15 years after disturbance (Lepilin et al., 2019). SC3 and BR1 seismic lines are all at least 34 years old at the time of sampling, allowing for many years of peat volume recovery.

Recently made mounds would not have recovered from the disturbance caused during the restoration treatment. Inverted mounding had significantly higher bulk density than all other cores at the 0–10 and 10–20 depth intervals. Although bulk densities could not be calculated for the hummock transfer treatment, their bulk density would be expected to be similar or slightly lower than natural hummocks due to the mechanism of how the hummocks are collected and transferred. The higher bulk densities of the inverted mounds would have various impacts linked to hydrology, gas exchange, soil stability, and microbial communities. The major structural impact of higher bulk densities is a decrease in macroporosity. Lower macroporosity results in increased water retention and unsaturated hydraulic conductivity and decreased gas exchange (Frey et al., 2009; Gauthier, McCarter, & Price, 2018). A bulk density of 0.2 g/cm^3 has been presented as a critical threshold for identifying degraded peat (Liu & Lennartz, 2018). Additionally, starting at a 15% increase, higher bulk density has been found to negatively impact soil microbes, increase water retention, and decrease gas exchange (Frey et al., 2009). At SC3, inverted mounding increased bulk density by an average of 541% and 324% for 0–10 cm and 10–20 cm depths, respectively. These changes may cause the peat to become waterlogged and anoxic, which would inhibit the growth and survival of both microbial and vegetation communities (Kozlowski, 1999; Frey et al., 2009). These structural changes are also linked to peat collapsing, which is a common issue with mounding in peatlands (Kool, Buurman, & Hoekman, 2006; Lieffers, Caners, & Ge, 2017; Filicetti et al., 2019). While inverted mounds were heavily compacted, upright mounding bulk densities were comparable to natural conditions. The unaffected bulk densities of the upright mounding may provide an advantage in vegetation recovery and mound persistence over the inverted mounding.

The inverted mounding method also resulted in significantly lower OM content, while upright mounding and hummock transfer had similar OM to natural hummocks and low-lying areas. The preservation of OM and moss cover on upright mounds and transferred hummocks may also be advantageous as it reflects the preservation of the moss layer and less decomposed peat. Moss cover on inverted mounds was 16 ± 7% compared to 96 ± 2% on upright mounds and 92 ± 5% on transferred hummocks. While the exposure of mineral soil and removal of the moss layer has been found to increase seedling growth (Lafleur et al., 2011b), small disturbances of the moss layer without exposing mineral soil have also been found to increase seedling growth (Lafleur et al., 2011a). Seedling growth was increased after gently disturbing the moss layer as a result of increased nutrient availability and reduced competitive shrub cover (Lafleur et al., 2011a). In both papers, 2-year-old black spruce seedlings were used. Upright mounding may result in a similar disturbance as in Lafleur et al. (2011a) as the shrub and graminoid cover decreased slightly (Table 1). Transferred hummocks did not show a decrease in shrub cover but did show a reduction in the graminoid cover. Decreasing the shrub and graminoid cover can promote tree survival and growth by removing competition (Nelson & Jobidon, 2011; Bilodeau-Gauthier et al., 2011). The disturbance of upright mounding may be sufficient in promoting tree growth without large changes in substrate quality from the exposure of mineral soils and deeper peat and with preservation of much of the ground layer plant community, but further research on the growth of trees on the mounds is needed to evaluate this.

In Lafleur et al. (2011a) and Lafleur et al. (2011b), the increases in seedling growth were attributed to comparably lower C/N ratios due to an increase in N, specifically NH_4^+ (Lafleur et al., 2011a; Lafleur et al., 2011b). While available and foliar nutrients were not measured in this study, lower C/N ratios driven by increases in TN were observed for both inverted and upright mounds at 0–20 cm depth (Figure 4) with only changes at the inverted mounds being statistically significantly lower than low-lying areas. Lower C/N ratios are associated with N availability and can promote tree growth, but too low C/N ratios indicating C limitations negatively affect vegetation growth and survival, availability of nutrients, and microbial activity (Asada, Warner, & Schiff, 2005). More in-depth research on available nutrients and limitations would be required to determine how lower C/N affects vegetation recovery on seismic lines.

