

Effects of restoring peatland seismic lines on soil properties in boreal Alberta, Canada

by

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Author's Declaration

This thesis consists of material all of which I authored or co-authored: see Statement of Contributions included in the thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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Statement of Contributions

To reflect the results of this research, this thesis is written in manuscript format. Two independent manuscripts to be submitted for publication are presented as chapters 2 and 3 of this thesis. As a result, repeated information may be included.

Chapter 2 reports on data collected from seismic lines crossing fens near Cold Lake, Alberta in August 2019. Chapter 3 reports on data collected from seismic lines crossing fens near Cold Lake, Alberta in September 2020 and near Brazeau, Alberta in August 2020. S.J. Davidson assisted with both sampling design and execution in 2019 while M. Schmidt, T. Vodopija, and J. Malbeuf assisted with sampling in 2020. M. Strack assisted with the study planning and design as well as manuscript revisions. Each manuscript, including figures and tables, was written in its entirety by K. Kleinke and reviewed by M. Strack.

Abstract

Long, linear disturbances called seismic lines have been and continue to be created through the boreal forest in Alberta for petroleum exploration. Restoration of these seismic lines has shown some success but is often unreliable in peatlands, not resulting in appropriate vegetation recovery. Unrestored seismic lines through peatlands often have a lack of tree cover and shifts in the overall vegetation community. Implications of the lack of tree cover include declining caribou populations due to the increased sight and mobility of predators such as wolves. Additionally, peatlands with seismic lines are observed to shift from important, large C sinks to C sources. The most common restoration method is called mounding; the practice of replicating natural hummocks by digging and building mounds of peat on the lines. The major purpose of the mounds is to create drier microsites for tree growth, which has been successful in upland areas. Mounding methods generally involve inverting the peat profile, which likely exposes older, more decomposed peat. New mounding methods to keep the peat profile intact may prevent changes in peat properties observed with classic, inverted mounding. Understanding the effects of seismic line restoration on soil properties, which in turn drive vegetation recovery, will provide information to better assess the use of mounding techniques.

Effects of mounding on soil properties were determined through analysis of surface (0-10 cm) peat samples from seismic lines crossing fens near Cold Lake, Alberta. Peat samples were taken from inverted mounds restored in different years, adjacent low-lying areas on treated seismic lines, untreated seismic lines, and natural areas in August 2019. Further peat samples were used in an incubation study to determine the effectiveness of easily measured decomposition markers as indicators of C loss from mineralization. Additionally, peat cores were sampled from the same fens near Cold Lake, Alberta, and from another system of seismic lines crossing fens that were restored using new upright mounding and hummock transfer techniques near Brazeau, Alberta. These peat cores were used to compare different mounding techniques.

Overall, the physical and chemical soil properties and results from the incubation study indicated lower substrate quality on the inverted mounds. The goal of drier microsites for improved tree growth was likely not achieved as volumetric water content (VWC) remained higher than both natural hummocks and hollows. The high VWC could be linked to the high bulk densities observed on the mounds as increased compaction increases water retention. Inverted mounds may also have increased decomposition rates as evidenced from the peat cores indicated aerobic conditions and further changes to peat properties past the exposure of deeper peat. While true total carbon (TC) losses on and off mounds were not quantified from the incubation study, $\delta^{13}\text{C}$ and C/N ratios may be able to be used as an indicator of TC loss in the field to better understand C cycling on seismic lines. Low-lying areas on seismic lines with inverted mounds had heavier isotopes and lower C/N ratios than the natural areas. Without the exposure of deeper peat, the change in low-lying areas may be from increased decomposition rates. This was not observed on the lines restored by upright mounding or hummock transfer where low-lying areas were comparable to natural areas. Additionally, only minor, and potentially beneficial, changes to soil properties and vegetation functional group cover occurred on upright mounds and transferred hummocks. Findings from this study suggest potential benefits to soil properties and subsequent vegetation recovery of upright mounding and hummock transfer over the classic, inverted mounding.

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The University of Waterloo acknowledges that much of our work takes place on the traditional territory of the Neutral, Anishinaabeg, and Haudenosaunee peoples. Our main campus is situated on the Haldimand Tract, the land granted to the Six Nations that includes six miles on each side of the Grand River. Our active work toward reconciliation takes place across our campuses through research, learning, teaching, and community building, and is centralized within our Indigenous Initiatives Office.

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Chapter 1 Introduction

Seismic lines are being created through the boreal forest for petroleum exploration at a high density of up to 10 km per 1 km² of forest in northern Canada (Lee & Boutin, 2006). Although seismic line restoration is currently being conducted at a large scale, ecosystem recovery is widely unpredictable and unreliable with seismic lines remaining unforested for decades (Filicetti et al., 2018). The current method of restoration, called mounding, attempts to recreate microtopography with the specific goal to provide drier microsites for tree growth (Filicetti et al., 2018). Mounding in peatlands is especially unreliable with a tendency for mounds to collapse and issues with vegetation recovery to remain (Filicetti et al., 2019; Lieffers, Caners, & Ge, 2017; Echiverri, Macdonald, & Nielsen, 2020). The unreliable success of mounding in peatlands and further implications on vegetation recovery are not well understood. Few studies focused on the changes to soil properties from seismic line creation and subsequent restoration, yet peat soil properties have been shown to influence vegetation re-establishment in other types of peatland restoration (Price et al., 1998). This thesis investigates changes to soil properties on unrestored and restored seismic lines crossing peatlands.

1.1 Implications of seismic lines

The creation and persistence of seismic lines cause shifts in vegetation community composition. Removal of trees and flooding at other disturbed peatlands caused the vegetation community to shift to a higher cover of vascular plants than mosses (Locky & Bayley, 2007). There has been a disappearance of native conifers such as *Picea mariana* and *Larix laricina* on flooded, disturbed peatlands (Asada, Warner, & Schiff, 2005). Similarly, across 628 townships in northeastern Alberta, only 8.2% of seismic lines were found to recover over 50% of original woody vegetation cover after 35 years (Lee & Boutin, 2006). Instead, more disturbance-tolerant species such as *Salix* spp., *Betula* spp., ericaceous shrubs, and hollow forming *Sphagnum* mosses such as *S. fallax* dominate (Finnegan et al.,

2018; Asada, Warner, & Schiff, 2005; Locky & Bayley, 2007). The cause behind this lack of recovery has yet to be explained with low competition for plants and proximity to healthy forests providing a healthy seed bank (Filicetti et al., 2018). This is an on-going and rapidly growing concern with more than 60% of seismic lines over the last 30-40 years remaining in the early stages of succession with very little woody vegetation recovery and reduced ecosystem productivity (Dabros et al., 2018; Lee & Boutin, 2006). The lack of natural tree regeneration on seismic lines is strongly linked to the presence of fens and flooded conditions (van Rensen et al., 2015). Predictive modeling suggests that about one-third of seismic lines will not recover, judged by reaching 3 m vegetation height, even after 50 years (van Rensen et al., 2015).

The implications of unrestored seismic lines are broad with both global and regional impacts. On a global scale, seismic lines have been found to contribute to climate change. There is a consensus in the literature that seismic lines, especially those through peatlands, are shifting from a carbon sink to a carbon source (Dabros et al., 2018). This shift can be attributed to multiple factors. The first being the loss of carbon (C) storage through the loss of trees and lack of regrowth (Filicetti et al., 2018). There is also a loss of soil C storage as the disturbance of peatlands has been found to increase both carbon dioxide (CO₂) and methane (CH₄) emissions (Asada, Warner, & Schiff, 2005). In northern boreal regions, loss of soil C storage is amplified by increased permafrost thaw through warmer, exposed soils, and increased albedo effect with more exposed snow (Dabros et al., 2018).

A major, regional impact gaining public interest is the decline of the already threatened woodland caribou. Caribou populations are suffering greatly from the failure of seismic line restoration due to declining habitat and increasing predation, which has been observed to be the greatest factor in caribou survival (Finnegan et al., 2018). There are an increasing number of wolf-caribou encounters as

wolves utilize the seismic lines for hunting, with wolves gaining advantage with greater speeds and visibility on the straight and flat lines (Finnegan et al., 2018).

1.2 Seismic line restoration

Restoration can have many different goals and measures of success. The commonly applied current method of restoration in peatlands, mechanical mounding, focuses on restoring microtopography to encourage woody vegetation regrowth and ultimately protect caribou populations. Microtopography is flattened on seismic lines from heavy machinery causing peat compaction and does not recover over decades (Stevenson, Filicetti, & Nielsen, 2019). Recreating the microtopography has been shown to increase tree seedling growth and survival in upland areas by providing drier microsites (Filicetti et al. 2019). The mounds also provide a physical deterrent to both wolves and caribou using seismic lines.

Mounding is currently the most used and best studied seismic line restoration technique. Using a backhoe, 1 m by 1 m mounds of peat are created to promote drier microsites for improved seedling survival and growth (Filicetti et al., 2019). Mounding has been observed to increase tree regeneration in both upland areas and peatlands (Filicetti et al., 2019; Lieffers, Caners, & Ge, 2017; Bilodeau-Gauthier et al., 2011). Additionally, these mounds may have benefits for nutrient cycling through increased temperature and aeration (Nelson & Jobidon, 2011). However, the success of mounding is variable with peatlands having the least success with most mounds collapsing within a few years (Filicetti et al., 2019; Lieffers, Caners, & Ge, 2017). Peatland type is known to effect vegetation recovery on both untreated and treated seismic lines. Fens are less likely to support natural conifer regeneration than bogs due to higher water tables and more flooding (van Rensen et al., 2015). Out of bogs, poor fens, rich fens, and poor mesic sites, poor fens showed the least success after mounding with significantly lower tree regeneration rates potentially due to higher lichen and graminoid cover (Filicetti et al., 2019). In

addition to a lack of success in restoring peatlands, mounding may also shift the recovering vegetation community away from the surrounding undisturbed state. Untreated seismic lines lack woody vegetation recovery but can support indicator species that suggest recovery towards surrounding undisturbed reference areas (Echiverri, Macdonald, & Nielsen, 2020). In low-impact, narrow seismic lines, mounding was found to alter this trajectory with vegetation communities different from reference areas (Echiverri, Macdonald, & Nielsen, 2020).

Despite potential issues, mounding remains the most promising method of seismic line restoration. However, changes to this method may be required to ensure restoration success. Current research advances include creating upright mounds with an intact peat profile and transferring natural hummocks onto seismic lines (Xu, 2019). The usual mounding technique essentially flips over the peat to bury any vegetation that has grown on the seismic lines. This is thought to further set back succession by exposing bare, recalcitrant peat. Additionally, flipping over the mounds increases peat compaction and decreasing stability, which could lead to the collapse of most mounds (Davidson et al., 2020). By keeping mounds intact and upright, any vegetation already growing can continue to survive and stabilize the peat while keeping the benefits of the other technique of mounding. Another potential improvement to mounding is using natural hummocks from the surrounding area. This could provide additional benefits as it would move in the desired species as well as prevent holes from being created to make the mounds. Issues with hummock transfer include disturbing natural areas, transferring only moss and not appropriate peat substrate for seedling establishment, and the transferred hummocks may also flatten, losing some benefits of mounding.

There are significant research gaps in the effects of seismic lines on the disturbed peatlands and how this impacts restoration success. Along with the general lack of understanding of the effects of seismic lines and their restoration, research gaps exist with little or no structured monitoring connected

to the goals of recovery and no reliable way of predicting future recovery probabilities and trajectories (Dabros et al., 2018). Recently, however, there has been a renewed effort to reclaim seismic lines with the goal of regenerating forest cover due to the many implications of failed seismic line reclamation (Dabros et al., 2018).

1.3 Peat soil properties

A main difference between peatlands and uplands that could possibly be contributing to the lack of restoration success is soil moisture. Waterlogged conditions, a defining feature of peatlands, create anoxic conditions where anaerobic decomposition dominates (Limpens et al., 2008). A higher water table is generally known to decrease faster aerobic decomposition and increase slower anaerobic decomposition as an increase in the water table reduces the active, oxic layer of peat. (Gazovic et al., 2013; Beer & Blodau, 2007).

In pristine peatlands, the loss of carbon in peatlands through decomposition is very slow and outweighed by primary productivity (Limpens et al., 2008). An increase in the water table, as expected to occur on seismic lines, generally decreases primary productivity and production of litter due to shifts in vegetation communities (Strakova et al., 2012). The primary productivity of trees has been observed to decrease with increasing water tables causing high oxygen stress on roots (Dimitrov et al., 2014). Although mosses responded positively to higher water tables with increased primary productivity, high water tables overall decrease ecosystem primary productivity (Dimitrov et al., 2014).

Soil compaction from machinery used in the creation and restoration of seismic lines is a well-known cause of soil degradation. In one study, seismic line creation on average flattened microtopography by 46 cm, and mean water table depth decreased by 15.4 cm (Lovitt et al., 2018). Natural recovery of compacted peat was found to occur within 15 years after disturbance in logged peatlands (Lepilin et al., 2019). However, the few studies of compaction on seismic lines indicate that

they have not seen this recovery of compacted peat (Davidson et al., 2020; Lovitt et al., 2018; Dabros et al., 2018; Lee & Boutin, 2006).

Peat compaction is strongly interlinked with hydrological parameters that have implications for plant growth. Compaction decreases microporosity in the peat, which increases bulk density (Frey et al., 2009). A higher bulk density increases water retention and decreases hydraulic conductivity (Frey et al., 2009; Gauthier, McCarter, & Price, 2018; McCarter et al., 2020). Higher bulk densities also reduce gas exchange due to decreases in porosity and increases in pore tortuosity (McCarter et al., 2020; Lepilin et al., 2019). This results in more waterlogged, anoxic peat (Lepilin et al., 2019). Due to anoxic, waterlogged conditions and high soil strength seed germination and plant growth is limited in compacted soils (Kozłowski, 1999). In compacted soils, conifer seedlings showed reductions in rooting volumes and ectomycorrhizal fungi, which would reduce N uptake (Page-Dumroese et al., 1998).

Soil quality is potentially degraded by the creation of seismic lines and subsequent loss of labile C and available N and P from leaching and runoff on the flooded lines. C/N ratios can be used to determine substrate quality as they can control vegetation growth and available nutrients (Asada, Warner, & Schiff, 2005). C/N ratios of peat have long been used to determine levels of decomposition (Malmer & Holm, 1984; Biester et al., 2014). Generally, C is preferentially lost as decomposition occurs while N remains relatively constant in peatlands (Malmer & Holm, 1984). Flooding of peat has been found to cause a rapid release of dissolved organic carbon (DOC) from litter through decomposition and leaching within the first three weeks (Kim et al., 2014). The loss of DOC in the Kim et al., 2014 study and another study on the long-term impacts of logged peatlands indicated that there should be lower peat C/N ratios and more recalcitrant C on seismic lines (Trettin et al., 2011). Along with hydrology, peat compaction on seismic lines and logged peatlands has implications on C/N ratios. Increasing peat

compaction is linked to decreasing C/N ratios in peat (Liu et al., 2019). With the loss of DOC and increased compaction, seismic lines likely have lower peat C/N ratios than the surrounding area.

There are potentially contradicting factors at play on seismic lines relating to altered C cycling and vegetation recovery. An increase of recalcitrant C with the loss of DOC and decreased decomposition in waterlogged conditions was found to decrease substrate quality, microbial activity, and plant growth and survival (Asada, Warner, & Schiff, 2005). While more recalcitrant C will lower soil quality, lower peat C/N ratios may have a positive impact on vegetation recovery as this has been shown to promote seedling growth (Lafleur et al., 2011a). In order to further investigate changes in soil quality and organic matter decomposition status on seismic lines in peatlands, indicators of decomposition status may provide insight.

Stable isotopic composition, such as $\delta^{13}\text{C}$, can be used as an indicator of decomposition. $\delta^{13}\text{C}$ is closely tied to decomposition and has been found to be highly correlated with other decomposition markers such as bulk density and C/N ratios (Biester et al., 2014; Alewell et al., 2014). Selective loss of ^{12}C occurs during decomposition (Nadelhoffer & Fry, 1988). $\delta^{15}\text{N}$ is a less reliable indicator of decomposition. Like $\delta^{13}\text{C}$, $\delta^{15}\text{N}$ can become heavier with decomposition due to preferential loss of the lighter isotope (Asada, Warner, & Aravena, 2005). However, different studies have found $\delta^{15}\text{N}$ to become lighter with decomposition (Hobbie, Macko, & Shugart, 1998) or remain unchanged (Biester et al., 2014). One possible explanation for different $\delta^{15}\text{N}$ responses to decomposition is the difference in fractionation between fungal and bacterial decomposition. Litter decomposition driven by fungi has been found to produce byproducts with heavier $\delta^{15}\text{N}$ while bacteria can decrease $\delta^{15}\text{N}$ through ^{15}N depleted nitrate immobilization (Bragazza et al., 2010). Another study found N recycling processes and plant uptake overrode any effects of decomposition on $\delta^{15}\text{N}$ (Biester et al., 2014).

Lastly, Fourier transform infrared spectrometry (FTIR) can be used to assess substrate quality. Absorbance bands in FTIR spectra can be used to show relative abundances of major organic compounds such as carbohydrates, aromatics like lignin, and aliphatics such as lipids, fats, and waxes (Hodgkins, 2016). Humification indices, ratios of recalcitrant compounds to easily decomposed carbohydrates, have been shown to represent the degree of decomposition as carbohydrates are preferentially lost (Cocozza, et al., 2003; Broder et al., 2012; Biester et al., 2014; Hodgkins, 2016).

1.4 Potential carbon loss from seismic lines

As mentioned above, restoration goals vary and may contradict each other. With the current focus on restoring woody vegetation cover, the implications of carbon loss from seismic line restoration may be overlooked. Although peatlands are generally thought to be large carbon sinks due to peat accumulation, they are also a source of significant amounts of CH₄ (Wu et al., 2012). There are several natural and anthropogenic sources of CH₄, with wetlands contributing about one-third of global emissions (Zhang et al., 2017). Due to constant waterlogged conditions in peatlands, microbes produce high concentrations of CH₄ through the anaerobic process of methanogenesis; this CH₄ is transported to the atmosphere by gas diffusion, ebullition, and pathways via plants (Limpens et al., 2008). Carbon can also be lost from the system through leaching and runoff of DOC, a product released from decomposition and plant roots (Gazovic et al., 2013). In pristine, undisturbed peatlands, CH₄ emissions are outweighed by the accumulation of soil C (Wu et al., 2012). However, after disturbance and even years after restoration, peatlands have been found to be C sources (Wu et al., 2012). Additionally, recent research suggests global climate change and seismic line disturbance may cause peatlands to lose their carbon storage potential and become carbon sources (Limpens et al., 2008; Dabros et al., 2018). This could create a positive feedback loop with seismic lines contributing to climate change through increased permafrost thaw and carbon loss and increasing climate change accelerating seismic line degradation (Dabros et al., 2018).

Seismic lines have been predicted and observed to have increased CH₄ emissions due to higher temperatures, shallower water tables, and changes in vegetation communities (Strack et al., 2018; Strack et al., 2019; Lovitt et al., 2018; Turetsky et al., 2014). Increasing temperatures stimulate decomposition and the release of both CO₂ and CH₄ (Asemaninejad et al., 2018; Leroy et al., 2017). However, the increase in the water table on seismic lines would likely decrease aerobic decomposition and increase anaerobic decomposition as an increase in the water table reduces the thickness of the oxic layer of peat. (Gazovic et al., 2013). While seismic line conditions would promote CH₄ emissions, CO₂ emissions may be inhibited by a lack of oxic peat.

Vegetation communities also play an important role by supplying C compounds for decomposition through litter inputs. Decomposability of litter differs among functional groups and plant species; decomposability decreases from herbs to graminoids to feather mosses to *Sphagnum* mosses (Strakova et al., 2012). Declining decomposability depends on chemical composition including nutrient, lignin, and cellulose content (Strakova et al., 2012). Shifting vegetation communities on seismic lines may be increasing labile C inputs with increased graminoid cover and decreased moss cover. Vegetation mediated transport of CH₄ also varies among species with graminoids providing increased transportation pathways (Askear et al., 2011). With an increased supply of labile C and transport, wetlands dominated by graminoids have been observed to have the highest CH₄ emissions (Turetsky et al., 2014).

Currently, studies regarding CO₂ and CH₄ emissions from mounded seismic lines are lacking. Mounding would alter conditions by creating drier, more aerated microsites. This may result in an increase in CO₂ emissions that were previously inhibited by flooded conditions and a decrease in CH₄ emissions. Low-lying areas around the mounds and holes created from the mounding process may be larger sources of CH₄ due to flooded conditions. Mounding exposes deeper peat, which may increase or

decrease decomposition. The exposure of deeper peat would provide a lower quality substrate with less labile C (Leifeld, Steffens, & Galego-Sala, 2012), which is further limited with the removal of vegetation during the mounding process. However, decomposition at depth is also limited by the lack of oxygen, and increased aeration and temperature on the mounds may allow for decomposition of the exposed recalcitrant C (Beer & Blodau, 2007; Leifeld, Steffens, & Galego-Sala, 2012).