Previous studies on logged peatlands would suggest that seismic lines may have lower C/N ratios from loss of dissolved organic carbon due to flooded conditions and leaching (Trettin et al., 2011; Kim et al., 2014). The similar TC among treatments and depths suggests this did not occur (Figure 4), yet the quality of the carbon present was likely affected. FTIR analysis of peat showed how the abundance of different C compounds changed between and within cores. A higher HI represents a higher degree of decomposition as carbohydrates are preferentially lost (Cocozza, et al., 2003; Broder et al., 2012; Biester et al., 2014; Hodgkins, 2016). The HI for the top 40 cm of peat was highest for inverted mounds. Upright mounds and transferred hummocks only had elevated HI for the 20–30 cm depths, otherwise, BR1 cores were comparable at shallower depths. In addition to HI, the shape of the FTIR absorbance can be used to assess substrate quality. The merging of aromatic peaks seen for the inverted mounds and low-lying areas is indicative of the loss of easily decomposed compounds during aerobic decomposition (Cocozza, et al., 2003). Although inverted mounds did not lose TC, inverting the peat profile likely increased the amount of recalcitrant C compounds and decreased labile C compounds. This may negatively impact restoration efforts as increases in recalcitrant C compounds have been observed to lower substrate quality by limiting microbial and plant growth and survival (Asada, Warner, & Aravena, 2005).

Isotopic data indicate reduced substrate quality on the inverted mounds. $\delta^{13}C$ and $\delta^{15}N$ can be used as decomposition indicators as lighter isotopes are preferentially lost during decomposition (Broder et al., 2012; Biester et al., 2014). $\delta^{13}C$ in the inverted mound cores was heavier in the top 30 cm but the difference was not statistically significant. $\delta^{15}N$ was also constant with depth for the inverted mounds. Constant $\delta^{13}C$ and $\delta^{15}N$ at depth can result from moderate disturbance while intensive disturbance has been shown to cause surface $\delta^{13}C$ and $\delta^{15}N$ to be heavier than greater depths (Krüger et al., 2015). All other cores became heavier with depth until around 30 cm, below which $\delta^{13}C$ and $\delta^{15}N$ became constant. This is consistent with other studies as $\delta^{13}C$ and $\delta^{15}N$ should become heavier as decomposition proceeds through the peat profile until lower depths where decomposition stops or is greatly reduced (Broder et al., 2012; Biester et al., 2014; Krüger et al., 2015). As with bulk density and OM, stable isotopes were only impacted by inverted mounding while upright mounding and hummock transfer maintained patterns observed in undisturbed hummocks.

Decomposition

The shift of labile to recalcitrant OM and lighter to heavier stable isotopes on mounds could be from the exposure of deeper, more decomposed peat or because of increased decomposition rates following mounding. Peatlands are characterized by low decomposition rates under anoxic conditions (Limpens et al., 2008). At both BR1 and SC3, $\delta^{13}C$ and $\delta^{15}N$ show an aerobic zone in the top

0–20 cm where decomposition rates could be increased by shifting from slower anaerobic to aerobic decomposition. In water-saturated peatlands, $\delta^{13}C$ and $\delta^{15}N$ would be expected to be constant at depth with little decomposition and fractionation occurring (Krüger et al., 2015; Drollinger, Kuzyakov, & Glatzel, 2019). Anaerobic decomposition of ^{13}C enriched lignin can result in lighter $\delta\,^{13}C$, but decomposition rates are often too slow to show changes in $\delta\,^{13}C$ (Drollinger, Kuzyakov, & Glatzel, 2019). Stable isotopes vary with depth within the cores. In the top layers of peat, isotopes become steadily heavier then remain constant at depths below 20–30 cm. This suggests aerobic decomposition is occurring in the top 0–20 cm.

Trends in TN with depth also support a zone of aerobic decomposition in the top 0–20 cm. As with the stable isotopes, TN is normally constant in peatlands due to anoxic conditions from waterlogged peat (Kuhry & Vitt, 1996). However, TN can increase during decomposition due to inputs from microbe biomass after microbial N immobilization (Malmer & Holm, 1984; Damman, 1988). The inverted mounds and low-lying areas had higher TN than the natural hummocks up to 60 cm but the increase in TN was only significant in the top 20 cm. Upright mounding also had slightly higher TN than other cores in the top 20 cm. Consistent with the stable isotope data, the increase in TN suggests aerobic decomposition is occurring in at least the top 20 cm.

In addition to water-saturated conditions, decomposition in peatlands is slowed by its inhibition by organic acids ($R\text{-}COO^-$) produced by *Sphagnum* (Mellegård et al., 2009). FTIR analysis showed a decrease in organic acids for the top 20 cm of inverted mounds. The disappearance or decrease in the acids peak is representative of deep peat samples or a higher pH closer to neutral (Hodgkins et al., 2018). This decrease in organic acids may support higher rates of decomposition in the surface of inverted mounds.

Mounds may be able to support higher rates of decomposition with aerobic conditions and decreases in organic acids. To determine if decomposition rates were increased on mounds, decomposition indicators of the mound peat were compared to deeper peat. If peat on the mounds matches conditions in deeper peat, changes in soil properties would be from the exposure of deeper peat and not increased decomposition rates. Bulk density and OM content showed a clear threshold for inverted mounding. At the beginning of the mound interface, 40 cm below the surface, both bulk density and OM content were similar to surrounding natural values. As the highest bulk density for inverted mounds was at 0–30 cm depths, further compaction would have occurred on mounds beyond that caused by exposure of deep peat alone. Further compaction may occur during mounding as operators use the backhoe bucket to push down onto the mounds with the aim of increasing mound persistence. Despite not being statistically significant due to high variability between cores, there was also a potential loss of OM content on the mounds. The average OM content for the top 30 cm of the inverted mounds was 84.2% while the 30 cm below the mounds had an average of 90.6%. This suggests a loss of OM to decomposition in addition to mechanical compaction of the mounds.

Unlike bulk density and OM, C/N ratios were lower on both mounds and low-lying areas. The lower C/N ratios at low-lying areas at SC3 and on upright mounds indicate further changes to peat properties past the exposure of deeper peat and mineral soils. The top layers of peat in low-lying areas and upright mounds should consist of younger peat that should reflect high C/N ratio litter inputs from vegetation (Malmer & Holm, 1984; Biester et al., 2014). C/N ratios decrease as decomposition occurs (Malmer & Holm, 1984), which suggests that decomposition rates may be increased above natural conditions for both mounds and low-lying areas. Direct measurements of litter decomposition, litter inputs, and soil respiration are needed to better quantify changes in C cycling and decomposition rates following seismic line disturbance and restoration by mounding.

Implications of restoration

Out of the three mounding treatments evaluated, the classic method of inverted mounds showed the most differences in peat properties to the natural hummocks. The inversion of the peat profile introduced significant bare ground cover and greatly reduced moss cover. Inverted mounds had higher bulk densities, lower OM, heavier stable isotopes, more recalcitrant C compounds, and lower C/N ratios. The degree of these changes combined with the evidence of increased decomposition indicates lower substrate quality on the inverted mounds. The high bulk densities of the inverted mounds may have further implications for hydrological conditions resulting in more waterlogged and anoxic microsites instead of the desired drier and aerated microsites that are beneficial for tree establishment and growth.

Disturbance during mounding and subsequent oxic conditions in mounds may be able to support higher rates of decomposition indicated by trends in stable isotopes and TN. Inverted mounds specifically also showed decreases in decomposition-inhibiting organic acids. Changes in peat properties along depth profiles of inverted mounds that were greater than those expected from the inversion of the peat profile alone, which suggests an increase in decomposition in response to mounding. At SC3, C/N ratios were lower for both mounds and low-lying areas where there was no exposure of deeper peat, which indicates increased decomposition may not be isolated to mounds but occurring throughout the line.

Newly tested upright mounding and hummock transfer techniques were found to not add costs or time to the classic mounding. The same equipment and operators, with minimal, in-field instruction, were able to employ new mounding techniques in comparable time to the classic mounding. The newer treatments also showed minimal changes to peat properties on both mounds and low-lying areas. Transferred hummocks showed no differences from natural hummocks while upright mounding had slightly lower C/N ratios. While lower C/N ratios are indicative of disturbance and lower substrate quality, lower C/N may be beneficial for tree growth with potentially higher N availability. Vegetation communities that were similar to natural conditions on the two upright mounding techniques reflected the lack of changes in soil properties and the preservation of plants during mounding. Additionally, the upright mounds did have a decrease in graminoid and shrub cover that may be important in promoting tree growth by lessening competition. The soil properties and vegetation communities of the different mounding treatments suggest that upright mounds and hummock transfer may provide additional benefits to the whole ecosystem recovery over the inverted mounds, while likely still supporting a return to tree cover. Although more research will be required on long-term effects of restoration such as tree growth and survival, upright mounding and hummock transfer techniques showed advantages over inverted mounding.