1.5 Research objectives

Investigating the impacts of seismic line restoration on soil properties will provide important information for understanding and determining restoration success. The major goal of mounding, vegetation recovery with an emphasis on tree growth, is highly dependent on substrate quality as determined by soil chemical and physical properties. Maintaining peatlands' carbon storage is another important goal of restoration. With the difficulty of measuring C loss on remote seismic lines, soil properties such as C/N ratios and stable isotopes that can act as decomposition indicators could be useful as indicators of C loss. In addition to a lack of understanding of how soil properties change on seismic lines and with restoration, the cause of these changes is not known. Peat processes such as decomposition or the inversion of the peat profile during mounding may result in changing peat properties. With current methods of mounding resulting in variable and unpredictable restoration success, new methods of mounding may provide more or different benefits. Therefore, this study aims to provide an understanding of changes to peat soil properties on seismic lines from different methods of mounding. The main objectives of this study are to:

1. Determine changes, relative to undisturbed peatlands, to physical and chemical soil properties on restored and unrestored seismic lines through peatlands (Chapter 2)
2. Assess the effectiveness of easily measured soil properties as indicators of C loss from CO₂ and CH₄ emissions (Chapter 2)

3. Evaluate different seismic line mounding restoration techniques by comparing impacts on physical and chemical soil properties, potential rates of decomposition, and vegetation cover (Chapter 3).

Chapter 2 Changes in peat soil properties following seismic lines disturbance and restoration by mounding

2.1 Introduction

Seismic lines are long, linear disturbances created for oil and gas exploration. Seismic lines are common throughout the boreal forest with densities up to 10 km of seismic lines per 1 km² of land area (Lee & Boutin, 2006). On many seismic lines, there has been a lack of natural recovery with little woody vegetation regrowth and a shift to a graminoid-dominated vegetation community (Lee & Boutin, 2006). Recovery of tree cover on seismic lines is particularly slow in peatland ecosystems, which is a cause for concern as peatlands cover up to 50% of northern Alberta (Filicetti et al., 2018). In Alberta, an estimated 345,000 km of seismic lines cross through peatlands (Strack et al., 2019). However, the effectiveness of restoration methods remains unclear. Peatlands are ecosystems defined by the presence of excess water that slows decomposition, allowing for an accumulation of biomass, or peat, deeper than 40 cm (Vitt, 2006). Due to the dependence of peatland persistence on the presence of water, hydrology is an important defining feature of peatlands (Vitt, 2006). As a result, there has been a focus on hydrology when studying seismic lines (Dabros et al., 2018). Hydrology of peatlands is predicted to be impacted by seismic lines as removing vegetation is known to reduce water intake and evapotranspiration, increase soil compaction, reduce microtopographic variation, and alter water storage and flow (Dabros et al., 2018).

Due to flooding on seismic lines in peatlands, restoration methods focus on providing drier microsites for tree growth and recovery (Filicetti et al., 2019). In a technique called mounding, drier microsites are created on seismic lines by digging, inverting, and placing mounds of peat (Filicetti et al., 2019). The drier mounds have been successful in improving tree regeneration (Filicetti et al., 2019; Lieffers, Caners, & Ge, 2017; Bilodeau-Gauthier et al., 2011) but there have also been issues with mounding in peatlands mainly with mounds collapsing within a few years (Filicetti et al., 2019; Lieffers,

Caners, & Ge, 2017). Mounding could also be shifting vegetation succession trajectories away from the surrounding natural areas (Echiverri, Macdonald, & Nielsen, 2020). With little knowledge on the effects of mounding, this study aims to investigate the changes in peat soil properties on seismic lines and additional changes caused by restoration.

While hydrology and microtopography are important to vegetation recovery, substrate quality can also be a limiting factor. Substrate quality can determine the pathway of vegetation succession. The degree of peat decomposition can help predict recovery pathways in extracted peatlands where water table levels could not (Triisberg et al., 2013). Variables such as peat depth, degree of decomposition, nutrient availability, and macro-porosity are known to influence vegetation survival and growth (Kozłowski, 1999; Triisberg et al., 2013; Pacé et al., 2018). In addition, substrate quality could explain the collapsing of some mounds. Increased decomposition after disturbance can cause structural damage such as macropore collapse (McCarter et al., 2020; Kool, Buurman, & Hoekman, 2006). Despite the importance to vegetation recovery, knowledge of peat physical and chemical properties on both unrestored and restored seismic lines is limited.

Easily measured decomposition indicators can be used to determine substrate quality. Carbon (C) to nitrogen (N) ratios are commonly used to assess peat decomposition. Fresh peat will have large C/N ratios reflecting litter inputs from vegetation, while decomposed peat has smaller C/N ratios as C is preferentially lost during microbial decomposition (Malmer & Holm, 1984; Biester et al., 2014). Along with decomposition, peat compaction can lower C/N ratios (Liu et al., 2019). C/N ratios are important to substrate quality by influencing vegetation growth (Asada, Warner, & Schiff, 2005). More recently, stable isotopes, specifically $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$, have been used as decomposition indicators (Biester et al., 2014; Broder et al., 2012; Alewell et al., 2014; Asada, Warner, & Aravena, 2005). $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ reflect the ratios of heavier and lighter isotopes, ^{13}C and ^{12}C and ^{15}N and ^{14}N , respectively. $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ can be used to represent the degree of decomposition as lighter isotopes are preferentially lost

during microbial decomposition of organic matter due to lower energy requirements (Nadelhoffer & Fry, 1988; Asada, Warner, & Aravena, 2005). $\delta^{13}\text{C}$ has often been strongly correlated with other decomposition markers such as bulk density and C/N ratios (Biester et al., 2014; Broder et al., 2012; Alewell et al., 2014). $\delta^{15}\text{N}$ has been a less reliable indicator of decomposition. $\delta^{15}\text{N}$ can experience more fractionation during decomposition that can result in enrichment of either or neither isotope (Hobbie, Macko, & Shugart, 1998). Other peat processes such as nitrogen recycling and uptake can also interfere with the relationship between $\delta^{15}\text{N}$ and decomposition status (Biester et al., 2014).

Humification indices, ratios between labile carbohydrates and recalcitrant aromatic or aliphatic compounds, have also been used to assess the degree of decomposition and substrate quality. Carbohydrates are generally preferentially lost during decomposition over aromatic or aliphatic compounds (Cocozza, et al., 2003; Hodgkins, 2016). In peatlands, humification indices have been shown to be strongly correlated with more common decomposition indicators such as C/N ratios (Broder et al., 2012; Biester et al., 2014).

In addition to vegetation recovery, C loss from peatlands is a major concern for unrestored seismic lines. Peatlands are important C sinks, storing about 15-30% of global soil C despite only covering about 3% of the global land surface (Limpens et al., 2008). The large C storage potential of peatlands is due to the defining feature of peatlands, waterlogged conditions, driving net primary productivity to be higher than organic matter decomposition (Wu et al., 2012). Seismic line disturbance can cause peatlands to shift from a C sink to a C source (Dabros et al., 2018). The effects of seismic line restoration on C loss are not well understood. The process of mounding disturbs the peat profile, exposes deeper peat to oxygen, and removes vegetation. While deeper peat would largely consist of recalcitrant organic matter, the drier, aerated, and warmer conditions on the mounds may result in further decomposition and C loss (Beer & Blodau, 2007; Leifeld, Steffens, & Galego-Sala, 2012). The holes created from mounding and surrounding wet, low-lying areas may result in higher CH_4 emissions.

Along with the lack of research, C loss can be difficult to determine on seismic lines due to the difficulty of accessing the remote locations for regular flux measurements. As C fluxes are highly influenced by substrate quality, easily measured decomposition markers could be used to estimate C loss on remote seismic lines (Davidson et al., 2020).

Despite the growing interest in seismic line restoration, there are still significant research gaps in the effects of seismic lines on the disturbed peatlands and how this impacts restoration success. The additional disturbance that occurs during mounding may result in lower soil quality with the exposure of deeper peat and compaction from machinery. Lower soil quality could explain why mounding is not always as successful as expected. This study will examine the effects of seismic line creation and restoration in peatlands on peat properties and evaluate the implications of these changes for restoration outcomes. The specific objectives were to:

1. Compare peat physical and chemical properties as indicators of substrate quality on restored and unrestored seismic lines in peatlands to undisturbed reference areas,
2. Quantify potential rate of C emission of restored seismic lines and determine if easily measured decomposition markers can be used to indicate C loss from disturbance.

2.2 Study Sites

2.2.1 Site Information

The study area is a series of peatlands in eastern boreal Alberta (Figure 2.1). While the area consists of many different peatland types, wooded fens were exclusively chosen for this study. Each site was further classified as a wooded moderate-rich fen or wooded poor fen following the Alberta Wetland Classification System (ESRD, 2015). Seismic lines in the area were created in different years between the mid-1980s and early 2000s. Restoration work started in 2012 and is on-going. Due to the large size of the study area, each site consists of multiple lines, and some lines were sampled twice in different

sections at least 100 m apart. We sampled poor fens and moderate-rich fens equally at each site to represent the range of variation, but do not investigate specific differences in the fen types in this study.

The first site, Foster Creek 5-7 years post mounding (FC5-7) (55° 03'04" N, 110° 28'24" W), consists of seismic lines created between 1996 and 1998 as shown by satellite imagery. FC5-7 is the oldest restored site in the area with restoration occurring between 2012 and 2015. As it was the first site in the area to be restored with the mounding treatment was further refined on the newer sites in this study. When visited on July 31, 2019, FC5-7 was dominated largely by bare ground and graminoids along with mosses and dwarf shrubs. Both the moderate-rich and poor fens in FC5-7 consisted of *Carex* spp., *Equisetum* sp., *Larix laricina*, *Picea mariana*, *Pleurozium schreberi*, *Rhododendron groenlandicum*, *Sphagnum* spp., and *Vaccinium vitis idaeae*. In addition, the moderate-rich fens had *Betula pumila*, *Pleurozium schreberi*, *Salix* spp., and *Smilacina trifolia*. The poor fens also had *Cladonia* sp., *Cladonia chlorophaea*, *Epilobium angustifolium*, *Polytrichum strictum*, and *Rubus chamaemorus*. Orientation of the lines also varied. The moderate-rich fens had both NE/SW and E/W lines while the poor fens were all E/W.

The second site, South Clyde 2nd year post mounding (SC2) (55° 04'49" N, 111° 11'39" W), was restored in January 2017. Based on satellite imagery, seismic lines were created between 1985 and 1986. Sampled on August 3, 2019, SC2 was dominated by moss, bare ground, graminoids, and dwarf shrubs. Both moderate-rich fens and poor fens consisted of *Betula pumila*, *Carex* spp., *Epilobium angustifolium*, *Equisetum* sp., *Larix laricina*, *Oxycoccus microcarpus*, *Picea mariana*, *Polytrichum strictum*, *Rhododendron groenlandicum*, *Salix* spp., *Smilacina trifolia*, *Sphagnum* spp., and *Tomenthypnum nitens*. The poor fens also had *Chamaedaphne calyculata*, *Drosera* spp., *Ledum palustre*, *Rubus chamaemorus*, and *Vaccinium vitis idaeae* while the moderate-rich fens had the addition of *Pleurozium schreberi*. Both fens and poor fens had E/W lines and the moderate-rich fens also had N/S lines.

The third site, West Clyde year 0 post mounding (WC0) (55° 17'22" N, 111° 11'37" W), was the newest site restored in February 2019. Satellite imagery shows that the seismic lines were created between 1982 and 1984. When visited on August 4, 2019, the site was dominated by bare ground with some mosses and graminoids. Although largely covered by bare ground, the poor and moderate-rich fens both had *Betula pumila*, *Carex* spp., *Epilobium angustifolium*, *Equisetum* sp., *Rhododendron groenlandicum*, *Salix* spp., *Smilacina trifolia*, *Sphagnum* spp., and *Tomenthypnum nitens*. Unique to the poor fens were *Aulacomnium palustre* and *Ledum palustre* while moderate-rich fens had *Oxycoccus microcarpus* and *Vaccinium vitis idaeae*. Both poor fens and moderate-rich fens had lines that were oriented NW/SE and E/W.

Additionally, unrestored lines in West Clyde (WCU) were sampled in this study. The WCU lines were dominated by mosses, graminoids, and dwarf shrubs. *Aulacomnium palustre*, *Betula pumila*, *Carex* spp., *Equisetum* sp., *Rubus chamaemorus*, *Salix* spp., *Smilacina trifolia*, *Sphagnum* spp., and *Tomenthypnum nitens* were present at both the moderate-rich fens and the poor fens. The moderate-rich fens had the addition of *Vaccinium vitis idaeae* and the poor fens had *Epilobium angustifolium* and *Ledum palustre*. Lines in both the moderate-rich and poor fens were E/W oriented.

Lastly, natural poor and moderate-rich fens adjacent to FC5-7 and SC2 were included as a reference. The natural areas were dominated by mosses and dwarf shrubs with some forbs and graminoids. Species present included *Betula pumila*, *Carex* spp., *Cladonia* sp., *Cladonia chlorophaea*, *Epilobium angustifolium*, *Equisetum* sp., *Icmadophila ericetorum*, *Larix laricina*, *Oxycoccus microcarpus*, *Picea mariana*, *Pleurozium schreberi*, *Rhododendron groenlandicum*, *Rubus chamaemorus*, *Salix* spp., *Smilacina trifolia*, *Sphagnum* spp., *Tomenthypnum nitens*, and *Rosa* sp.

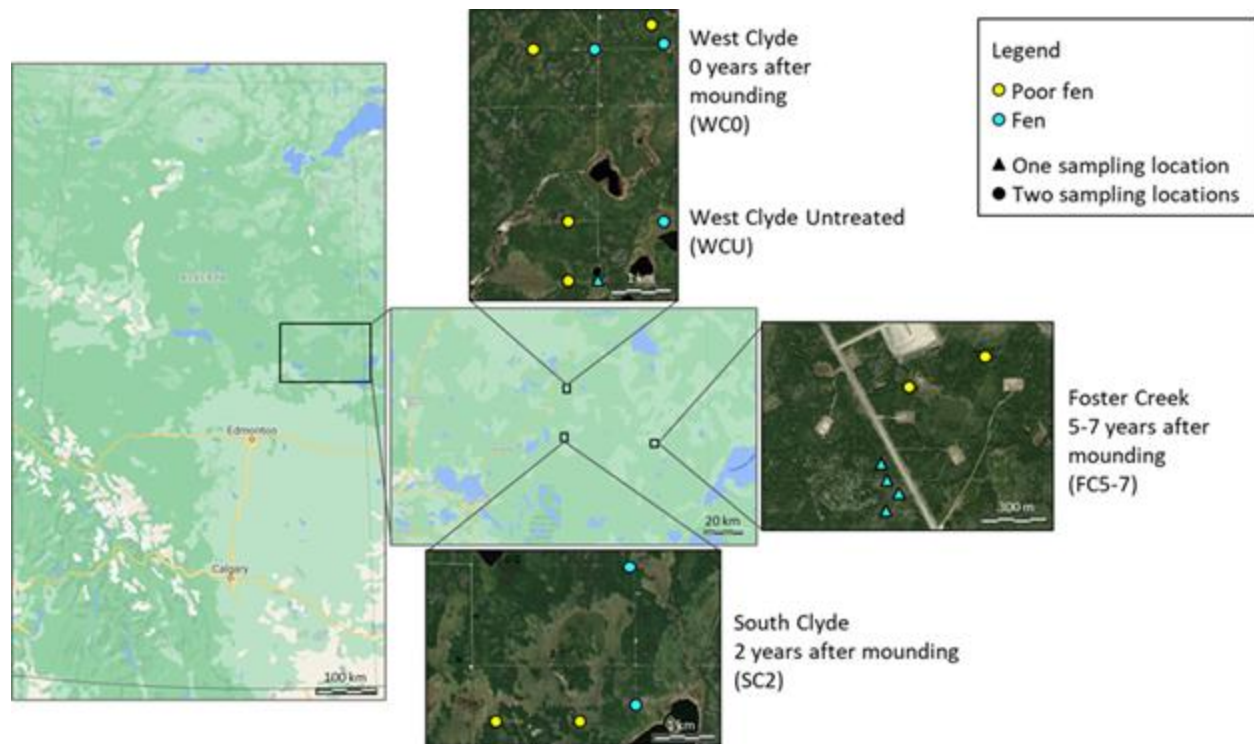


Figure 2.1: Map of the study sites in Alberta, Canada. Natural reference samples were taken adjacent to seismic lines at SC2 and FC5-7.

2.2.2 Restoration

The restored lines in FC5-7, SC2, and WCO were all restored by Cenovus Energy using the same machinery and restoration methods. However, it is important to note that these methods were refined through practice and a better understanding of mounding after the initial FC5-7 restoration. As a result, the results from FC5-7 should not be interpreted as a prediction of future conditions at SC2 and WCO. As described by Filicetti et al. (2018), a construction excavator with a 1 m³ bucket was used to create mounds sized roughly 0.75 m wide, 1 m long, and 0.8 m high (Figure 2.2). As the peat was inverted to form the mounds, some mounds consisted of a mix of exposed deeper peat, mineral soils, and potentially clay or sand. Mounds were placed in a checkered pattern with alternating 1 or 2 mounds on the seismic width.



Figure 2.2: Photos of the site with close-ups on mounds or hummocks; a) FC5-7, b) SC2, c) WCO, d) WCU, e) natural area.

2.3 Methods

2.3.1 Sampling Methods

Between July 31 and August 5, 2019, peat samples were collected in triplicate from mound and adjacent low-lying area pairs or hummocks and hollows for the natural areas (Figure 2.3). Although untreated lines did not have natural hummocks or created mounds, samples were taken in pairs of locally higher and lower areas. A soup can (562.70 cm³) was used to collect a known, consistent volume of peat. A serrated knife was used to cut through moss, peat, and roots around the soup can to prevent compaction when sampling. The first 10 cm of peat was sampled with the top of the moss surface

considered as the top of the peat profile. Sample pairs were collected from four sections of the poor fen lines and four sections of the moderate-rich fen lines at each of the five sites (Natural, FC5-7, SC2, WC0, and WCU) for a total of eight triplicate pairs per site. Triplicate grab samples were also collected directly adjacent to the soup can samples to be used in a C loss experiment.

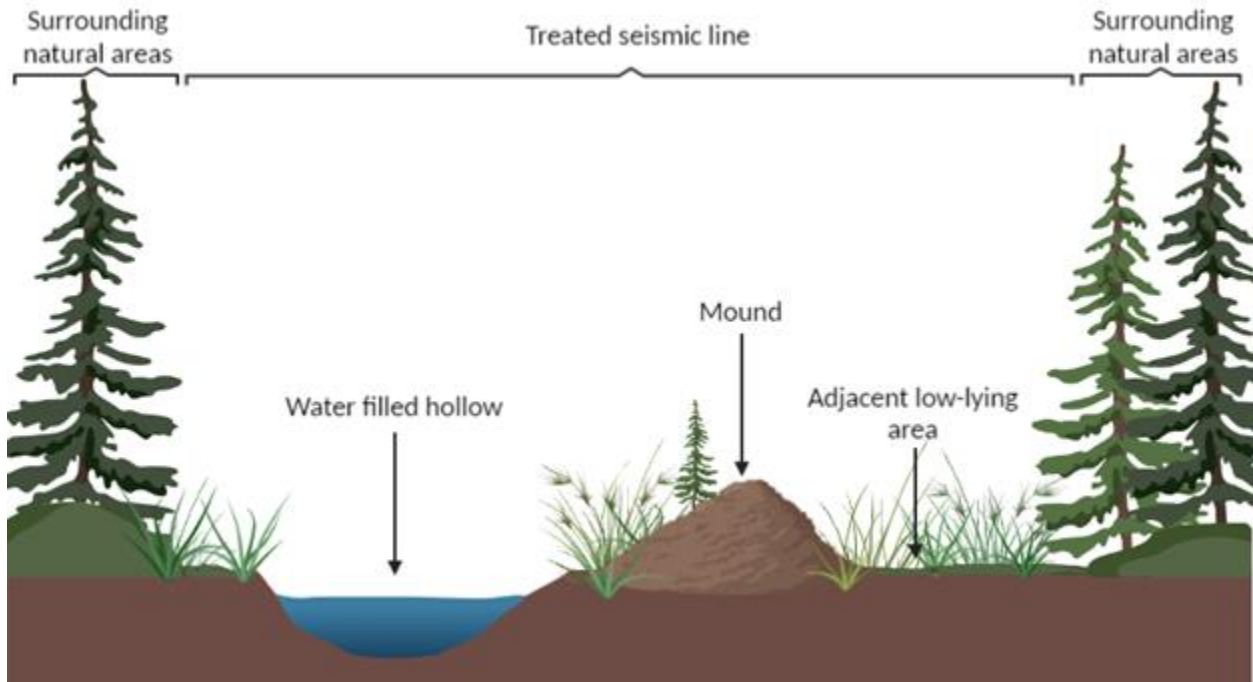


Figure 2.3: Simplified illustration of mounding technique and sampling locations. Samples were taken from mounds, adjacent low-lying areas, and surrounding natural areas. Created with BioRender.com.