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Tables

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

Figures

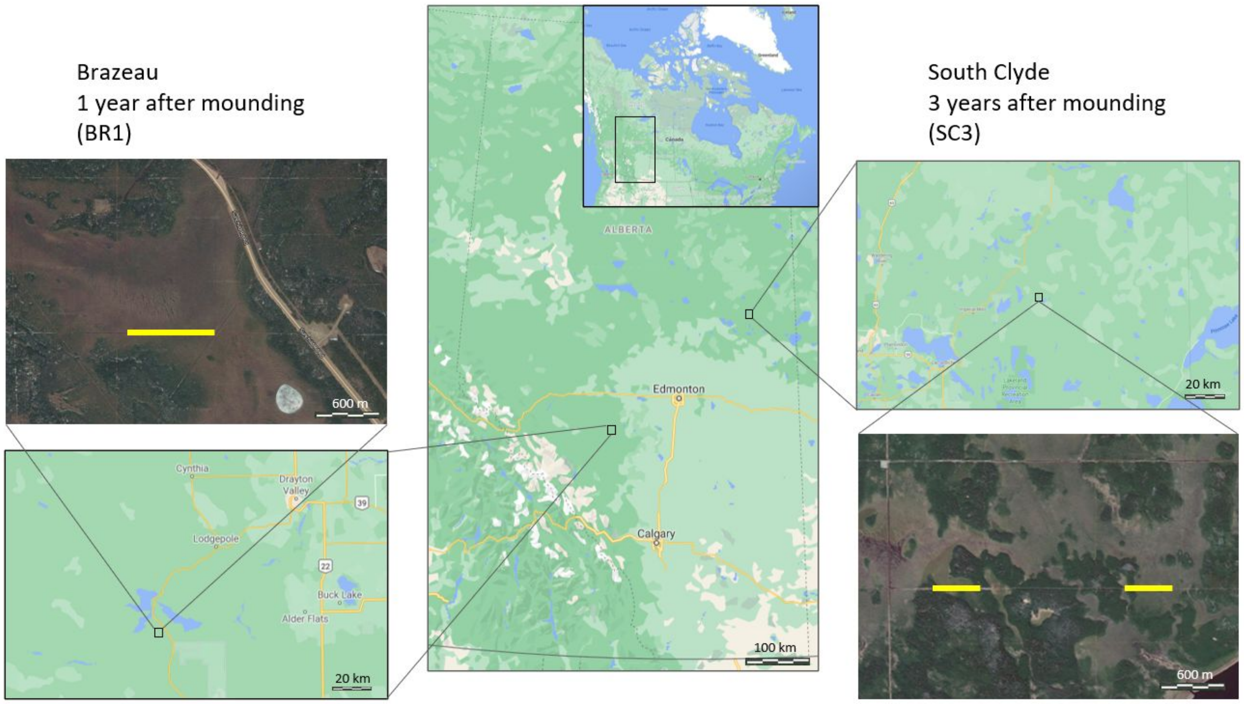


Figure 1: Map of the two study areas in Alberta, Canada. All maps sourced from Google maps available at http://maps.google.ca