2.3.2 Peat Properties

Peat samples were frozen and shipped to Waterloo, Ontario after sampling. On arrival, soup can peat samples were thawed, weighed, then dried for at least 48 hours at 80 °C until a constant weight was achieved and weighed again to calculate bulk density and volumetric water content (VWC). Although VWC can be influenced by the date collected, all sampling was completed within 6 days and without rain events. Organic matter content (OM) was determined from loss on ignition. From the dried peat, 2 g of each sample was burned in a muffle furnace for 4 hours at 550 °C and then weighed the following day to calculate OM content. To ensure OM of the subsamples were representative of the

larger samples, samples were mixed before the subsamples were taken and replicate subsamples were analyzed and compared for reproducibility.

Total carbon (TC), total nitrogen (TN), $\delta^{13}\text{C}$, and $\delta^{15}\text{N}$ were determined 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. Small amounts from the dried peat samples were ground into a fine powder using a ball mill. Of the ground samples, 1 mg of peat was weighed out into tin capsules. Then, the samples were combusted at 1030 °C (~1750 °C with the addition of oxygen) to convert all C and N present in the sample to CO_2 and N_2 gas, respectively. The gases passed through a packed column within the EA and separated (by mass) where a small amount was then directed to the mass spectrometer for measurement. Standard quality control methods were 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 Appendix A for details).

Peat total phosphorus (TP) was determined by conducting digestions for nutrient colorimetric analysis in the Biogeochemistry Lab at the University of Waterloo according to O'Halloran & Cademnum (2007). Of the above-mentioned ground peat samples, 0.2 g were weighed out into 100 mL test tubes and mixed with 5 mL of sulphuric acid. Then, 4 mL of a prepared digestion mixture composed of 175 mL of H_2O_2 , 0.21 g of Se powder, and 7 g $\text{Li}_2\text{SO}_4 \cdot \text{H}_2\text{O}$ was slowly added to the tubes and mixed. The tubes were gradually heated to 360 °C over 1.5 hours. The temperature was then maintained at 360 °C for 30 minutes. After heating, tubes were allowed to cool to room temperature before 0.5 mL of H_2O_2 was added. Tubes were then mixed, heated for 30 minutes, and allowed to cool again for 30 minutes. Samples were diluted to a known volume with deionized water, sealed, and thoroughly mixed. Lastly, the samples were filtered before being analyzed on a Bran Luebbe Auto Analyzer 3 High resolution digital colorimeter.

Fourier Transform Infrared (FTIR) analysis was 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 divided by 1090 cm^{-1} bands representing carbohydrates (Hodgkins, 2016). HI can be calculated using other bands such as aliphatic bands at 2920 cm^{-1} and 2850 cm^{-1} , but these bands are often influenced by minerals such as clays (Biester et al., 2014).

2.3.3 Soil carbon emission incubation

Grab samples from SC2 and undisturbed areas were thawed and incubated in glass jars at room temperature and 60% VWC in the dark. Incubations were completed at 60% VWC as this has been reported as an ideal soil moisture to promote decomposition (Husen, Salma, & Agus, 2014; Wang et al., 2010; Yin et al., 2019). As illustrated in Figure 2.4, triplicate samples were gently mixed to create a bulk sample and then three sets of samples were created for the incubation. Each set had eight samples from each of SC2 and the undisturbed area. Half of the samples were from mounds or hummocks and half were from low-lying areas or hollows.

The first set of samples was dried immediately upon thawing and used as initial conditions. Initial VWC and bulk density were used to determine how much DI water was needed to reach 60% VWC. Samples were weighed weekly, and more DI water was added to keep samples at 60% VWC. The remaining two sets were used as different endpoint conditions; the second set was incubated for 4 months from June - October 2020 and the third set was incubated for 8 months from June 2020 - February 2021. At each endpoint, peat samples were dried and analyzed for OM content, TC, TN, $\delta^{13}\text{C}$, $\delta^{15}\text{N}$, and humification indices as described above.

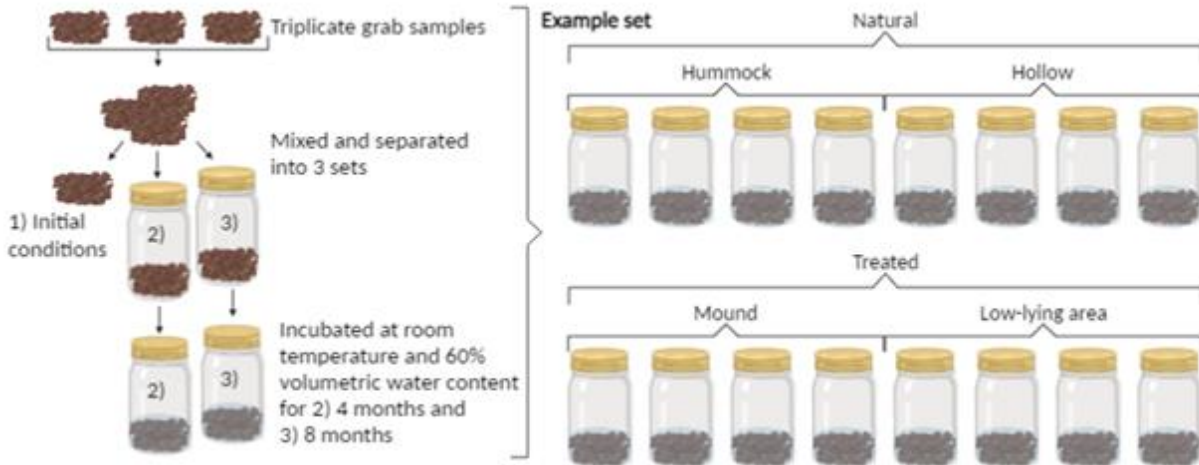


Figure 2.4: Illustration of incubation setup. Created with BioRender.com

CO₂ fluxes were measured using a portable infrared gas analyzer (IRGA; EGM-4 PP Systems, Massachusetts, USA). Measurements were taken every other day for the first week, then every week for a month, and then every other week for a total of 21 fluxes over the full 8 months. The set of jars measured for only the initial 4 months had 14 CO₂ fluxes while the other set had the full 21 fluxes. During a measurement, jars were sealed, the IRGA was connected via an inlet and outlet tube in the lid of the jar, and CO₂ concentrations were recorded every 15 seconds for 2 minutes. CH₄ fluxes were measured every 4 weeks using an Ultraportable Greenhouse Gas Analyzer (UGGA; Model 915-0011, Los Gatos Research, United States) resulting in four fluxes for the initial 4 months and a total of eight fluxes over the full 8 months. Realtime CH₄ concentrations were measured every second for 5 minutes. Measurements were temperature and volume corrected for each jar.

Total C loss was calculated as the sum of the C emitted over the entire incubation based on CO₂ and CH₄ fluxes. Fluxes were translated to C loss by multiplying CO₂ or CH₄ fluxes by the ratio of the molar masses of C and CO₂ or CH₄ and expressed per mass of dry peat incubated.

2.3.5 Statistical Analysis

All statistical analysis was conducted using the statistical program R (R Core Team, 2017), and a significance of $\alpha = 0.05$ was applied. Shapiro-Wilk tests and Q-Q normality plots were used to determine the normality of soil properties. Although overall samples were found to not be normal, groups of samples within treatments were normal. As a result, ANOVAs were used due to their robustness. One-way ANOVAs were used to determine if soil properties varied between treatments. When soil properties were significantly different between groups, Tukey post hoc tests were used to determine which groups were significantly different. Paired t-tests were used to determine if soil properties varied between pairs of mounds and low-lying areas at each site. Differences in TC loss and CO₂ and CH₄ emissions between site and microsite type of jar samples were determined with ANOVAs and Tukey post hoc tests. Statistical tests for TC loss and CO₂ and CH₄ emissions used log-transformed data to meet normality expectations. Lastly, relationships between TC loss and decomposition parameters were assessed by linear regressions.

2.4 Results

2.4.1 Peat Physical Properties

Bulk density ranged from 0.02 to 1.1 g/cm³ with natural areas having the lowest range and treated mounds having the highest (Table 2.1). Bulk densities for mounds at SC2 and WC0 were statistically higher than their corresponding low-lying areas while FC5-7 had no difference between microsities ($W = 55, p = 0.015$; $W = 61, p = 0.0011$). The natural areas had the opposite trend with hummocks having a lower bulk density than natural hollows ($W = 1, p = 0.00035$). For both the mounds and the lows, SC2 and WC0 bulk densities were comparable to each other while FC5-7 had the highest bulk densities for both mounds ($F_{4,35} = 6.93, p = 0.0032$) and lows ($F_{4,35} = 7.32, p = 0.00022$).

VWC varied greatly between sites with the entire range across sites spanning from 9.2 to 86.7% (Table 2.1). Mounds had lower VWC than corresponding low-lying areas at FC5-7 ($W = 0, p = 0.00016$),

WC0 ($W = 8, p = 0.010$), and the natural areas ($W = 8, p = 0.00079$) but not at SC2 or the untreated lines. Mounds at FC5-7, SC2, and WC0, and the untreated lines did not differ between each other. Similarly, low-lying areas did not differ at FC5-7, SC2, and WC0, and the untreated lines. The natural areas had lower VWC than all other sites for both mounds ($F_{4,35} = 9.612, p < 0.001$) and lows ($F_{4,35} = 11.85, p < 0.001$).

Like VWC, OM had a large range from 15.9 to 98.2% with FC5-7 having the lowest range and natural areas having the highest (Table 2.1). There was no difference in OM content between microsites at all treated lines. OM content was higher on natural mounds than corresponding low-lying areas ($W = 57, p = 0.0070$). At WC0, the opposite was true with OM content lower on the mounds than the low-lying areas ($W = 13, p = 0.049$). FC5-7 and WC0 mounds had lower OM content than the natural and untreated line, while SC2 did not differ from any site ($F_{4,35} = 6.344, p = 0.0006$). The low-lying areas at FC5-7 had lower OM content than all other sites ($F_{4,35} = 5.742, p = 0.0012$).

Table 2.1: Peat physical properties of treated and untreated seismic lines and natural reference areas. Averages and standard deviations were calculated from four sets of triplicate samples per microsite at each site. Letters represent statistical differences between sites and microsities for each column. Groups with the same letter indicate no statistical differences.

	Bulk density (g/cm ³)	VWC (%)	OM content (%)
FC5-7			
Mound	0.5 ± 0.1 ^a	36.5 ± 2.3 ^a	52.2 ± 10.1 ^a
Low	0.3 ± 0.08 ^a	64.6 ± 3.3 ^b	57.4 ± 9.8 ^a
SC2			
Mound	0.2 ± 0.04 ^{ab}	49.2 ± 4.2 ^{ab}	74.4 ± 7.5 ^{ab}
Low	0.08 ± 0.02 ^d	59.1 ± 4.6 ^{ab}	86.6 ± 3.4 ^{bc}
WCO			
Mound	0.3 ± 0.05 ^{ab}	43.9 ± 4.3 ^a	69.5 ± 6.5 ^{ab}
Low	0.07 ± 0.02 ^d	60.9 ± 2.7 ^b	84.8 ± 5.5 ^c
Untreated			
Mound	0.05 ± 0.008 ^{bce}	45.5 ± 5.9 ^{ab}	86.4 ± 3.3 ^{bc}
Low	0.06 ± 0.009 ^{de}	54.5 ± 5.8 ^{ab}	87.5 ± 3.2 ^{bc}
Natural			
Mound	0.03 ± 0.002 ^c	16.8 ± 2.3 ^c	95.8 ± 0.5 ^b
Low	0.05 ± 0.002 ^d	29.5 ± 4.5 ^d	91.0 ± 0.5 ^c

2.4.2 Peat Chemical Properties

Chemical properties for each microsite-site combination are given in Table 2.2. Treated lines had a much larger range of TC, 11.1-532.8 mg/g, than the natural areas, 434.6 to 490.5 mg/g. When divided into microsities, FC5-7 mounds had significantly lower TC than the natural sites and SC2 did not differ from any site ($F_{2,28} = 4.45$, $p = 0.021$). Low-lying areas at FC5-7 had lower TC than the natural site and SC2, while SC2 had lower TC than the natural areas ($F_{2,28} = 6.92$, $p = 0.0036$). TC was lower on natural hollows than hummocks ($W = 78$, $p = 0.036$). Treated lines had both lower minimum, 4.1 mg/g, and a higher maximum of TN, 19.4 mg/g, than natural areas with 5.8 to 11.0 mg/g. SC2 mounds had statistically higher TN than the natural areas ($F_{2,26} = 6.89$, $p = 0.0040$), while TN in low lying areas did not

differ ($F_{2,28} = 1.98$, $p = 0.16$). TN did not vary between microsites. TP did not vary between microsites or sites. Natural areas had a TP range of 0.27 to 0.91 mg/g. Although not significant, treated lines had a higher range of 0.27 to 1.43 mg/g for TP.

C/N ratios at the natural areas ranged from 39.51 to 90.43. Treated lines had a lower range of 22.99 to 62.54. C/N ratios were lower on low-lying areas than mounds at FC5-7 ($W = 92$, $p = 0.037$). C/N ratios on mounds were higher at the natural areas than SC2 and FC5-7, which did not vary ($F_{2,57} = 6.34$, $p < 0.001$). Low lying areas had a different result with the natural areas having a higher C/N ratio than FC5-7 only ($F_{2,28} = 7.06$, $p = 0.0033$). The range of natural C/P ratios, 281.03 to 1234.65, was smaller than the treated C/P ratios range of 207.85 to 1950.37. When divided into microsites, C/P ratios on mounds did not vary between sites, while low lying areas at SC2 had higher C/P ratios than at FC5-7 ($F_{2,26} = 3.85$, $p = 0.034$). C/P ratios did not vary between microsites. The range of N/P ratios was much smaller at the natural areas, 5.62 to 19.63, than at the treated lines, 6.02 to 46.82. SC2 mounds had higher N/P ratios than the natural hummocks ($F_{2,23} = 4.73$, $p = 0.019$). Low-lying areas at SC2 were higher than both FC2-7 low-lying areas and the natural hollows ($F_{2,26} = 6.40$, $p = 0.0055$). However, N/P ratios did not vary between microsites.

The range of $\delta^{13}\text{C}$ on the treated lines was shifted to be less negative, or heavier, than the natural areas. The treated lines ranged from -30.38 to -21.39‰ while the natural areas ranged from -33.95 to -29.00‰ . $\delta^{13}\text{C}$ was lighter on natural hummocks than hollows ($W = 20$, $p = 0.025$). FC5-7 had the opposite trend with mounds having heavier $\delta^{13}\text{C}$ than low-lying areas ($W = 71$, $p = 0.0079$). $\delta^{13}\text{C}$ was lighter at the natural areas than SC2 and FC5-7 for both mounds ($F_{2,28} = 12.88$, $p = 0.00011$) and low-lying areas ($F_{2,28} = 5.71$, $p = 0.0083$). Using a linear regression, $\delta^{13}\text{C}$ was correlated with C/N ($F_{1,58} = 30.06$, $p < 0.001$, $r^2 = 0.33$).

As with $\delta^{13}\text{C}$, $\delta^{15}\text{N}$ ranges were heavier on the treated lines, -3.46 to 4.03 ‰, when compared to the natural areas, -6 to 1.13 ‰. $\delta^{15}\text{N}$ was heavier on mounds than low-lying areas at SC2 ($W = 67, p = 0.021$). $\delta^{15}\text{N}$ was lighter at the natural areas than SC2 and FC5-7 for both mounds ($F_{2,26} = 10.99, p = 0.00035$) and low-lying areas ($F_{2,28} = 11.11, p = 0.00028$). Using linear regression, $\delta^{15}\text{N}$ was correlated with C/N ($F_{1,58} = 82.19, p < 0.001, r^2 = 0.58$).

Table 2.2: Peat chemical properties of treated seismic lines and natural reference areas. Averages and standard deviations were calculated from 4 sets of triplicate samples per microsite at each site. Letters represent statistical differences between sites and microsities for each column. Groups with the same letter indicate no statistical differences.

	Total Carbon (mg/g)	Total Nitrogen (mg/g)	Total Phosphorus (mg/g)	C/N	C/P	N/P	$\delta^{13}\text{C}$ (‰)	$\delta^{15}\text{N}$ (‰)
FC5-7								
Mound	322.38 ± 48.10 ^a	9.04 ± 0.93 ^a	0.66 ± 0.090 ^a	44.08 ± 2.33 ^{ac}	645.99 ± 95.91 ^a	14.14 ± 2.18 ^{ac}	-26.96 ± 0.83 ^a	-0.088 ± 0.90 ^{ab}
Low	336.63 ± 33.00 ^a	9.30 ± 0.97 ^a	0.74 ± 0.072 ^a	36.43 ± 1.93 ^{bc}	475.82 ± 54.34 ^a	12.64 ± 0.85 ^{ac}	-27.9 ± 0.36 ^b	0.63 ± 0.17 ^{ac}
SC2								
Mound	420.52 ± 34.62 ^{abc}	12.66 ± 1.77 ^b	0.68 ± 0.12 ^a	37.52 ± 4.74 ^c	877.34 ± 204.46 ^{ab}	23.76 ± 4.27 ^{ab}	-26.74 ± 0.12 ^{ab}	1.11 ± 0.36 ^b
Low	442.22 ± 23.18 ^{bd}	11.34 ± 1.24 ^a	0.62 ± 0.077 ^a	42.35 ± 4.72 ^{cd}	805.18 ± 104.46 ^b	20.73 ± 3.45 ^b	-27.92 ± 0.29 ^{ab}	-0.32 ± 0.41 ^c
Natural								
Mound	469.86 ± 3.97 ^c	6.72 ± 0.40 ^a	0.57 ± 0.082 ^a	72.16 ± 4.20 ^d	872.45 ± 112.41 ^a	11.84 ± 1.54 ^c	-30.89 ± 0.56 ^c	-3.23 ± 0.60 ^d
Low	452.60 ± 4.77 ^d	8.60 ± 0.63 ^a	0.86 ± 0.16 ^a	55.72 ± 4.75 ^d	677.49 ± 118.17 ^{ab}	10.85 ± 1.02 ^c	-29.14 ± 0.16 ^d	-1.73 ± 0.50 ^d

2.4.3 Incubation Study

TC loss ranged from 0.072 to 66.20 mg g peat⁻¹ d⁻¹. Most of the TC loss was as CO₂ emissions with fluxes ranging from 0.26 to 261.45 mg g peat⁻¹ d⁻¹. CH₄ fluxes were small and ranged from -0.77 to 209.23 μg g peat⁻¹ d⁻¹. As shown in Figure 2.5, TC loss was lower for treated mounds than treated low-lying areas and natural mounds ($F_{3,199} = 11.43, p < 0.001$). Methane flux was lower for treated and natural mounds than treated and natural low-lying areas ($F_{3,204} = 19.2, p < 0.001$). Carbon dioxide production was lower for treated mounds than treated low-lying areas and natural mounds ($F_{3,544} = 75.97, p < 0.001$).

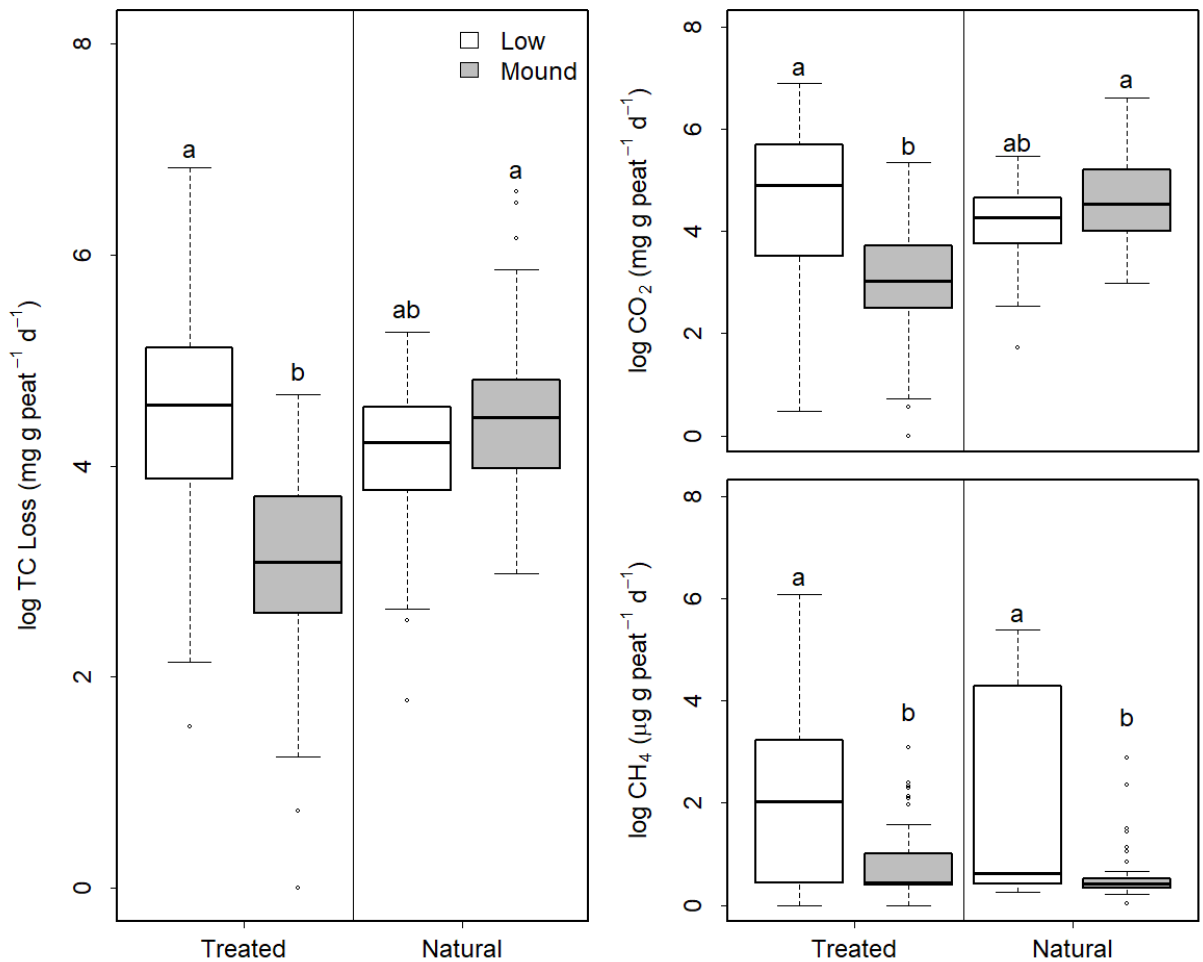


Figure 2.5: CO₂ and CH₄ emissions and TC loss from treated and natural microsites. Letters indicate a significant difference between fluxes across sample types. Samples with the same letters had no significant difference.