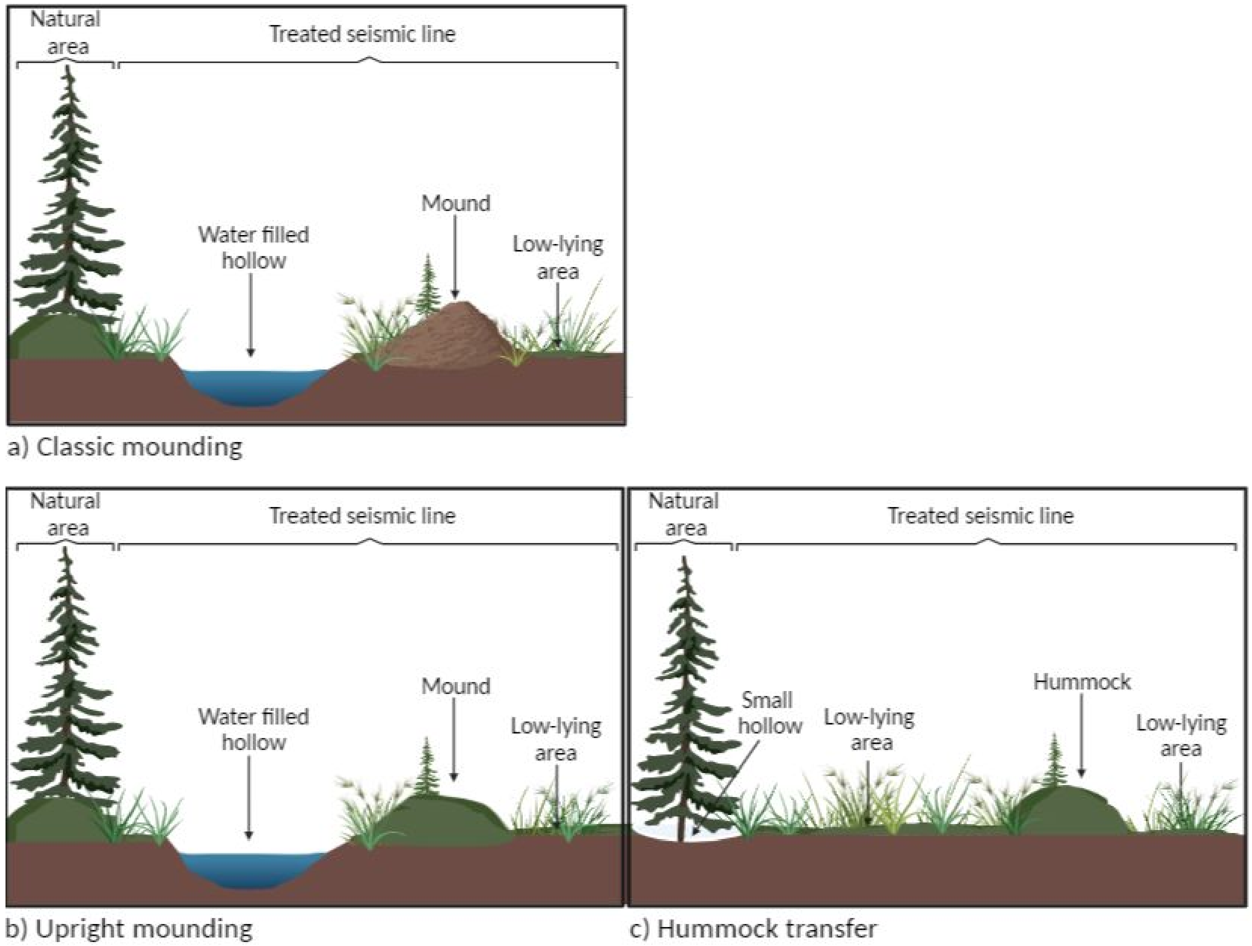


Figure 2: Illustration of different mounding techniques used on seismic lines: a) inverted mounding, b) intact mounding, and c) hummock transfer. Sampled seismic lines were about 6 m wide. Classic mounds were about 50 cm tall while upright mounds and transferred were smaller around 30 cm tall. Created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