Initial $\delta^{13}\text{C}$ of incubated peat had linear relationships with TC loss during the total 8 months ($F_{1,14} = 6.87, r^2 = 0.28, p = 0.020$), initial 4 months ($F_{1,14} = 6.76, r^2 = 0.28, p = 0.021$), and final 4 months ($F_{1,14} = 6.00, r^2 = 0.25, p = 0.028$). $\delta^{13}\text{C}$ from the first endpoint, measured at the end of the initial 4 months, also had linear relationships with TC loss during the first-time interval ($F_{1,14} = 7.96, r^2 = 0.32, p = 0.014$), second time interval ($F_{1,14} = 6.33, r^2 = 0.26, p = 0.025$), and overall ($F_{1,14} = 8.01, r^2 = 0.32, p = 0.013$). There were no statistically significant relationships with $\delta^{13}\text{C}$ at the third endpoint measured at the end of 8 months ($F_{1,14} = 0.00013, r^2 = 0.071, p = 0.99$), initial 4 months ($F_{1,14} = 0.00025, r^2 = 0.071, p = 0.99$), and final 4 months ($F_{1,14} = 0.069, r^2 = 0.066, p = 0.80$) (Figure 2.6). There were weaker relationships with natural samples than treated samples. As most of the TC loss was from CO_2 emissions, the relationship between TC loss and $\delta^{13}\text{C}$ was driven by the CO_2 fluxes ($F_{1,14} = 6.84, r^2 = 0.28, p = 0.020$) while the CH_4 fluxes did not correlate with $\delta^{13}\text{C}$ ($F_{1,14} = 1.52, r^2 = 0.033, p = 0.24$) (Figure 2.7). CH_4 fluxes were close to 0 except for two samples, one natural and one treated.

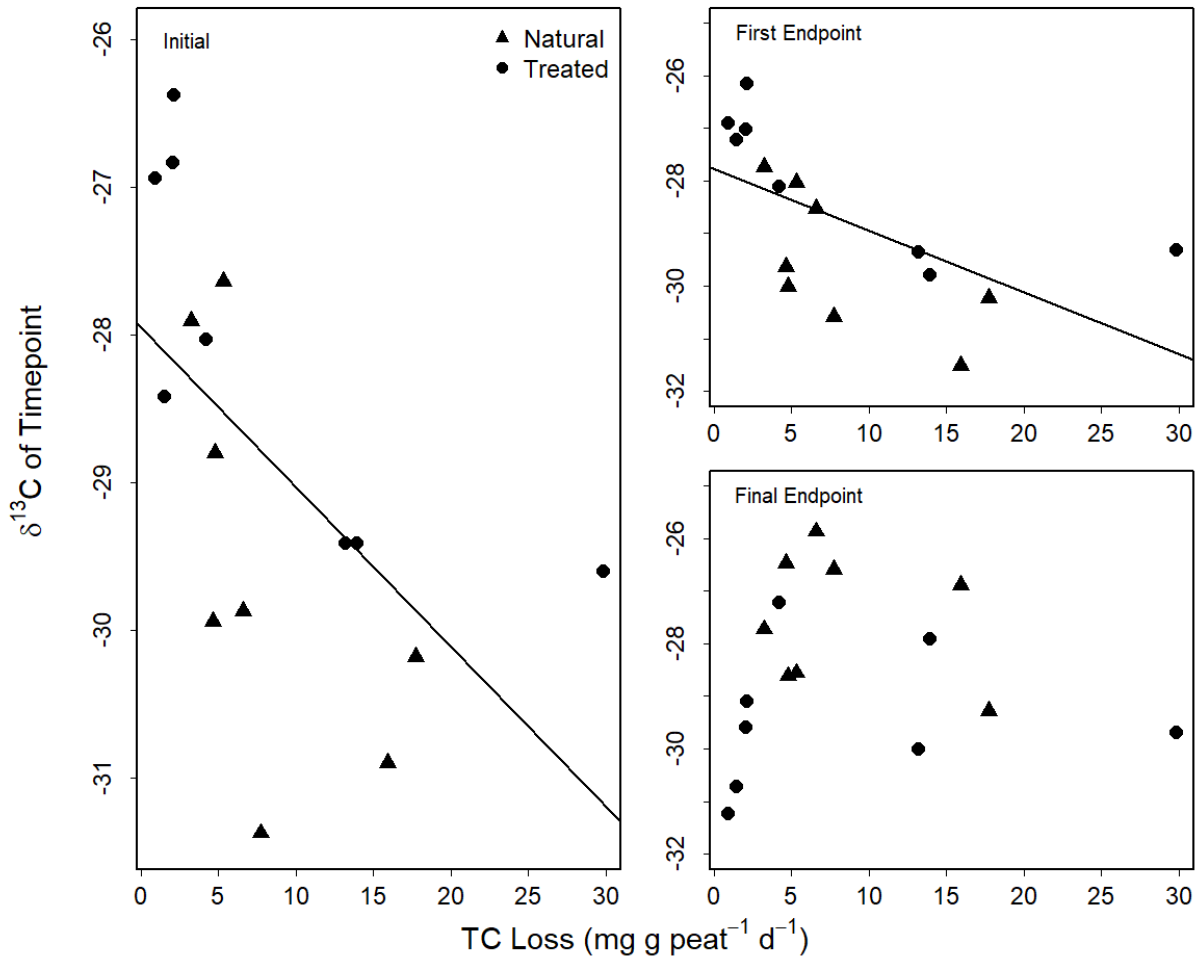


Figure 2.6: TC loss vs. initial, first endpoint, and final endpoint of $\delta^{13}\text{C}$ over the total 8 months of incubation. The initial and first endpoint of $\delta^{13}\text{C}$ both had a significant linear relationship with TC loss ($F_{1,14} = 6.87$, $r^2 = 0.28$, $p = 0.020$; $F_{1,14} = 8.01$, $r^2 = 0.32$, $p = 0.013$). The final endpoint of $\delta^{13}\text{C}$ was not related to TC loss ($F_{1,14} = 0.00013$, $r^2 = 0.071$, $p = 0.99$).

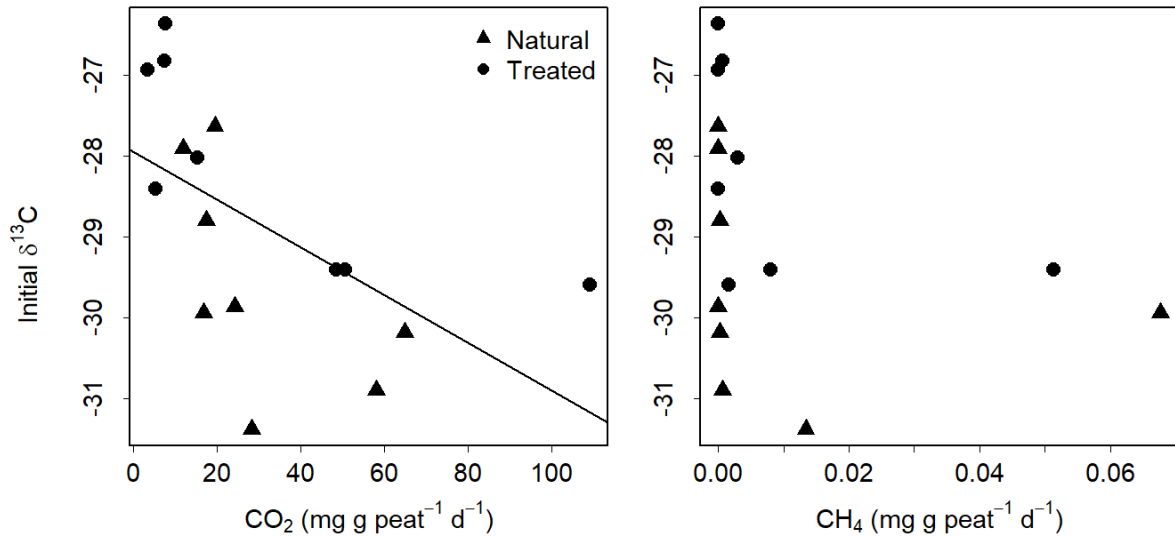


Figure 2.7: CO₂ and CH₄ emissions vs. change in $\delta^{13}C$. The change $\delta^{13}C$ was linearly related to CO₂ fluxes ($F_{1,14} = 6.84$, $r^2 = 0.28$, $p = 0.020$), and not CH₄ fluxes ($F_{1,14} = 1.52$, $r^2 = 0.033$, $p = 0.24$).

Initial C/N ratios also had a linear relationship with TC loss from the treated samples only for the full 8 months ($F_{1,6} = 6.69$, $r^2 = 0.45$, $p = 0.041$), initial 4 months ($F_{1,6} = 6.10$, $r^2 = 0.42$, $p = 0.049$), and final 4 months ($F_{1,6} = 16.45$, $r^2 = 0.69$, $p = 0.0067$) (Figure 2.8). The change in C/N ratios during the initial 4 months had a strong linear relationship with TC loss from the treated samples for the full 8 months ($F_{1,6} = 32.31$, $r^2 = 0.82$, $p = 0.0013$), initial 4 months ($F_{1,6} = 33.59$, $r^2 = 0.82$, $p = 0.0012$), and final 4 months ($F_{1,6} = 14.71$, $r^2 = 0.66$, $p = 0.0086$) (Figure 2.9). As with $\delta^{13}C$, relationships were driven by CO₂ fluxes. Initial and the change in TC and TN by themselves did not have a relationship with TC loss.

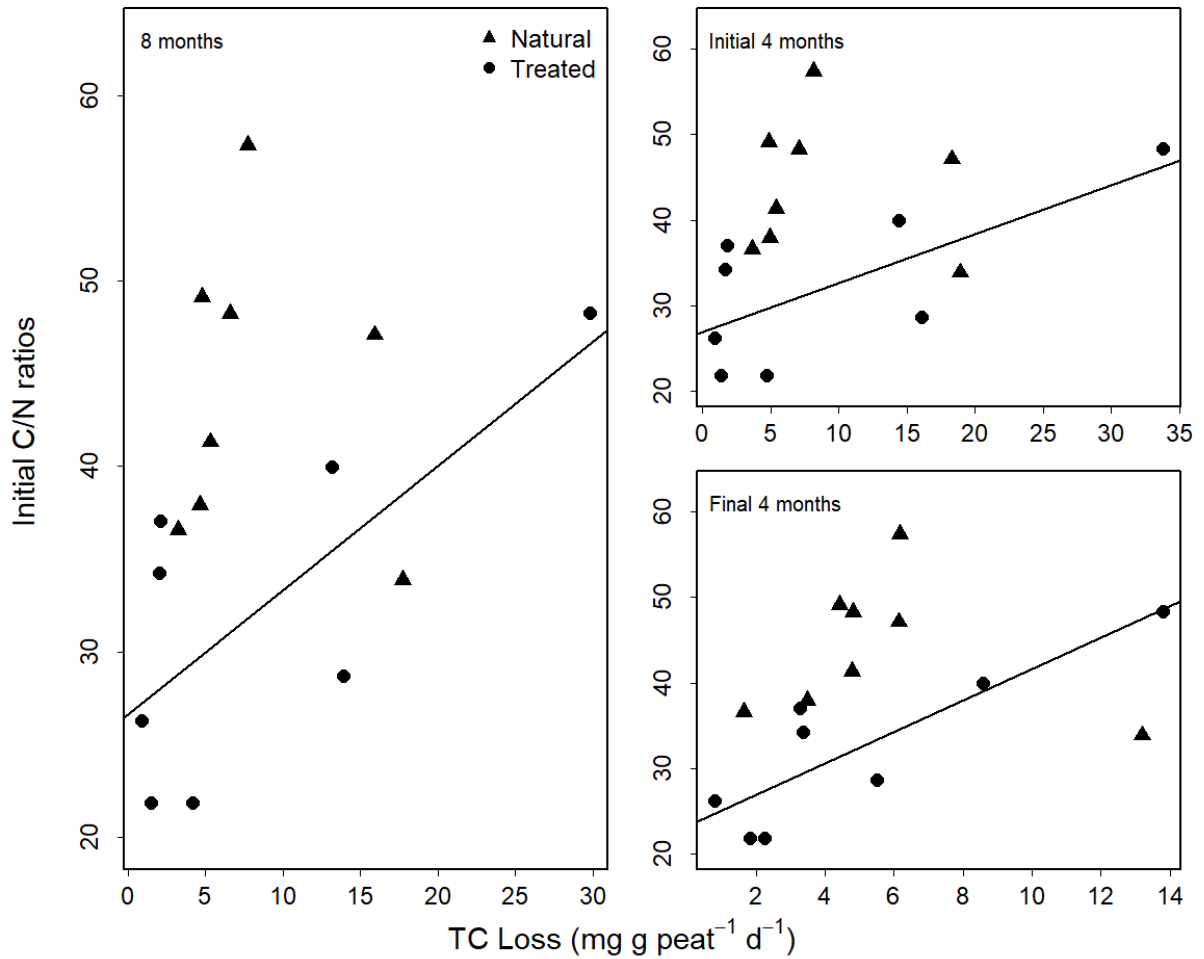


Figure 2.8: TC loss vs. initial C/N ratios over initial 4 months, final 4 months, and total 8 months of incubation. Initial C/N ratios were linearly correlated with TC loss of the treated samples only over the full 8 months ($F_{1,6} = 6.69$, $r^2 = 0.45$, $p = 0.041$), initial 4 months ($F_{1,6} = 6.10$, $r^2 = 0.42$, $p = 0.049$), and final 4 months ($F_{1,6} = 16.45$, $r^2 = 0.69$, $p = 0.0067$). Linear regressions of the C/N ratios of natural samples and TC loss were not significant and are not shown here.

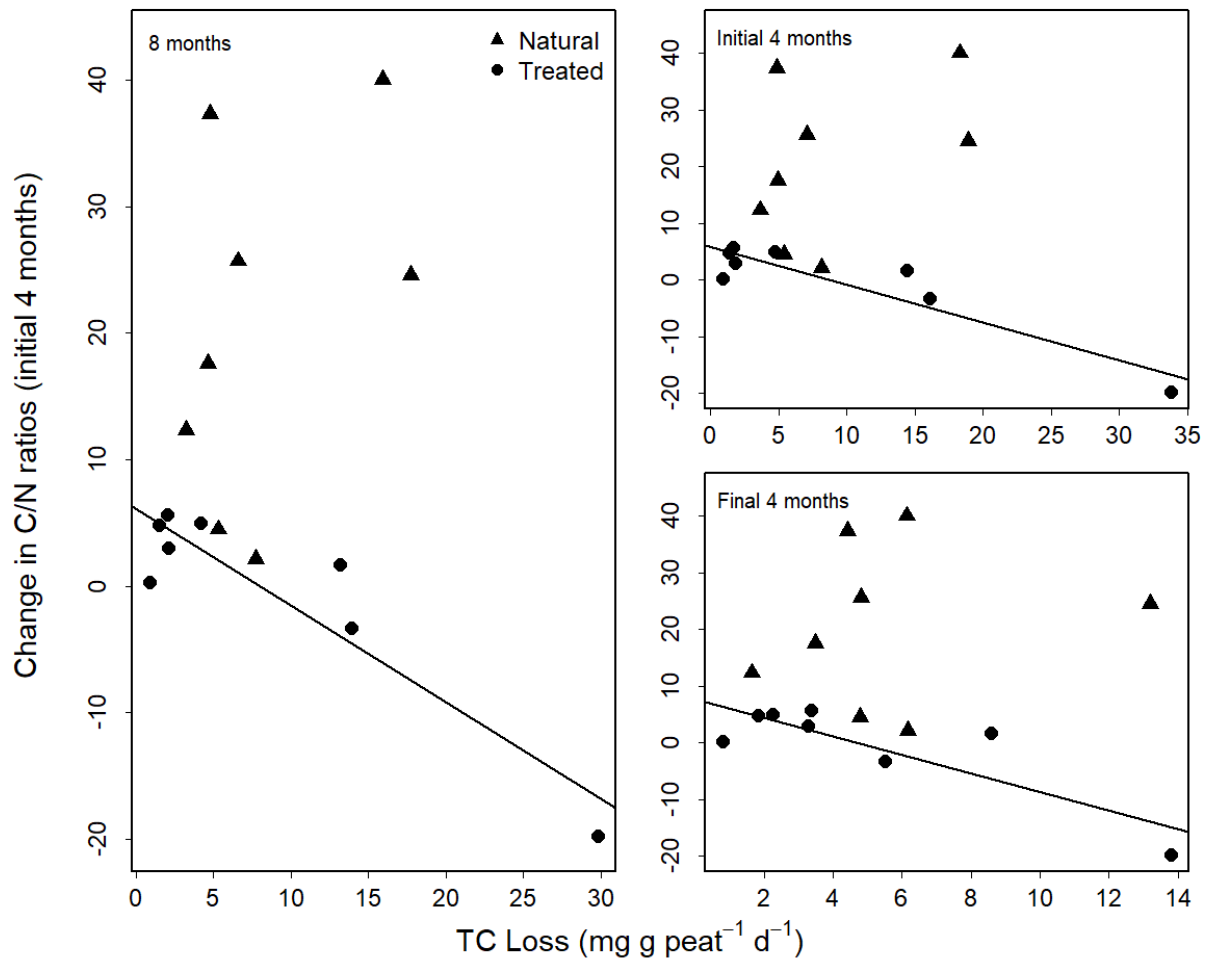


Figure 2.9: TC loss vs. changes in C/N ratios during the initial 4 months over initial 4 months, final 4 months, and total 8 months of incubation. The changes in C/N ratios during the initial 4 month had a linear relationship with TC loss of only the treated samples over the full 8 months ($F_{1,6} = 32.31$, $r^2 = 0.82$, $p = 0.0013$), initial 4 months ($F_{1,6} = 33.59$, $r^2 = 0.82$, $p = 0.0012$), and final 4 months ($F_{1,6} = 14.71$, $r^2 = 0.66$, $p = 0.0086$). Change in C/N ratios of natural samples had no relationship with TC loss and the linear regression is not shown.

Other decomposition indicators measured, HI, OM content, and $\delta^{15}\text{N}$, were not observed to have relationships with TC loss. Linear regressions between these indicators and TC loss were not significant (Appendix A).

Along with having different relationships with C/N ratios, treated and natural samples showed different trends in decomposition indicators changing over time (Table 2.3). C/N ratios of the treated samples generally increased while the natural samples showed an increase in C/N ratios at the 4-month endpoint and a decrease at the 8-month endpoint. Similarly, both stable isotopes generally

became heavier for the natural samples and became lighter for treated samples. $\delta^{15}\text{N}$ of the treated samples was found to become heavier at the 4-month endpoint and lighter at the 8-month endpoint. OM also behaved differently between the two groups. For the treated samples, OM decreased over time while OM of the natural samples did not change. HI were the only variable that showed the same trend for the treated and natural samples. For all samples, HI increased over time.

Table 2.3: Decomposition indicators in peat incubation samples over time.

		Treated		Natural	
		Mound	Low	Mound	Low
TC (mg/g)	Initial	368.53 ± 96.62	399.78 ± 65.20	444.10 ± 22.26	434.17 ± 54.08
	4 months	390.12 ± 44.14	431.88 ± 48.90	453.76 ± 22.88	464.64 ± 26.82
	8 months	463.45 ± 15.94	465.83 ± 9.44	400.58 ± 67.48	352.91 ± 87.38
TN (mg/g)	Initial	12.90 ± 2.65	12.24 ± 1.61	10.56 ± 0.84	9.86 ± 0.76
	4 months	11.96 ± 0.78	14.62 ± 1.59	6.95 ± 0.94	8.00 ± 0.70
	8 months	8.32 ± 1.15	7.37 ± 0.69	11.08 ± 0.19	10.43 ± 1.41
C/N	Initial	29.86 ± 3.51	34.71 ± 5.87	42.84 ± 3.42	45.01 ± 4.85
	4 months	33.34 ± 3.84	30.56 ± 3.75	69.43 ± 10.34	59.44 ± 5.29
	8 months	59.78 ± 9.85	65.05 ± 6.75	36.19 ± 3.20	34.92 ± 5.26
$\delta^{13}\text{C}$ (‰)	Initial	-27.04 ± 0.35	-29.21 ± 0.27	-29.38 ± 0.73	-29.77 ± 0.71
	4 months	-27.04 ± 0.40	-28.91 ± 0.58	-29.95 ± 0.72	-29.12 ± 0.62
	8 months	-29.28 ± 0.83	-29.57 ± 0.59	-28.34 ± 0.51	-26.67 ± 0.39
$\delta^{15}\text{N}$ (‰)	Initial	-0.86 ± 0.48	-0.90 ± 0.55	-6.05 ± 1.43	-7.67 ± 1.76
	4 months	0.83 ± 0.48	0.61 ± 0.41	-3.19 ± 1.10	-2.56 ± 0.69
	8 months	-1.63 ± 1.00	-1.39 ± 1.00	1.29 ± 0.57	1.89 ± 0.52
Organic matter content (%)	Initial	67.9 ± 11.5	82.0 ± 6.4	93.6 ± 2.2	90.0 ± 3.0
	4 months	67.0 ± 12.1	84.0 ± 6.7	92.7 ± 3.2	92.2 ± 2.0
	8 months	63.8 ± 13.8	79.2 ± 10.0	93.1 ± 2.3	90.0 ± 3.1
Humification index (HI)	Initial	0.19 ± 0.024	0.37 ± 0.071	0.14 ± 0.020	0.16 ± 0.033
	4 months	0.27 ± 0.066	0.22 ± 0.025	0.14 ± 0.016	0.18 ± 0.013
	8 months	0.22 ± 0.041	0.23 ± 0.0055	0.16 ± 0.0095	0.19 ± 0.017

2.5 Discussion

The main goal of mounding on seismic lines is to restore forest cover to preserve caribou populations. As a result, restoration success is often determined by tree seedling growth and survival in the first few years after mounding. Although mounding has been shown to increase tree regeneration, overall vegetation communities may shift away from the surrounding natural vegetation (Echiverri, Macdonald, & Nielsen, 2020; Dabros et al., 2018). Effects of mounding on conditions other than tree regeneration are understudied, with few studies on soil properties. Flooded conditions of seismic lines have been assumed to prevent tree growth and survival but other soil properties such as nutrient availability may be limiting tree and overall vegetation recovery (Pacé et al., 2018; Bilodeau-Gauthier et al., 2011). Substrate quality, including factors such as nutrient availability, labile C, and bulk density, can also control vegetation recovery (Kozłowski, 1999; Triisberg et al., 2013) and were observed to vary between natural peatlands and both untreated seismic lines, with further changes following mounding.

2.5.1 Physical Properties

Bulk density was greatly increased on the mounds (Table 2.1), likely due to the exposure of deeper peat, or mineral soil and clay at FC5-7. Natural conditions, WCU, and low-lying areas at SC2 and WCO were within the range of average bulk density of $0.08 \pm 0.04 \text{ g/cm}^3$ from 215 northern, undisturbed peatlands (Loisel et al., 2014). Bulk densities of mounds at FC5-7, SC2, and WCO were well above the reported average with 0.5 ± 0.1 , 0.2 ± 0.04 , and $0.4 \pm 0.05 \text{ g/cm}^3$, respectively. Bulk density is linked to hydrological parameters such as water retention and hydraulic conductivity, which can affect water availability for plants. Compaction decreases macroporosity, which is reflected in increases in bulk density (Frey et al., 2009). Lower macroporosity and higher bulk density increase water retention and unsaturated hydraulic conductivity (Frey et al., 2009; Gauthier, McCarter, & Price, 2018). Saturated hydraulic conductivity is linked to bulk density through factors such as pore diameter and pore tortuosity (McCarter et al., 2020). With increasing bulk density, pore diameter decreases, and pore

tortuosity increases, which in turn decreases hydraulic conductivity (McCarter et al., 2020). A bulk density of 0.2 g/cm³ has been presented as a critical threshold for identifying degraded peat (Liu & Lennartz, 2018). Above this threshold, the hydrology of compacted peat was more similar to mineral soils with macroporosity and saturated hydraulic conductivity no longer decreasing with increasing bulk density (Liu & Lennartz, 2018). Changes in hydrology from compaction can negatively impact vegetation recovery by creating anoxic, waterlogged conditions with high soil strength that decrease root growth (Kozłowski, 1999). In addition to negatively impacting roots, compacted soil has been found to reduce tree relationships with ectomycorrhizal fungi that are important for N uptake (Page-Dumroese et al., 1998). The increases in bulk density observed on mounds could have significant negative impacts on plant community recovery. 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 the newer sites, mounding increased bulk density by an average of 697%. At FC5-7, mounding increased bulk density both on the mounds and on the adjacent low-lying areas by 1424% and 460% relative to natural areas.

Untreated seismic lines at WCU did not show an increase in bulk density. This conflicted with previous studies that reported that seismic lines are often compacted (Davidson et al., 2020; Lovitt et al., 2018; Dabros et al., 2018; Lee & Boutin, 2006). Public use of seismic lines, such as hikers and snowmobiles, has significant impacts on peat bulk density (Dabros et al., 2018). The remoteness of the present study site prevents human use from further compacting the peat. With the lack of human use, compacted peat on seismic lines may be able to naturally recover. Natural recovery of compacted peat is possible with recovery observed to occur within 15 years after disturbance in logged peatlands (Lepilin et al., 2019).

Additionally, the low-lying areas adjacent to mounds at SC2 and WCO were not affected by the mounding process despite the use of backhoes. The lack of increase in bulk density on the low-lying

areas at SC2 and WC0 could be because operators only drove over the lines once while mounding (Jeff Malbeuf, North Pine Environmental Ltd., personal communication). During the treatment, specific lines were put aside as access lines to ensure the treated lines would not be more disturbed by heavy machinery traffic. At FC5-7, this method was not employed, and operators would have driven over the treated lines multiple times. Mounding in the winter when the ground is frozen may also reduce compaction from heavy machinery but can also result in safety challenges for operators (Michael Cody, Cenovus Energy, personal communication).

Previous studies have suggested peat compaction on seismic lines results in ground subsidence bringing the surface closer to the water table (Davidson et al., 2020). As expected, untreated and treated lines had higher VWC than the natural areas. Ground subsidence may be occurring as a higher bulk density was correlated with a higher VWC on the untreated lines. The higher VWC on lines may also be from higher water retention in compacted peat (Frey et al., 2009; Lepilin et al., 2019) but treated lines had no relationship between bulk density and VWC. With the mounding process moving and inverting the peat profile, effects from ground subsidence on soil density could be confounded due to the potential mixing of mineral soil into the peat, thereby increasing bulk density.

At FC5-7 and WC0, mounding decreased the VWC from approximately 60% to 40%. At SC2, mounds did not have a statistically lower VWC than the corresponding low-lying areas or the untreated lines. This supports previous findings of high VWC after mounding in peatlands (Davidson et al., 2020). Unlike with upland mounding (Filicetti et al., 2019), mounds still had a significantly higher VWC than both the natural hummocks and hollows (Table 2.1). Mounds were not observed to slump and were still elevated above the water table. The high bulk densities of the mounds may reduce drying and aeration of mounds due to increased water retention. Future studies should focus on the pore size distribution and hydraulic properties of soils following mounding to better describe these changes.

Although the changes to porosity and hydraulic properties were not determined, VWC alone can greatly impact substrate quality for vegetation growth. One study on white spruce found the ideal VWC to be 40% for height and biomass growth initially and then 25% for the second growing season (Lamhamedi et al., 2006). Black spruce likely has similar requirements for growth. Black spruce probability of survival was found to be dependent on moisture classes. In a study comparing moisture regimes in peatlands, the probability of survival in plots with standing water was around 15% and 60% in “wet”, or consistently saturated conditions (Morris et al., 2009). In drier conditions, classified as “moist”, “fresh”, and “dry”, the probabilities of survival were all close to 80% (Morris et al., 2009). Another study found that black spruce seedlings' growth and water use decreased when the water table was raised from 30 cm to 15 cm below the surface (Woken et al., 2011). Our results indicate that while mounding in peatlands lowers VWC compared to low-lying areas, it may not be able to provide dry enough microsites for tree growth as mounds continue to have higher VWC than natural conditions years after treatment. High moisture conditions on seismic lines are a main driving factor of the lack of natural vegetation recovery (van Rensen et al., 2015). Highly disturbed and wet conditions on seismic lines likely promote the growth of graminoids such as *Carex aquatilis* (Dabros et al., 2018). *Sphagnum* would be expected to recover on mounds as the VWC was high enough to not limit productivity (Price and Whitehead, 2004; Cagampan and Waddington, 2008). *Sphagnum* also generally dominates with high light availability (Fenton & Bergeron, 2006). However, *Sphagnum* and other moss cover were close to zero on mounds (see Chapter 3), likely due to soil inversion during the mounding treatment. The degree of disturbance from creating the mounds may be further encouraging competitive, disturbance tolerant graminoids.

The lack of moss cover and exposure of mineral soils on mounds was reflected in the OM content. FC5-7 and WC0 mounds had lower OM content, 52.21 ± 10.14 and $69.47 \pm 6.52\%$, than the natural areas and untreated lines at 95.00 ± 0.85 and $86.35 \pm 3.26\%$, respectively. The OM content on the smaller mounds at SC2 was comparable to all sites. The difference in OM content at the three

different treated lines was likely due to the amount of mineral soil exposure. Although SC2 was older than WCO, there was not significant moss recovery that could explain the higher OM content.

Although removing OM content shifts the lines away from natural peatland conditions, some studies show increased seedling growth on mounds with exposed mineral soils due to increased N and P availability (Lafleur et al., 2011b) but this has not been observed in all studies (Henneb et al., 2019). In studies where mineral soils provided a benefit to tree growth, the mounds with a mineral and organic mix were drier than the natural areas with a thick organic layer. In this study, mounds with mineral soil were not drier than the natural hummocks. Whether low OM content provides a benefit or hindrance to vegetation recovery at the study sites depends on if nutrient availability is increased.

2.5.2 Total Nutrient Pools

Although available nutrients were not measured, N/P ratios higher than 16:1 on both SC2 mounds and low-lying areas suggested a shift from N to P limitation while FC5-7 and natural areas remain N limited (Wang et al., 2015). N/P ratios were solely driven by increases in TN while TP remained constant between all sites and microsites. With elevated N/P ratios in low-lying areas at SC2 and no increase in N at FC5-7, the exposure of mineral soils was likely not responsible for increased TN. As chemical properties were only measured at FC5-7, SC2, and natural areas and not at WCO or WCU, it is not known whether the increase in TN occurred after seismic line creation or restoration.

Peatlands are often N limiting but can shift to P limiting in prolonged flooded conditions (Charman, 2002). Plant growth can be easily influenced by small changes in nutrient availability (Charman, 2002). Additionally, the form of N can affect vegetation communities. Studies on logged, flooded peatlands with similar conditions to seismic lines showed a shift in available N from nitrate to ammonium, which would also have implications for vegetation competition (Westbrook et al., 2006;

Finnegan et al., 2014). For example, increased ammonium from mineral soil exposure in a logged peatland improved black spruce seedling growth (Lafleur et al., 2011a).

The measurements of TN do not distinguish between organic and inorganic N. Depending on which form the increased TN at SC2 was in, plants may not be able to quickly take up the increased N. Estimations of N mineralization could indicate if TN is easily and quickly available to plants. N mineralization rates, as well as C mineralization rates, have been predicted to increase with mounding due to increased soil temperature and aeration (Bilodeau-Gauthier et al., 2011; Updegraff et al., 1995). However, studies on mounding have not found N mineralization to change significantly (Smolander & Heiskanen, 2006; Bilodeau-Gauthier et al., 2013). While the lack of increased N mineralization was not explained, a decrease in C mineralization on mounds was suggested to be from a limitation of labile C supply and not soil moisture (Smolander & Heiskanen, 2006). Although moisture and temperature conditions on mounds may support higher mineralization rates, decreases in substrate quality, specifically labile C and N, can confound these effects (Updegraff et al., 1995; Westbrook et al., 2006). Lower C/N ratios on seismic lines, especially on the mounds (Table 2.2), suggest a loss of labile C that could inhibit C mineralization rates as observed in the literature. More recalcitrant OM decreases substrate quality and may hinder microbial activity and vegetation recovery (Lafleur et al., 2011a). Although indicative of lower substrate quality, lower C/N ratios have been observed to increase N mineralization (Liu et al., 2019). Lower C/N ratios and elevated TN on SC2 mounds may be a result of increase N mineralization rates but more research would be required to determine mineralization rates.

The level of disturbance during mounding and subsequent nutrient availability is important for vegetation recovery and succession trajectories. Nutrient availability in disturbed peatlands has been observed to have significant controls on vegetation cover and composition, especially in early successional stages (Huotari et al., 2007). The establishment of pioneer species is important for later vegetation recovery and important pioneer species such as *Polytrichum strictum* are inhibited by P

limitation (Huotari et al., 2007). Although N availability can be beneficial for tree growth, increasing N availability also can result in a loss of *Sphagnum* and an increase in vascular plant cover (Lafleur et al., 2011a; Limpens et al., 2008). The changes in nutrient cycling on seismic lines may cause vegetation community shifts that prevent further succession from occurring through competition and controlling available nutrients.

2.5.3 Decomposition, C loss, and shifts in C/N

With the focus of seismic line restoration on a return to forest cover, there have been few studies on carbon loss from CO₂ and CH₄ emissions. Seismic lines may shift peatlands from C sinks to C sources due to the removal of vegetation and increased temperatures (Dabros et al., 2018). Mounding may further increase C loss due to additional vegetation loss and greater aeration and higher temperatures on the mounds. Increased C emissions can lower substrate quality and alter peat structure leading to collapse (McCarter et al., 2020; Kool, Buurman, & Hoekman, 2006). Due to the remoteness and difficulty accessing seismic lines, traditional methods of measuring C fluxes are difficult to use. The goal of this study was to determine if easily measured decomposition markers can be used to predict C loss on seismic lines.

C/N ratios are commonly used to determine decomposition degree and are even used to assess the usefulness of other decomposition indicators, such as stable isotopes (Biester et al., 2014; Broder et al., 2012). C/N ratios from the incubation study were related to TC loss with higher initial C/N ratios resulting in higher TC loss. A higher C/N would indicate less decomposed peat that would support more decomposition and TC loss than a highly decomposed peat with lower C/N ratios. Therefore, the C/N ratio in the undisturbed section of the peatland appears to be an indicator of the potential for C loss during seismic line construction and restoration.

For the treated samples only, larger decreases in C/N were associated with greater TC loss. C/N ratios are generally observed to decrease during decomposition to a critical ratio, around 40:1 in Canadian forests, close to the ratios of decomposers (Moore et al., 2011). This critical ratio may be different in peatlands, but C/N ratios would still be expected to decrease towards ratios of decomposers (Moore et al., 2011). In contrast to this relationship, C/N ratios of treated samples were observed to increase on average over time. Treated samples generally started below the critical ratio and increased above the critical ratio. Natural samples started close to the critical ratio, increased at the 4-month endpoint, and then decreased below the critical ratio at the 8-month endpoint. This may indicate an accumulation of decomposer biomass in the samples that affected C/N ratios.

In the incubation study, both TC and TN changed over time. TC decreased as expected for the natural samples but remained constant for the treated samples. TN also decreased or remained constant resulting in variable but generally increasing C/N ratios over time. Balances between TC and TN could be controlled by microbial C or N limitation when oxygen supplies are constant. When microbes are N limited, they retain immobilized N, and N mineralization is low (Mooshammer et al., 2014). When C is limited, microbes release N through increased mineralization (Mooshammer et al., 2014). As treated samples consisted of older, more decomposed peat, samples were likely more C-limited than natural samples.

Field results showed expected trends of C/N ratios. Mounds at both FC5-7 and SC2 had C/N ratios close to the observed critical C/N of around 40. This was expected as mounds have more decomposed peat than the surrounding areas from the exposure of deep peat. With measurements of only C/N ratios, it is difficult to determine the cause in lower C/N ratios on the mounds as both exposed deeper peat and increased decomposition rates could explain lower C/N ratios.

C/N ratios at low-lying areas would not be expected to be as affected as mounds due to lower levels of disturbance and change at SC2. FC5-7 was heavily disturbed with exposed clay and mineral soils on both low-lying areas and mounds. As a result, low-lying areas at FC5-7 had significantly lower C/N ratios than the natural areas. Additionally, C/N ratios at FC5-7 were below the critical ratio of 40 suggesting that presence of mineral soils and clay was likely responsible for the change in the value over increased peat decomposition. This was different at the less disturbed SC2. SC2 low-lying areas had lower C/N ratios approaching the critical ratio without evidence of mineral soils and clay mixed into the peat. This would suggest that decreased C/N ratios on SC2 low-lying areas could be from increased decomposition instead of from exposure of deeper, more decomposed peat. High VWC on the lines could conflict with higher decomposition rates. However, VWC was only measured on one day and past hydrological conditions may have been different to allow for increased decomposition. C/N ratios can also be impacted by other ways of C loss. Studies on logged peatlands with flooded conditions observed leaching to result in labile C loss, an increase in recalcitrant C, and a decrease in C/N ratios (Kim et al., 2014; Trettin et al., 2011). In seismic line creation, the top layer of peat is often removed and in restoration, the top layer is buried. This could have further implications for C/N ratios as labile C is highest in the top layer of peat and decreases with depth (Leifeld, Steffens, & Galego-Sala, 2012).

Generally, C is preferentially lost as decomposition occurs while N remains relatively constant in peatlands during anaerobic decomposition (Kuhry and Vitt, 1996). This occurred at FC5-7 where C/N ratios were driven by decreased TC. Similar to OM content, TC was lower for both mounds and lows at FC5-7 when compared to the natural areas while SC2 was comparable to all sites. With TC and OM lower than expected for peat and the observed exposed clay and mineral soil, FC5-7 soil properties are expected to be more influenced by the high degree of disturbance than changes in soil processes from the mounding processes. SC2 did not show preferential loss of TC and instead, TC was relatively constant while TN increased on both mounds and low-lying areas. TN at SC2 was significantly higher

than FC5-7, natural conditions, and a reference peat database (Loisel et al., 2014). One explanation for this could be that immobilized N is returned to the TN pool as microbe litter from increased N mineralization in aerobic conditions (Malmer & Holm, 1984; Damman, 1988). Observed changes in decomposition indicators on the mounds may be from increased decomposition or from the exposure of deeper, more decomposed peat.

2.5.4 C Loss and shifts in stable isotope composition

Reflecting the above results of highly disturbed and decomposed mounds, field samples showed heavier $\delta^{13}\text{C}$ on the seismic lines with the heaviest $\delta^{13}\text{C}$ on the mounds. Enrichment of ^{13}C can reflect the degree decomposition as ^{12}C is preferentially lost during OM mineralization (Nadelhoffer & Fry, 1988). This would support an increase in decomposition on seismic lines. Exposure of deep peat likely also contributes to the shift as $\delta^{13}\text{C}$ was heavier on mounds than the low-lying areas at SC2 where low-lying areas did not have exposed deep peat. At FC5-7 where low-lying areas did have exposed deeper peat or mineral soil and clay, there was no difference in $\delta^{13}\text{C}$ between microsites.

Treated samples in the incubation study were also found to have heavier starting $\delta^{13}\text{C}$ than the natural samples. However, treated samples then became enriched in ^{12}C over time while natural samples were enriched in ^{13}C as expected. While uncommon, $\delta^{13}\text{C}$ has been observed to become lighter during decomposition. One possible explanation is based on compound-specific decomposition. Litter from some species, like saltmarsh *Spartina alterniflora*, have been found to deplete peat ^{13}C due to preferential decomposition of polysaccharides and prevalence of lignin (Benner et al., 1987). While easier to decompose, polysaccharides, such as cellulose and hemicellulose, are generally heavier in $\delta^{13}\text{C}$ compared to the whole plant, while lignin is lighter (Benner et al., 1987). The shift in vegetation composition towards more graminoids on seismic lines may result in lighter $\delta^{13}\text{C}$ during decomposition as observed in the incubation.

The initial and second endpoint $\delta^{13}\text{C}$ was strongly correlated with TC loss throughout the experiment, which suggests that a single $\delta^{13}\text{C}$ measurement may be able to help predict TC loss in the future. Lighter $\delta^{13}\text{C}$ was found to result in more TC loss. If a starting substrate is more enriched in ^{12}C , decomposition can likely occur more rapidly than substrates enriched in the more energetically costly ^{13}C . The lack of correlation between the third endpoint and TC loss suggests that $\delta^{13}\text{C}$ cannot be used to estimate past TC loss.