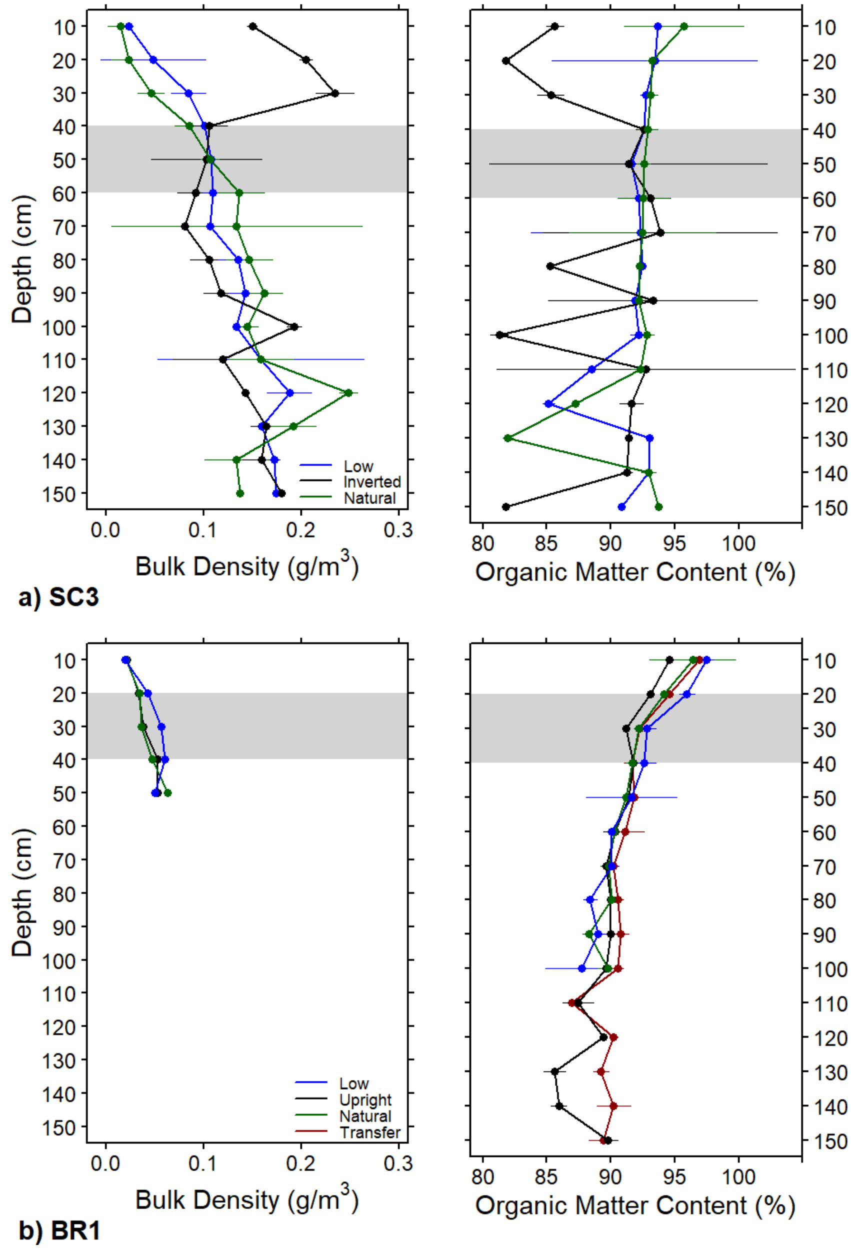


Figure 3: Profiles of bulk density and organic matter content for a) SC3 and b) BR1. When present, error bars represent one standard error. Points without errors bars did not have a large enough sample size to calculate the standard error. Grey bars show the range depth of the interface of the mound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

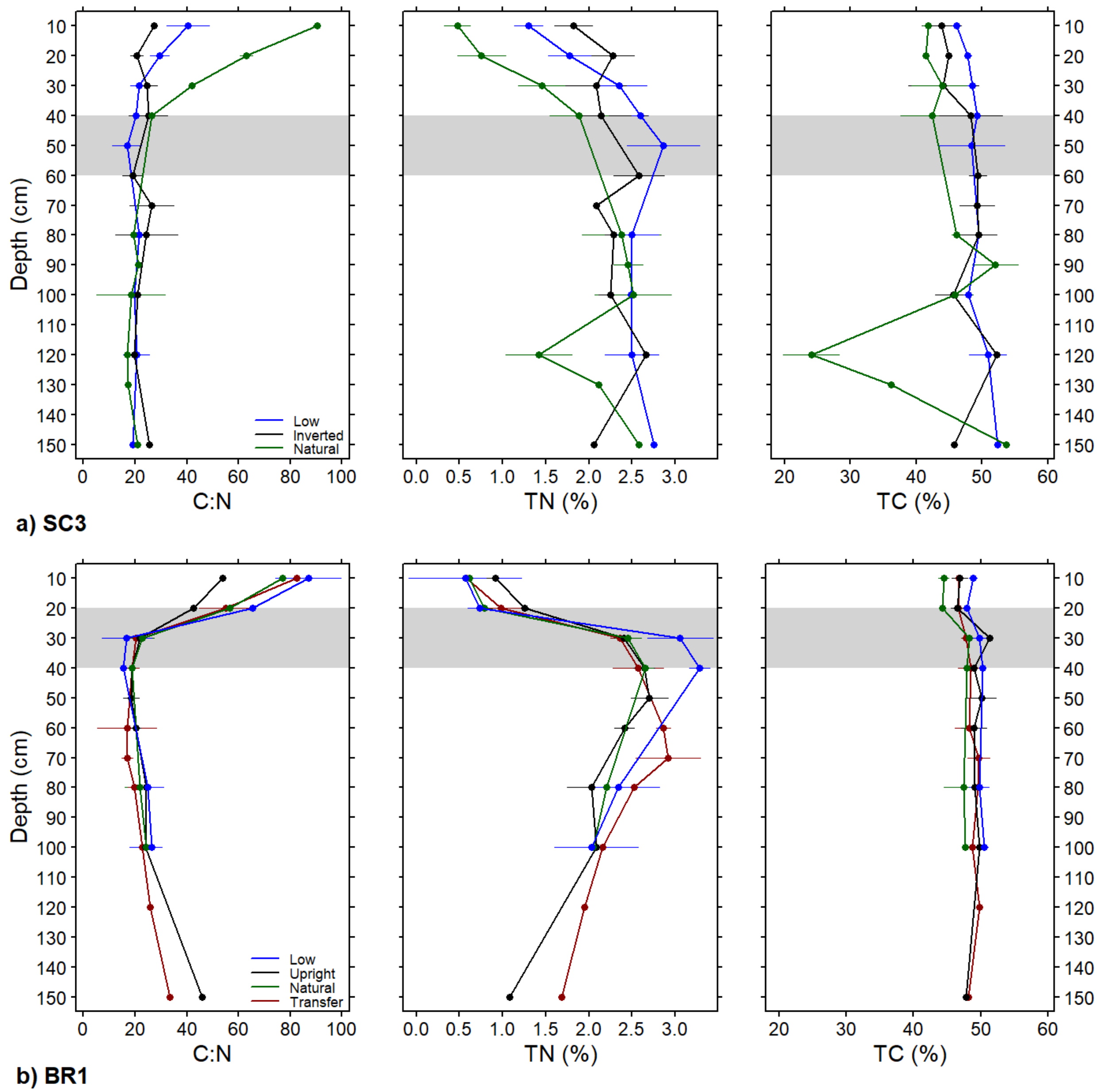
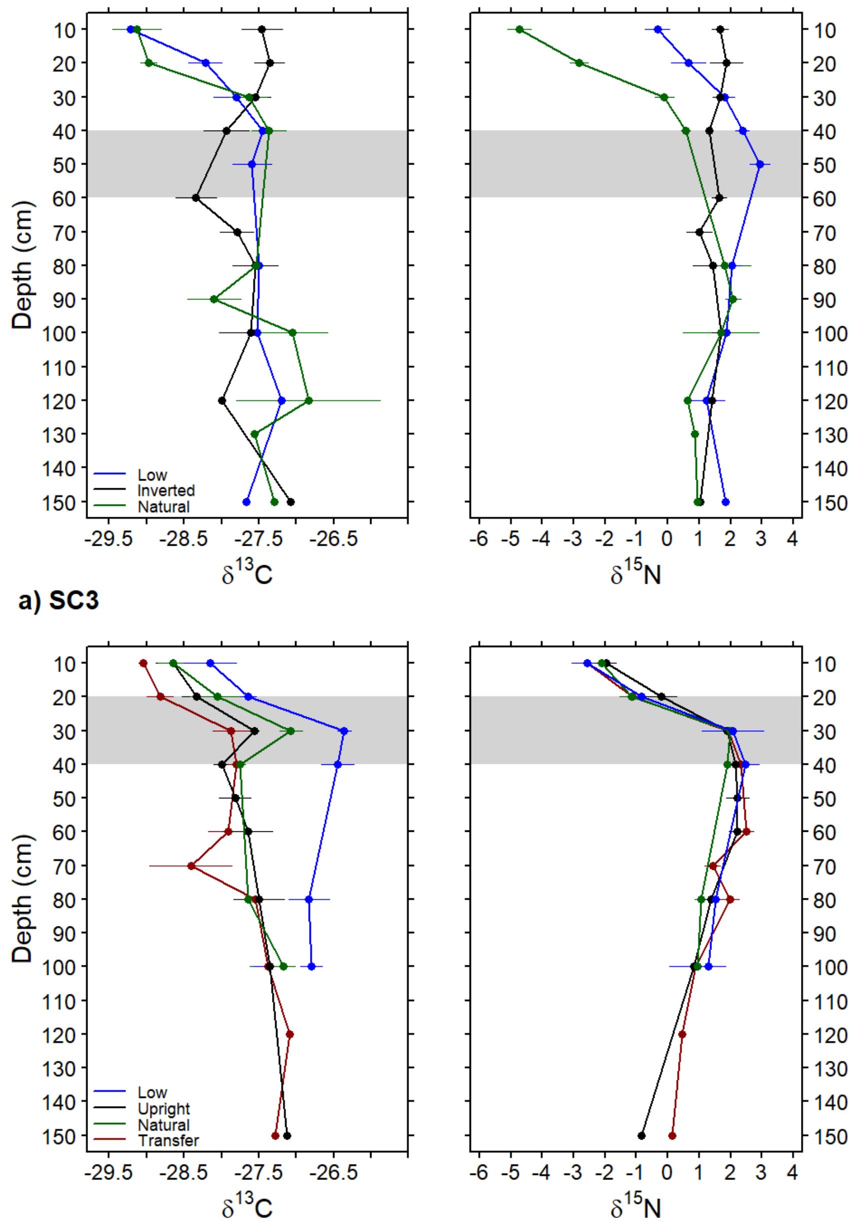


Figure 4: Profiles of C/N, TN, and TC at depth for a) SC3, and b) BR1. When present, error bars represent one standard error. Points without errors bars did not have a large enough sample size to calculate the standard error. Grey bars show the range depth of the interface of the mound to the ground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



b) BR1

Figure 5: Profiles of $\delta^{13}C$ and $\delta^{15}N$ 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.