Results from both the field and incubation study suggest that $\delta^{13}\text{C}$ was linked with decomposition and subsequent C loss. However, mounding may confound or alter the relationships between decomposition, TC loss, and $\delta^{13}\text{C}$. The exposed deeper peat, mineral soils, or even clay, along with changes in litter input on the mounds will shift $\delta^{13}\text{C}$ of soil, which would result in lower reliability in using $\delta^{13}\text{C}$ as a decomposition indicator or measure of TC loss.

$\delta^{15}\text{N}$, a more debated indicator of decomposition, showed the same trends of $\delta^{13}\text{C}$ in the field with heavier $\delta^{15}\text{N}$ on seismic lines overall and heaviest $\delta^{15}\text{N}$ on the mounds. Although field measurements indicated $\delta^{15}\text{N}$ becomes heavier with decomposition, in the incubation study $\delta^{15}\text{N}$ was not found to be related to TC loss. Some studies have observed the same result with $\delta^{15}\text{N}$ being unchanged during decomposition (Biester et al., 2014) while others have shown both heavier and lighter $\delta^{15}\text{N}$ in response to decomposition (Hobbie, Macko, & Shugart, 1998; Bragazza et al., 2010; Asada, Warner, & Aravena, 2005; Krüger et al., 2017; Drollinger, Kuzyakoy, & Glatzel, 2019). For field results, $\delta^{15}\text{N}$ would be expected to become lighter during decomposition due to anaerobic conditions. Anaerobic conditions increase denitrification and reduce isotopically heavier nitrate (Hobbie, Macko, & Shugart, 1998). Additionally, the lower C/N ratios on the lines are more suitable for bacterial decomposition, which results in lighter $\delta^{15}\text{N}$ due to nitrate immobilization, over fungal decomposition (Bragazza et al., 2010). However, there was a strong negative, linear relationship between $\delta^{15}\text{N}$ and C/N ratios in the field as found in other studies, supporting a shift to heavier $\delta^{15}\text{N}$ with decomposition

(Asada, Warner, & Aravena, 2005; Krüger et al., 2017; Drollinger, Kuzyakoy, & Glatzel, 2019). Although the incubation study does not show a relationship between $\delta^{15}\text{N}$ and C/N ratios or TC loss, $\delta^{15}\text{N}$ was observed to become heavier over time. Seismic lines may support enough aerobic decomposition to result in heavier $\delta^{15}\text{N}$ and the incubation study was conducted in controlled oxic conditions.

2.5.5 CO₂ and CH₄ Emissions

As would be expected in oxic conditions, CH₄ emissions for all samples in the incubation study were small and did not contribute significantly to TC loss. CH₄ emissions were unaffected by the mounding treatment. CH₄ emissions from mounds were comparable to natural hummocks, and low-lying areas on the lines were comparable to natural hollows. Mounds and hummocks had significantly lower CH₄ emissions than low-lying areas and hollows. In past studies, seismic lines have been found to increase CH₄ emissions likely due to higher water tables, higher temperatures, and increased graminoid cover providing a labile C source and CH₄ transport (Strack et al., 2018; Strack et al., 2019). The incubation study would have removed soil temperature and moisture as variables with peat samples stored at a consistent VWC and temperature. As a result, the difference between microsites was not expected. In another 20-day incubation study, CH₄ emissions were still controlled by field moisture conditions and had no relation to moisture conditions held constant during the incubation (Basiliko et al., 2007).

With soil temperature and moisture held constant, differences in CH₄ emissions would be expected to be from differences in peat composition and microbial community. If peat composition were controlling CH₄ emissions, then natural and treated samples would not be expected to be comparable. Additionally, indicators of substrate quality, BD, OM, C/N ratios, $\delta^{13}\text{C}$, $\delta^{15}\text{N}$, and humification indices, were not related to CH₄ emissions. Although labile C was not directly measured, humification indices would be expected to reflect changes in labile to recalcitrant C ratios. There are also other measurements of substrate quality such as available P that can influence CH₄ emissions (Basiliko et

al., 2007). Substrate structure can also be important for CH₄ production by creating anaerobic microsites within the overall aerobic substrate (Glatzel, Basiliko, & Moore, 2004). It is possible that differences in the microbial community arising from varying field conditions contributed to the measured CH₄ flux during the incubation. Further research on the effect of seismic lines on microbial community composition and activity are needed.

As with CH₄, CO₂ emissions during the incubation would be expected to be influenced mainly by substrate quality. CO₂ emissions have been found to decrease with depth and soil quality (Leifeld, Steffens, & Galego-Sala, 2012; Hardie et al., 2011). The initial substrate quality as indicated by $\delta^{13}\text{C}$ and C/N was observed to be related to CO₂ emissions. Mound samples with heavier $\delta^{13}\text{C}$ and lower C/N ratios had lower CO₂ emissions than natural samples with lighter $\delta^{13}\text{C}$ and higher C/N ratios. The exposure of deep peat on the mounds could explain the lower emissions on the treated mounds. In a study using peat cores, CO₂ emissions started to decrease at 10-20 cm below the surface due to changes in substrate quality (Hardie et al., 2011). Lower substrate quality appeared to decrease CO₂ emissions and TC loss in the incubation study. However, these results cannot be used as representative of field conditions. Substrate quality is likely related to TC loss in the field but other conditions such as temperature and moisture that were controlled in the incubation study could influence results.

2.6 Conclusions and Implications for Restoration

While restoration success can be measured in multiple ways, a major goal of the mounding treatment is to provide a drier, more aerated microsite for increased tree survival and growth. Although mounds are elevated above the water table, VWC was not consistently decreased on mounds. A potential explanation for this could be the increased bulk density of mounds that would increase water retention of the peat. Both the high bulk density and low OM content were likely directly related to the amount of exposed deeper peat, mineral soil, or clay. The predicted benefits of mixing mineral soil with

low OM content on mounds include higher nutrient availability and drier conditions. However, in this study, low OM content was not observed to be linked to higher nutrient content or drier conditions. Observed changes in physical peat properties may prevent mounds from being beneficial microsites for tree growth.

Unlike the mounds, low-lying areas on treated lines and both microsites on untreated lines had comparable bulk densities and OM content to natural conditions. Mounding has been found to only alter soil physical properties locally on the created mounds while adjacent low-lying areas were unaffected. Created holes were not sampled and likely have altered soil properties but would not be acceptable sites for woody vegetation growth regardless of soil conditions due to being filled with water. Although physical properties in low-lying areas on treated lines were largely unaffected by mounding, peat was enriched in heavier isotopes and had lower C/N on both mounds and low-lying areas when compared to natural areas. Overall, changes to stable isotopes and C/N ratios further indicate a decrease in substrate quality on mounds and adjacent low-lying areas. These changes may represent a poor substrate quality that may not benefit tree recovery as planned and result in altered vegetation communities.

In the incubation study, TC loss was decreased for the mound samples likely due to lower substrate quality reducing CO₂ emissions. CH₄ did not vary between treated and natural samples likely due to the controlled water content and oxic conditions in the jars. As samples were incubated in constant moisture and temperature conditions and were kept in a relatively closed system, measured fluxes are likely not representative of field conditions. With the difficulty of measuring CO₂ and CH₄ emissions on remote seismic lines, easily measured decomposition indicators could be helpful in better understanding TC loss. Endpoint measurements of $\delta^{13}\text{C}$ and C/N ratios showed potential to be used as an indicator of future TC loss. More research would be required to determine TC losses on seismic lines and the implications of mounding on decomposition rates.

Chapter 3 How mounds are made matters: Seismic line restoration techniques affect peat physical and chemical properties throughout the peat profile

3.1 Introduction

An estimated 345,000 km of seismic lines have been created in Alberta peatlands for oil and gas exploration (Strack et al., 2019). These long, linear disturbances have not returned to tree cover as initially expected and are now being restored through a method called mounding (Lee & Boutin, 2006). Mounding 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 (Liefers, Caners, & Ge, 2017; Bilodeau-Gauthier et al., 2011; Lafleur et al., 2011; Filicetti et al., 2018; Bilodeau-Gauthier et al., 2013; Smolander & Heiskanen, 2007) 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). This study aims to investigate how various mounding techniques alter the physical and chemical properties of the soil profile in peatlands.

Peatlands are important ecosystems defined by the presence of excess water that slows decomposition to allow for an accumulation of biomass, or peat, deeper than 40 cm (Vitt, 2006). Depending on the sources of water, peatlands are commonly divided into bogs and fens (Vitt, 2006). Bogs are peatlands fed only by precipitation while fens can be fed by streams and groundwater (Vitt, 2006). Peatlands can also be classified as swamps, which are defined in the Alberta Wetland Classification System by fluctuating water table levels and having at least 25% woody cover (ESRD, 2015). The differences in hydrology and source of nutrients between peatlands cause differences in soil composition, water chemistry, vegetation composition, and carbon cycling (Wu et al., 2012).

While often successful for promoting tree growth, classic 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). As untreated seismic lines often have recovering vegetation on the trajectory of restoring natural peatland plant communities, mounding on the line could be more viable if the peat profile is kept intact instead of inverting the soil and burying recovering vegetation. Removing vegetation further flattens the microtopography, decreases water intake and evapotranspiration, increases soil compaction, 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 method of 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. Hummock transfer does not involve digging or inverting the peat but often leaves a small depression where the hummock was removed. 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.

Inverted mounding impacts surface peat properties with unknown implications for vegetation recovery (Chapter 2, 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).

To determine the degree of peat decomposition, easily measured soil properties such as the ratio of carbon and nitrogen (C/N), stable isotopic composition ($\delta^{13}\text{C}$, $\delta^{15}\text{N}$), humification indices (HI), bulk density, and organic matter content (OM) are commonly used (Krüger et al., 2015; Drollinger et al., 2020; Biester et al., 2014; Broder et al., 2012). These decomposition indicators have known responses to aerobic and anaerobic decomposition throughout the peat profile due to preferential loss of certain compounds. C/N ratios are one of the most used indicators of decomposition and have been used to assess other soil properties' effectiveness in representing decomposition (Biester et al., 2014; Broder et al., 2012). C/N ratios decrease with decomposition as C is preferentially lost over N (Malmer & Holm, 1984; Biester et al., 2014). The ratio of heavier and lighter isotopes of C and N, represented by $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$, can also be used to show the degree of decomposition in peat (Nadelhoffer & Fry, 1988; Asada, Warner, & Aravena, 2005). For both C and N, lighter isotopes are decomposed first leaving behind heavier isotopes. $\delta^{15}\text{N}$ can be influenced by other peat processes, such as N cycling, which can result in the enrichment of the heavier or lighter isotope during decomposition (Hobbie, Macko, & Shugart, 1998). $\delta^{13}\text{C}$ is less affected by processes other than decomposition and has often been used reliably as a decomposition indicator (Biester et al., 2014; Broder et al., 2012; Alewell et al., 2014).

Along with C isotopes, types of C compounds are decomposed at different rates. HI represent the ratio of easily lost C compounds, carbohydrates, and more recalcitrant C compounds, usually aromatics or aliphatics (Cocozza, et al., 2003; Hodgkins, 2016). HI using aromatics are more commonly used, as aliphatics can easily be influenced by minerals and clay (Biester et al., 2014; Hodgkins, 2016). HI are determined through Fourier Transform Infrared spectroscopy (FTIR) analysis, which can also provide information on the soil C composition. The area of peaks from FTIR analysis provides the relative

abundance of C compounds, while the shape can be used to distinguish between the pH and depths of samples (Hodgkins, 2016).

Although the mechanism of change in peat properties following mounding is not well understood, inverted mounding greatly alters peat properties (Davidson et al. 2020; Chapter 2). 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 chapter 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) or from the exposure of deep peat

3.2 Study Sites

Two study sites, both wooded moderate-rich fens, were selected to compare the different mounding techniques. 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 3.1). The line was restored in 2017 by Cenovus Energy using inverted mounding techniques. Sampling was conducted in two sections of the line during September 2020. Dominant vegetation at SC3 includes *Betula pumila*, *Carex* spp., *Equisetum* sp., *Larix laricina*, *Oxycoccus microcarpus*, *Picea mariana*, *Polytrichum strictum*, *Rhododendron groenlandicum*, 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 3.1). The sampled BR1 line was created prior to 1982 as observed from satellite images. The line was restored in March 2019 and sampled during August 2020. The dominant vegetation at BR1 consists of *Picea mariana*, *Larix laricina*, *Rhododendron groenlandicum*, *Salix* spp., *Menyanthes trifoliata*, *Vaccinium oxycoccus*, *Sphagnum fuscum*, and *Sphagnum magellanicum*. At both sites, peat depth was at least 100 cm.

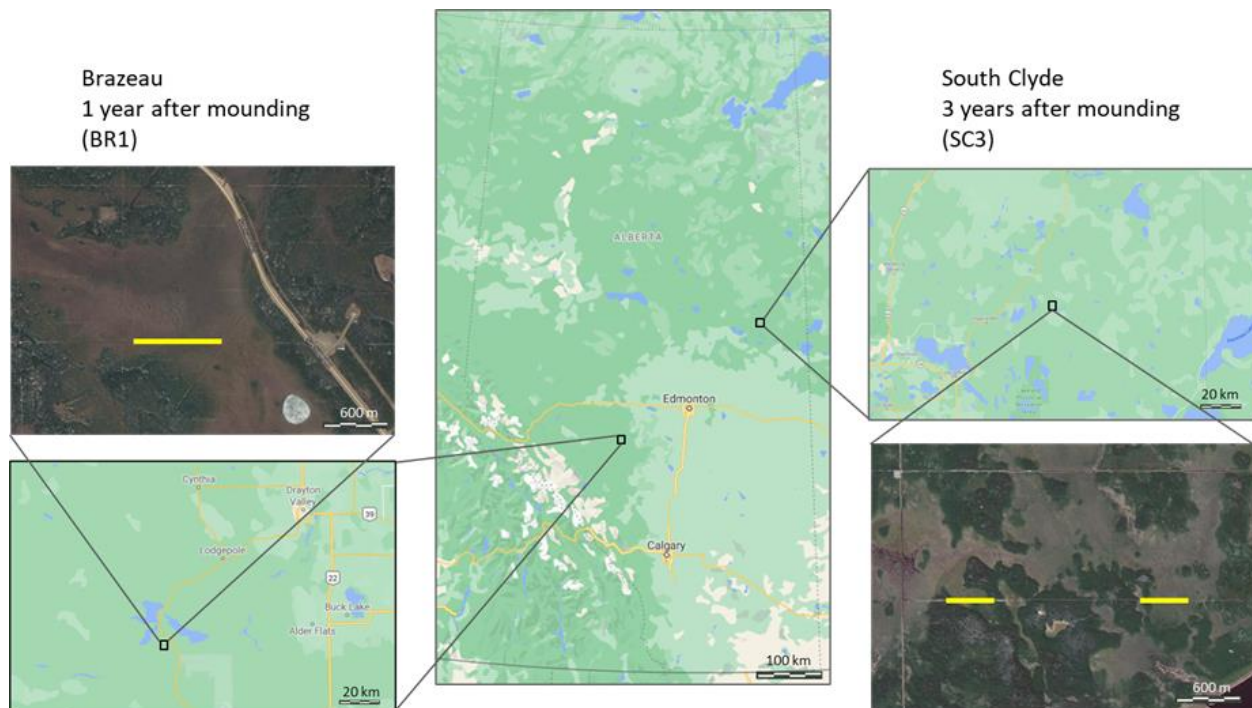


Figure 3.1: Map of the two study areas in Alberta, Canada.

The mounding at SC3 was conducted in the classic manner commonly used throughout Alberta. As described in Filicetti et al. (2019), an excavator with a 1 m³ bucket was used to create mounds by digging and inverting the peat onto the line. The resulting mound buried established vegetation and exposed deeper, more decomposed peat or mineral soils (Figure 3.2a). New mounding methods were used at BR1. The first, upright mounding, was similar to inverted mounding but preserves the soil profile by not inverting the peat. The mounds do not expose deeper peat and keep established vegetation intact (Figure 3.2b). The second method, hummock transfer, does not involve digging on the

line. Hummock transfer refers to the transfer of natural hummocks off the line to on the line (Figure 3.2c). 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 rotting depth of around 50 cm to allow regrowth in created hollows (Bin Xu, NAIT Centre for Boreal Research, personal communication).

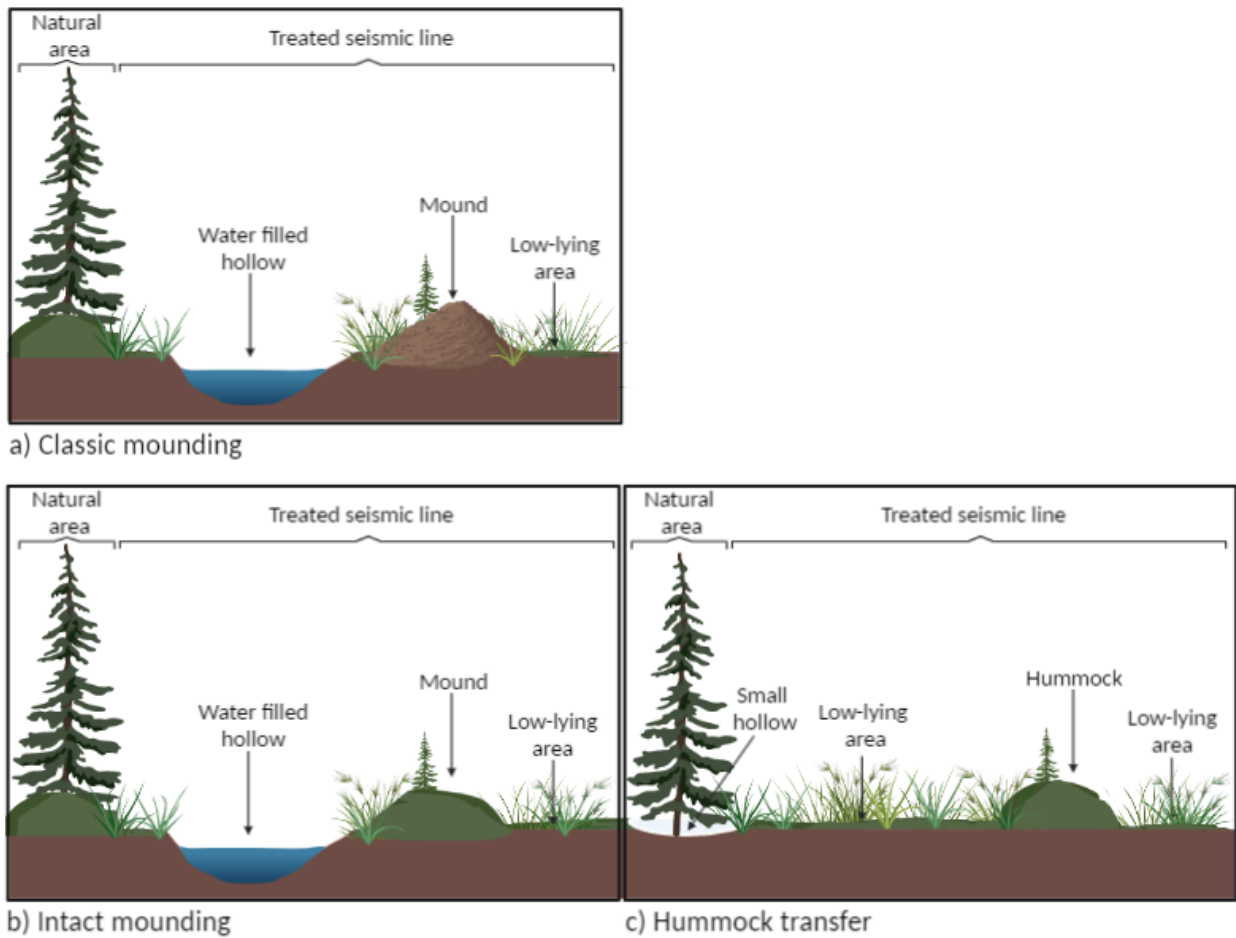


Figure 3.2: Illustration of different mounding techniques used on seismic lines: a) inverted mounding, b) intact mounding, and c) hummock transfer. Created with BioRender.com.

3.3 Methods

3.3.1 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 to a total of 18 cores. At BR1, four cores

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 to 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 soup can with a known volume of 562.70 cm³. Additionally, vegetation surveys to the functional group level were conducted in a 1 by 1 m square where each core was sampled.

3.3.2 Sample Processing

Upon arriving in Waterloo, Ontario 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 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.

The rest of the dried peat for depth intervals 0-40 cm, the interface of the mound and line (between 50-80 cm), 70-80 cm, 90-100 cm, and the deepest depth interval collected 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 $\delta^{13}\text{C}$, $\delta^{15}\text{N}$. TC, TN, $\delta^{13}\text{C}$, and $\delta^{15}\text{N}$ 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. Of the ground samples, 1 mg of peat was weighed out into tin capsules. Weighed out samples in tin capsules were combusted at 1030 °C (~1750 °C with the addition of oxygen) to convert all C and N present in the sample to CO₂ and N₂ gas, respectively. The gases passed through a packed column within the EA and separated (by mass) where a small amount was then directed to the mass spectrometer for measurement. Standard quality control methods were applied by the Environmental Isotope Lab, resulting in errors of 0.2‰ for δ¹³C and 0.3‰ for δ¹⁵N (see Appendix A for details)

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

3.3.3 Statistics

The statistical program R (R Core Team, 2017) was used for statistical analysis. A significance of $\alpha = 0.05$ was used for all statistical 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 cores 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 cores. When differences were significant, Tukey post hoc tests were used to determine which groups within and between sites differed from each other.