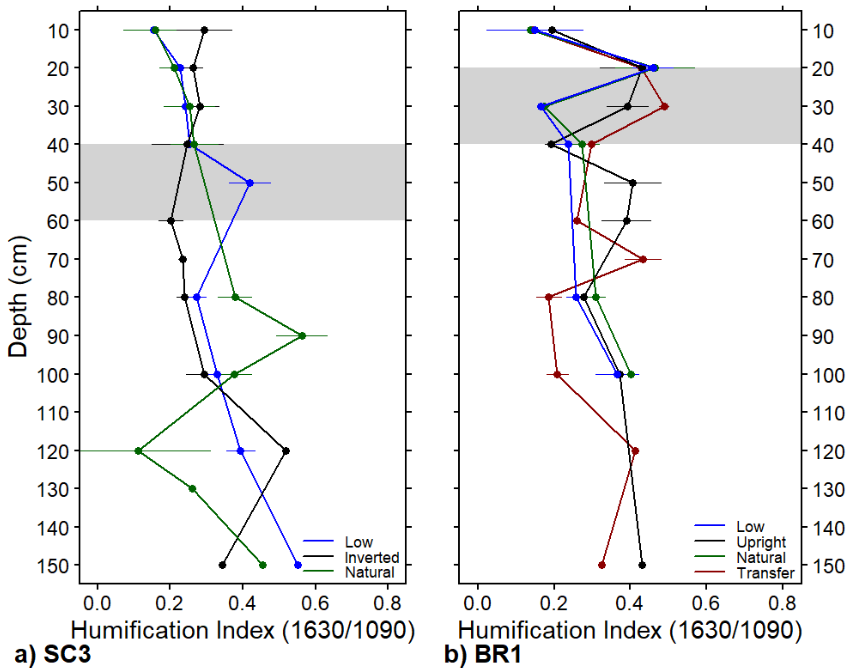
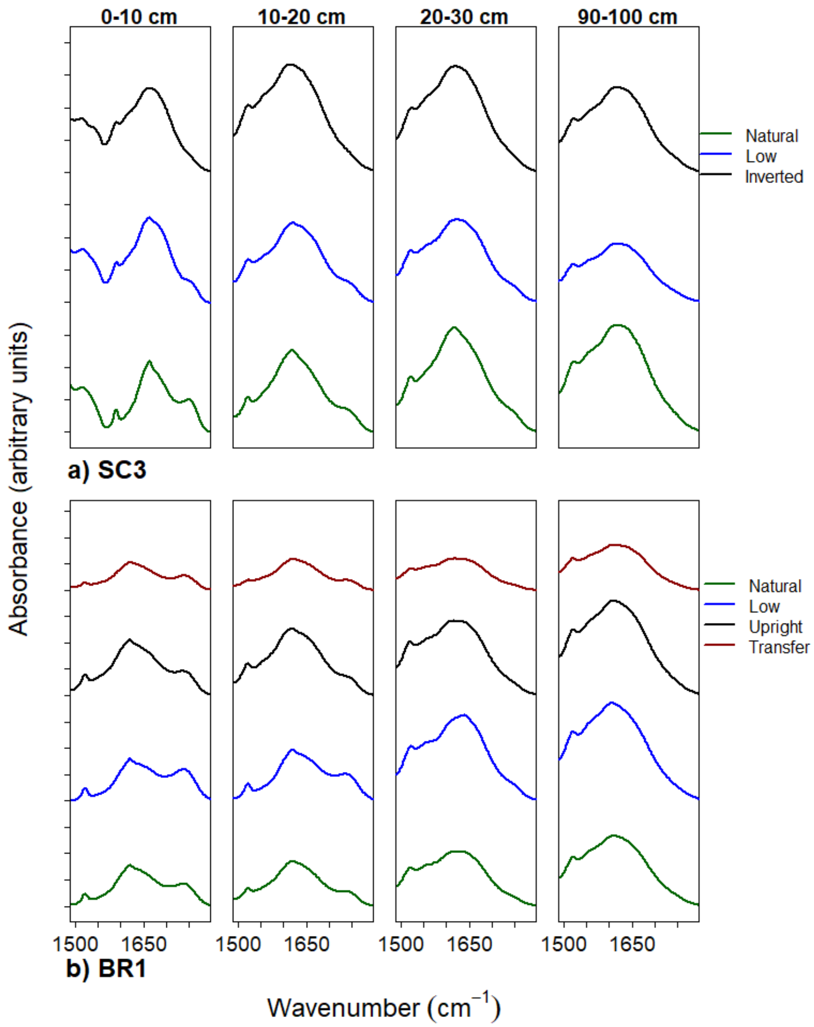


Figure 6: Profiles of humification indices (absorbance at wavenumbers 1630/1090) for a) SC3, and b) BR1. When present, error bars represent one standard error. Points without errors bars did not have a large enough sample size to calculate the standard error. Grey bars show the range depth of the interface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



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

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