3.4 Results

3.4.1 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/cm³ across all samples (Figure 3.3). 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: $F_{5,22} = 11.6$, $p < 0.001$). Bulk densities for transferred hummocks could not be calculated as the peat volume was not recorded. Among all other cores, both natural hummocks and low-lying areas, and the upright mounding were found to have similar bulk densities at all depths. Although the mean bulk density for inverted mounds at the 20-30 cm was also high, one core significantly increased the mean to 0.23 g/cm³ while the other five cores had an average of 0.11 g/cm³. As a result, the 20-30 cm depth interval was not statistically higher than the lower depths. Despite high bulk densities at shallower depths, inverted mounds did not vary significantly from other peat cores at any depth. Bulk densities of upright mounds were also comparable at all depths. Both low-lying areas and natural hummocks at the sites had significantly higher bulk density with increasing depths (Appendix B, Tables B.1-4).

There was a large range of OM content across all samples from 27.1 to 98.1% (Figure 3.3). However, the range was greatly skewed with only 13 out of 384 samples having an OM content below 80%. These samples were all either below 100 cm in depth or from the inverted mounds. 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 (Appendix B, Tables B.5-7).

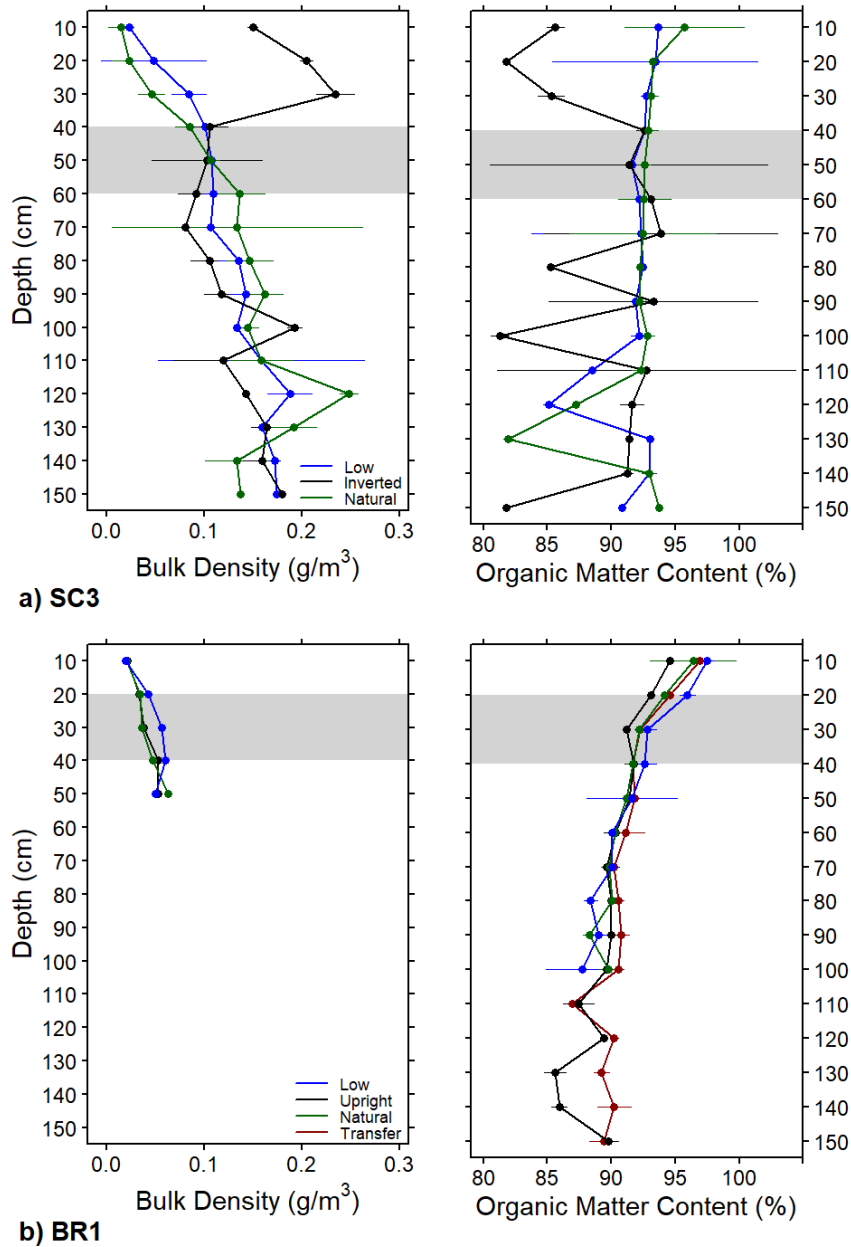


Figure 3.3: Profiles of bulk density and organic matter content for a) SC3 and b) BR1. When present, error bars represent one standard error. Points without errors bars did not have a large enough sample size to calculate the standard error. Grey bars show the range depth of the interface of the mound to the former ground surface.

3.4.2 Total C and N content

TC 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 depth than TC, but the range was smaller at 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, adjacent 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, the low-lying areas at SC3 also had more TN than the natural hummocks and low-lying areas at BR1. As with the C/N ratios, the 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. (Appendix B, Tables B.8-13).

Between all samples, C/N ratios ranged from 14.38 to 119.56 (Figure 3.4). At 0-10 cm, the low-lying areas and inverted mounds at SC3 had lower C/N ratios than both natural hummocks, low-lying areas at BR1, and transferred hummocks ($F_{6,28} = 12.29$, $p < 0.001$). Similarly, low-lying areas at SC3 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 (Appendix B, Tables B.14-19). 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.

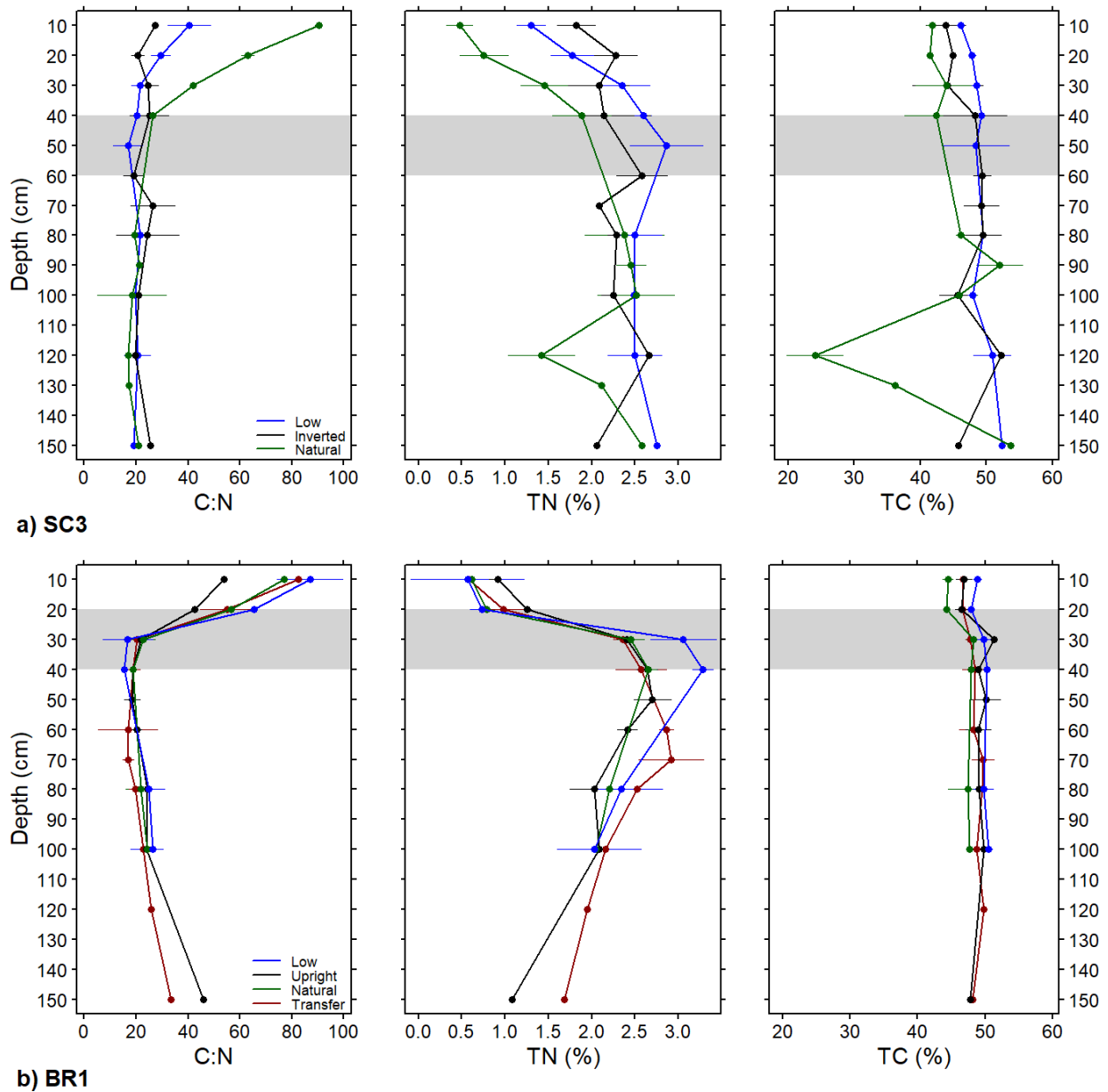


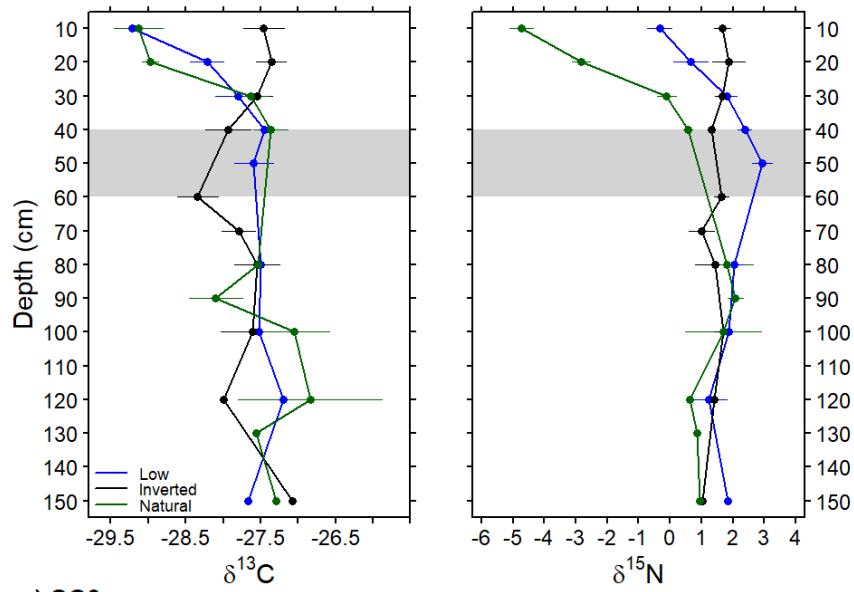
Figure 3.4: Profiles of C/N, TN, and TC at depth for a) SC3, and b) BR1. When present, error bars represent one standard error. Points without errors bars did not have a large enough sample size to calculate the standard error. Grey bars show the range depth of the interface of the mound to the ground surface.

3.4.3 Peat chemical properties

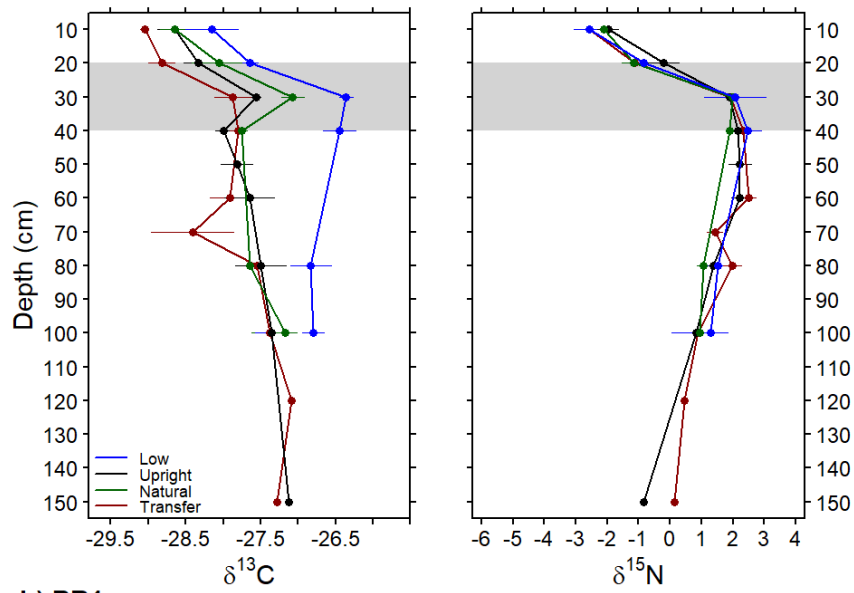
$\delta^{15}\text{N}$ was found to range from -5.94 to 3.22‰ (Figure 3.5). For all cores except for inverted mounding, $\delta^{15}\text{N}$ becomes heavier rapidly until 20-30 cm. At SC3, $\delta^{15}\text{N}$ remains constant at lower depths while at BR1, $\delta^{15}\text{N}$ becomes lighter again. The inverted mounding cores do not vary at depth (Appendix B, Tables B.20-25). When comparing across core types, at 0-10 cm, $\delta^{15}\text{N}$ was found to vary between

cores ($F_{6,28} = 30.62, p < 0.001$). SC3 natural hummocks had the most negative (lightest) $\delta^{15}\text{N}$ while inverted mounds had the most positive (heaviest) $\delta^{15}\text{N}$ followed by SC3 low-lying areas. Transferred hummocks, upright mounds, and BR1 natural hummocks and low-lying areas were in the middle and were all comparable to each other. $\delta^{15}\text{N}$ of the natural hummocks at SC3 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 low-lying areas at BR1 and transferred hummocks ($F_{6,25} = 10.05, p < 0.001$). At the 30-40 cm and 140-150 cm depths, the $\delta^{15}\text{N}$ of the SC3 natural hummocks was lighter than the low-lying areas at both sites ($F_{6,24} = 3.765, p = 0.0088$) ($F_{4,7} = 10.82, p = 0.0040$).

There was a relatively small range for $\delta^{13}\text{C}$ of -34.26 to -26.29‰ (Figure 3.5). Inverted mounds had the heaviest $\delta^{13}\text{C}$. For all cores except for inverted mounding, $\delta^{13}\text{C}$ becomes heavier rapidly until 20-30 cm and then remains constant (Appendix B, Tables B.26-30). At 0-10 cm, the $\delta^{13}\text{C}$ of inverted mounds was significantly heavier than the adjacent low-lying areas at SC3 ($F_{6,28} = 3.38, p = 0.012$). At 10-20 cm, the $\delta^{13}\text{C}$ 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 ($F_{6,25} = 6.21, p = 0.00043$).



a) SC3



b) BR1

Figure 3.5: Profiles of $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ at depth for a) SC3, and b) BR1. When present, error bars represent 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.

The HI of all samples fell within the range from 0.026 to 0.56 (Figure 3.6). There was a lot of variation in HI at depth below 50 cm, so we focus 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 (Appendix B, Tables B.31-36). At SC3, low-lying areas and natural

hummocks increased slightly with depth until 40 cm where lower depths had variable HI. HI for inverted mounds were higher than other cores and did not change throughout 0-40 cm depths. Cores at BR1 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. The cores at SC3 had a lower HI than the natural hummocks and low-lying areas at BR1 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 natural hummocks at BR1 ($F_{6,19} = 4.76, p = 0.0040$).

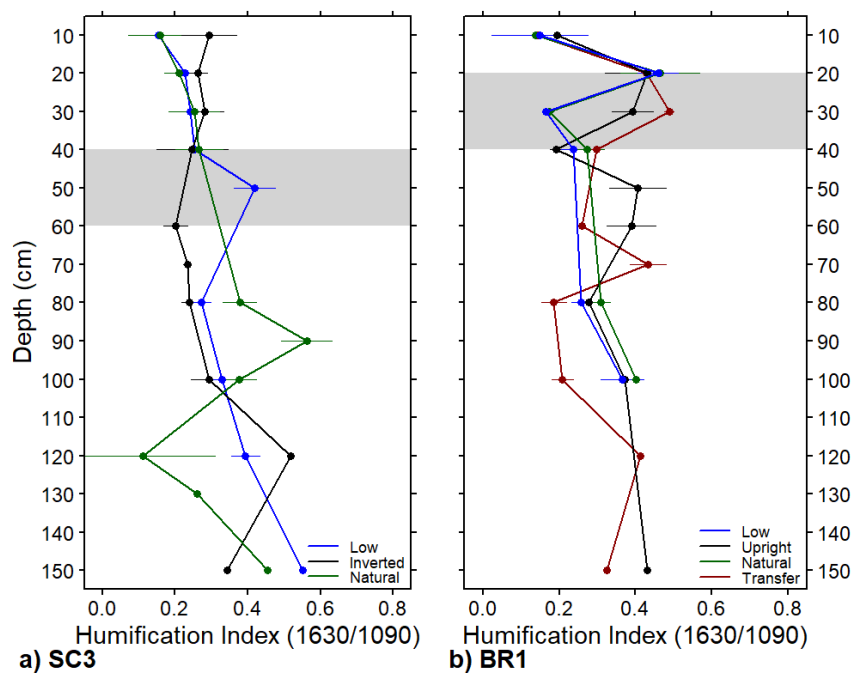


Figure 3.6: Profiles of humification indices (absorbance at wavenumbers 1630/1090) for a) SC3, and b) BR1. When present, error bars represent one standard error. Points without error bars did not have a large enough sample size to calculate the standard error. Grey bars show the range depth of the interface of the mound to the ground surface.

Figure 3.7 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 3.7, 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 once below 20 cm.

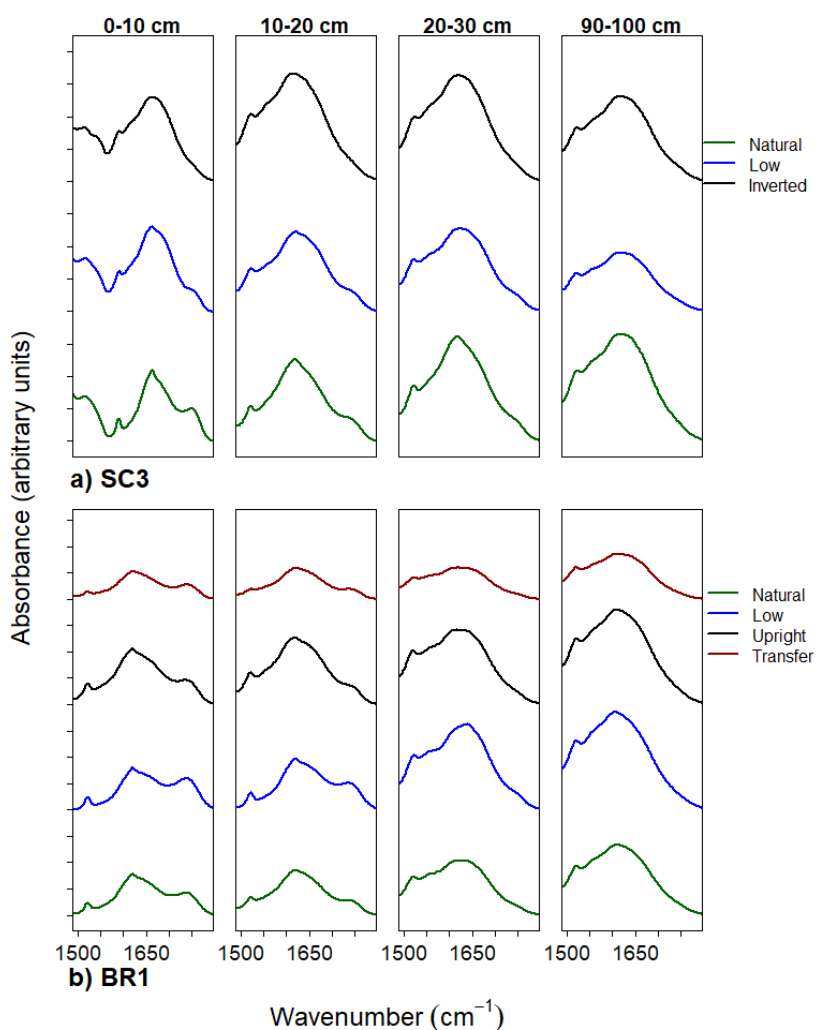


Figure 3.7: FTIR absorbance of aromatics between wavenumbers 1400 and 1650 for a) SC3, and b) BR1.

3.4.4 Vegetation surveys

Table 3.1 shows the vegetation cover of each treatment to the functional group level. Transferred hummocks and natural hummocks had a significantly higher shrub cover than SC3 ($F_{6,65} = 5.81, p < 0.001$). Low-lying areas at SC3 had higher graminoid cover than all mounding treatments and natural hummocks at SC3 ($F_{6,65} = 3.84, p = 0.0025$). All types within a site were comparable while SC3 had lower forb cover than BR1 ($F_{6,65} = 10.09, p < 0.001$). The inverted mounds had the lowest moss cover. Low-lying areas at SC3 also had lower moss cover than natural hummocks, BR1 mounding treatments, and low-lying areas ($F_{6,65} = 37.97, p < 0.001$). BR1 low-lying areas had higher open water cover than all other cores ($F_{6,65} = 5.63, p < 0.001$). Inverted mounds had higher bare ground cover than all other cores ($F_{6,65} = 13.66, p < 0.001$).

Table 3.1: 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

3.5 Discussion

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 (data not shown) indicate few changes over the year. By using t-tests, soil properties were largely found to be similar between SC2 and SC3 samples. The greatest changes were observed at the low-lying areas where TN increased on average from 11.34 to 18.24 mg/g ($t = 3.42$, $p = 0.0072$). $\delta^{13}\text{C}$ averages on mounds became lighter from -26.74 to -27.60 ‰ ($t = 2.58$, $p = 0.034$) and natural hummocks became heavier from -30.89 to -28.49 ‰ ($t = 2.72$, $p = 0.044$). Differences over time should not be substantial enough to prevent the comparison of the two mounding techniques. To address differences in sites, mounding techniques were primarily compared to their corresponding surrounding natural conditions.

3.5.1 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 (Davidson et al., 2020; Lovitt et al., 2018; Dabros et al., 2018; Lee & Boutin, 2006) but matches the previous sampling at the two study sites. Although SC3 is not accessible for public use, a common cause of seismic line disturbance (Dabros et al., 2018), BR1 is easily accessible by road and is situated on crown land. Snowmobiles are known to frequent the site in the winter. As summer traffic is less frequent, heavy snow may serve to protect the peat from compaction and degradation. 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 actions. Inverted mounding was found to have a significantly higher bulk density than all other cores at the 0-10 and 10-20 depth intervals. Bulk densities could not be calculated for the hummock transfer treatment. The high bulk densities of the inverted mounds would have various impacts relating to hydrology, gas exchange, structure 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). These changes cause the peat to become waterlogged and anoxic, which inhibits the growth and survival of both microbial and vegetation communities (Frey et al., 2009; Kozłowski, 1999). The structural changes are also linked to peat collapsing following excavation, which has been found to be an issue with mounding in peatlands (Kool, Buurman, & Hoekman, 2006; Filicetti et al., 2019; Lieffers, Caners, & Ge, 2017). While inverted mounds were heavily compacted, upright mounding bulk densities were comparable to natural conditions. The unaffected bulk densities of the upright mounding likely 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% compared to 96% on upright mounds and 92% 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). Upright mounding may result in a similar disturbance as in Lafleur et al. (2011a) as the shrub and graminoid cover was decreased (Table 3.1). 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, but further research on the growth of trees on the mounds is needed to evaluate this.

In the two aforementioned studies of exposed mineral soil and only lightly disturbed moss carpets, 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 3.4). Changes in the inverted mounds were greater than the upright mounds where C/N ratios were not statistically significantly lower than low-lying areas. Lower C/N ratios can promote tree growth, but too low C/N ratios with C limitations negatively affect vegetation growth and survival, availability of nutrients, and microbial activity (Asada, Warner, & Schiff, 2005).

Previous studies on logged peatlands would suggest that seismic lines may have lower C/N ratios from loss of DOC due to flooded conditions and leaching (Trettin et al., 2011; Kim et al., 2014). While this was not observed to occur as TC was constant between treatments and depths (Figure 3.4), the quality of the TC 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 showing a reduction in labile carbohydrates and an increase in recalcitrant aromatic

compounds. Upright mounds and transferred hummocks only had elevated HI for the 20-30 cm depths, otherwise, all cores at BR1 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 increases the amount of recalcitrant C compounds and decreases labile C compounds. Increases in recalcitrant C compounds have been observed to lower substrate quality by limiting microbial and plant growth and survival (Asada, Warner, & Schiff, 2005).

Isotopic data further indicates reduced substrate quality on the inverted mounds. $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ can be used as decomposition indicators as lighter isotopes are preferentially lost during decomposition (Biester et al., 2014; Broder et al., 2012). $\delta^{13}\text{C}$ in the inverted mound cores was heavier in the top 30 cm but the difference was not statistically significant. $\delta^{15}\text{N}$ was also constant with depth for the inverted mounds. Constant $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ at depth can result from moderate disturbance while intensive disturbance has been shown to cause surface $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ to be heavier than lower depths (Krüger et al., 2015). All other cores became heavier with depth until around 30 cm below which $\delta^{13}\text{C}$ 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 heavier as decomposition proceeds through the peat profile until lower depths where decomposition stops or is greatly reduced (Biester et al., 2014; Broder et al., 2012; 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 natural conditions.

3.5.2 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 as a result of increased decomposition rates resulting in soil disturbance during mounding activities. Peatlands are characterized by low

decomposition rates under anoxic 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 0-20 cm where decomposition rates could be increased by shifting from slower anaerobic to aerobic decomposition. In water-saturated peatlands, $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ 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 $\delta^{13}\text{C}$, but decomposition rates are often too slow to show changes in $\delta^{13}\text{C}$ (Drollinger, Kuzyakov, & Glatzel, 2019). Stable isotopes were not found to be constant 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.

TN trends support a zone of aerobic decomposition in the top 0-20 cm of peat. The inverted mounds and low-lying areas were found to have 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. 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 litter after microbial N immobilization (Malmer & Holm, 1984; Damman, 1988). 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-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). An increase in pH will decrease the organic acid peak because COO^- is transformed to COOH (Gondar et al., 2005; Hodgkins, 2016). Along with transforming organic acids, a reduction in acidity to a pH above 5.5 decreases *Sphagnum* cover (Vitt, 2006), which will reduce organic acids production.

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 returned to 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. 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 mounds was 84.2% while the 30 cm below the mounds had an average of 90.6%. The loss in OM content 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 adjacent 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 would 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 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.

3.6 Conclusions and Implications for 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, which all indicate lower substrate quality. 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.

Mounds may be able to support higher rates of decomposition in the presence of aerobic conditions indicated by trends in stable isotopes and TN. Inverted mounds specifically also showed decreases in decomposition-inhibiting organic acids. Evidence from changes in peat properties along depth profiles of inverted mounds supports an increase in decomposition in response to mounding. Bulk density and OM indicated a higher degree of decomposition in the top layers of peat in the mound than deeper layers below the mound, indicating that changes were greater than those expected from the inversion of the peat profile alone. This suggests that inverted mounding may increase decomposition. 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 be occurring throughout the line and may not be isolated to mounds.

The other two treatments 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 on the two upright mounding techniques reflected the lack of changes in soil properties and the preservation of plants during mounding. Functional group cover on the upright mounds and transferred hummocks were similar to natural hummocks, unlike the inverted mounds. 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. Although more research will be required on long term effects of restoration such as tree growth and survival, inline mounding and hummock transfer techniques showed advantages over inverted mounding.

Chapter 4 Summary and Conclusions

Unrestored seismic lines crossing peatlands have far-reaching consequences such as declines in native conifers and caribou populations and loss of important C storage function. Current methods of mounding have resulted in significant changes to soil properties and vegetation communities and yield unreliable restoration success in peatlands. Understanding these changes from classic, inverted mounding and comparing them to new, upright mounding and hummock transfer has important implications for ongoing seismic line restoration.

The main goal of mounding is to provide drier, more aerated microsites for tree growth. However, the results from this study suggest mounds may not be reaching this goal. Inverted mounds had higher VWC than natural conditions and were comparable to surrounding low-lying areas and untreated seismic lines. Further potential benefits of mounding to vegetation recovery include improved nutrient availability linked to lower organic matter content from the mixing of mineral soils. While nutrient availability was not measured in this study, lower OM on the mounds was not linked to higher nutrient content. Additionally, the significantly heavier isotopes and lower C/N ratios on the mounds indicate lower substrate quality. Lower substrate quality was supported by the incubation study where TC loss was reduced on mounds when temperature and moisture were held constant. The lower TC loss on the mounds in the incubation study may not be reflected in field conditions where environmental variables are not held constant. To determine TC losses on remote seismic lines, endpoint measurements of easily measured soil $\delta^{13}\text{C}$ and C/N ratios could replace or support traditional C flux measurements. More research is required to quantify TC loss and assess the effectiveness of soil $\delta^{13}\text{C}$ and C/N ratios to estimate TC loss in the field. Overall, the inversion of the peat profile resulted in high bare ground cover, low moss cover, higher bulk densities, lower OM, heavier stable isotopes, more recalcitrant C compounds, and lower C/N ratios (Figure 4.1). The changes on inverted mounds are indicative of lower substrate quality and may be reducing vegetation recovery.

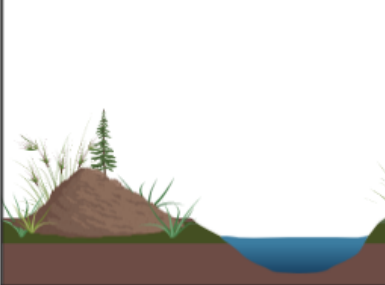
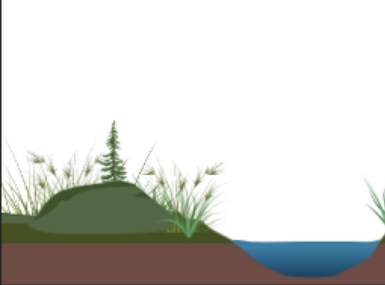

Inverted Mounding	Upright Mounding	Hummock Transfer
		
<ul style="list-style-type: none"> • Inverts peat profile • Creates water-filled hollows • High bare ground cover • High bulk density • Low organic matter content • Heavier stable isotopes • Lower C/N ratios • Recalcitrant C compounds 	<ul style="list-style-type: none"> • Preserves peat profile • Creates water-filled hollows • Natural moss cover • Natural bulk density • Natural organic matter content • Natural stable isotopes • Lower C/N ratios • Natural C compounds 	<ul style="list-style-type: none"> • Preserves peat profile • Creates small hollows off line • Natural moss cover • Natural bulk density • Natural organic matter content • Natural stable isotopes • Natural C/N ratios • Natural C compounds

Figure 4.1: Summary of the effects of different mounding techniques on soil properties and vegetation communities. Created with BioRender.com.

The exposure of deeper, more decomposed peat on inverted mounds may not be the only driver of altered soil properties. Soil profiles suggest that inverted mounds may be impacted by increased decomposition rates. Trends in stable isotopic composition and TN at depth indicate the presence of an aerobic zone at the peat surface despite measured high VWC. Soil chemistry on inverted mounds may further support increased decomposition rates as FTIR analysis showed a decrease in decomposition-inhibiting organic acids. Soil profiles also showed that soil properties of inverted mounds were indicative of more decomposed conditions than deeper peat previously at the same depth.

In addition to localized effects on created mounds, inverted mounding impacted adjacent low-lying areas on the seismic lines. Specifically, low-lying areas had heavier isotopes and lower C/N ratios than natural conditions and unrestored seismic lines despite the lack of exposure of deeper peat and mineral soils. These changes to soil properties in low-lying areas suggest that increased decomposition rates may not be isolated to mounds and increase throughout the restored seismic lines. Overall, inverted mounding was observed to result in lower substrate quality not only on mounds but also on

adjacent low-lying areas. The changes to soil properties from inverted mounding may not benefit tree and overall vegetation recovery as planned.

In contrast, the other two mounding treatments showed minimal changes to peat properties and vegetation communities (Figure 4.1). Transferred hummocks showed no statistical differences in peat properties or vegetation functional group cover compared to natural hummocks. Upright mounds had a small decrease in C/N ratios and a decrease in graminoid and shrub cover. Previous studies suggest that these changes on upright mounds will be beneficial to tree growth by reducing competition and increasing N availability. More research would be needed to confirm the direct effects on vegetation recovery, but results suggest upright mounds and transferred hummocks may better support peatland seismic line recovery over the inverted mounds.

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9647-96

Appendix A: Additional methodological details and soil chemical properties

$\delta^{13}\text{C}$, $\delta^{15}\text{N}$, TC, and TN

The following procedures were used by the Environmental Isotope Lab to ensure data quality. The primary reference scales for the $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ were Vienna Pee Dee Belemnite (VPDB) and Atmospheric Air, respectively. Data quality control was monitored, and corrections were made using an array of international reference material and in-house standards that are calibrated using certified international reference materials (i.e., IAEA-N1 + N2, IAEA-CH3 + CH6, USGS-40 + 41) with values provided through CIAAW. A mix of in-house and international materials was analyzed in each run. A 'like' material was also used when possible; usually, a NIST 2704 (River sediment) is used when analyzing soils and sediments. This provides a post-correction check throughout the analysis run for both isotopic and elemental percent data. Of the total sample number dropped in an analytical run, no less than 20% are Std/Ref materials. These Std/Ref measurements are used in data normalization and to ensure daily mass spec precision and accuracy; also, to assess linearity issues or mass spec drift throughout the run. With these QA/QC checks an error of 0.2‰ $\delta^{13}\text{C}$ and 0.3‰ $\delta^{15}\text{N}$ are required for reportable data. Additionally, 10% of samples were repeated measures to ensure reproducibility.

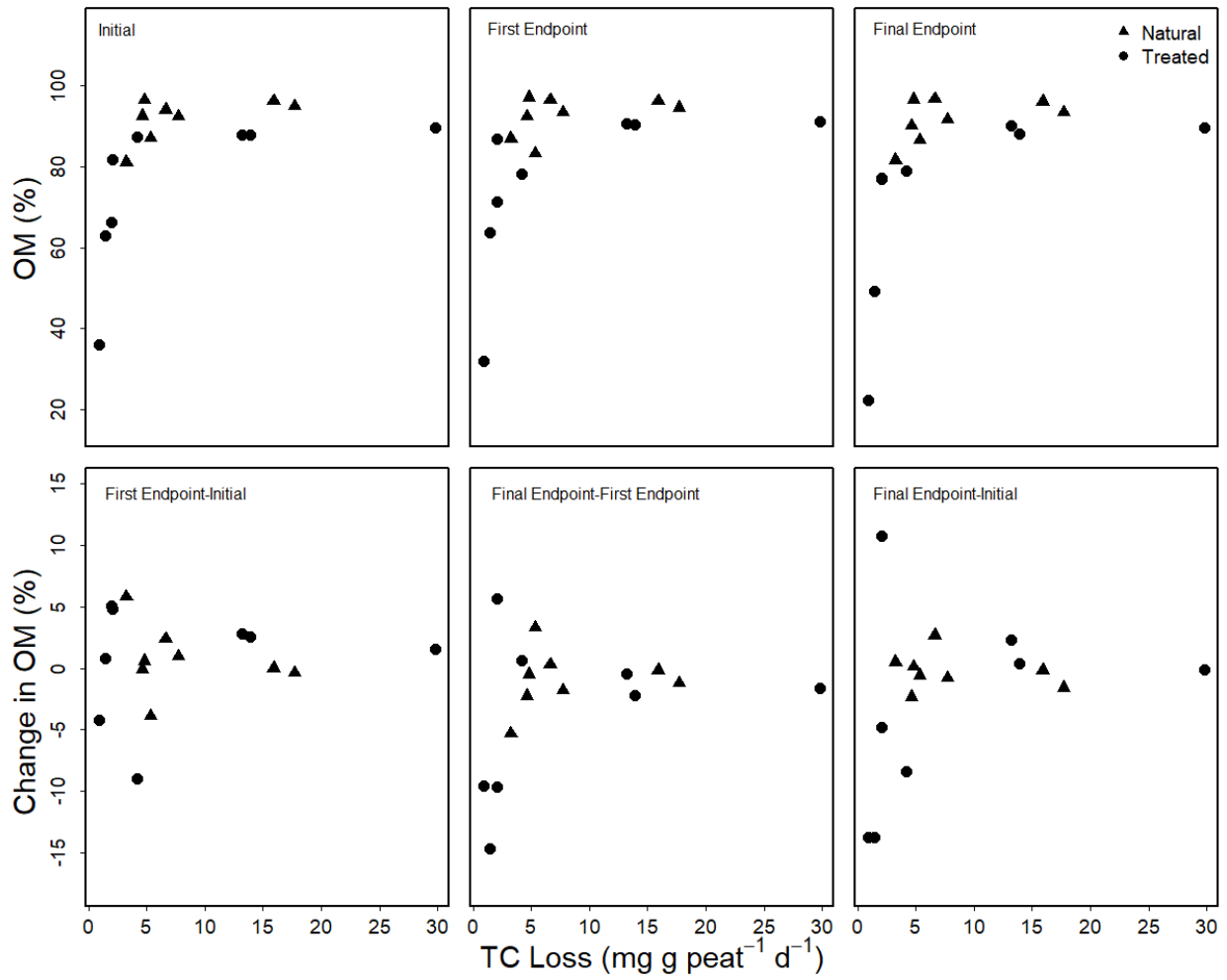


Figure A.1: TC loss vs. organic matter content. Top panels show the relationships between endpoint measurements of OM and TC loss while bottom panels show the relationship between the change between OM endpoints and TC loss. There were no significant linear relationships found.

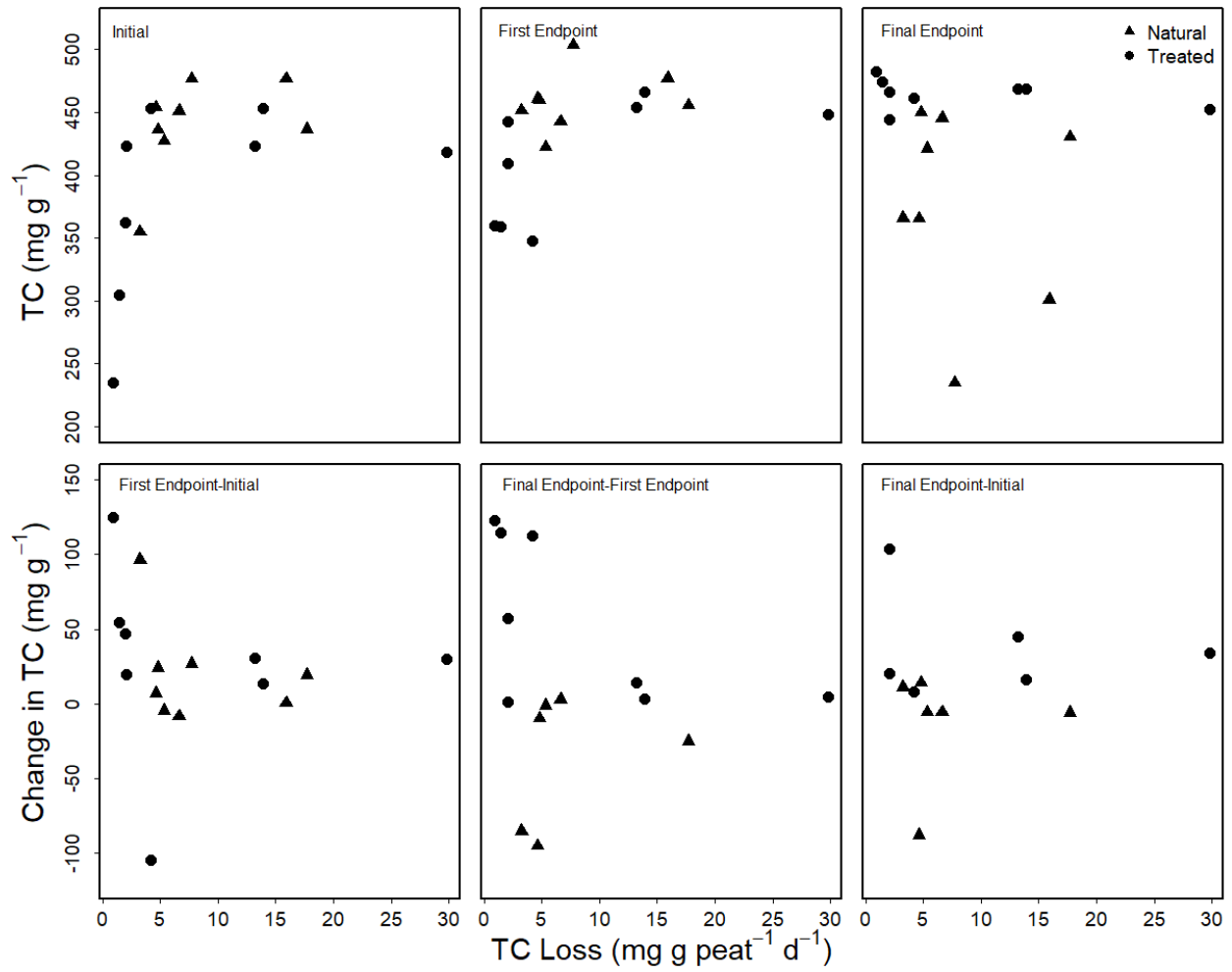


Figure A.2: TC loss vs. TC. Top panels show the relationships between endpoint measurements of TC and TC loss while bottom panels show the relationship between the change between TC endpoints and TC loss. There were no significant linear relationships found.

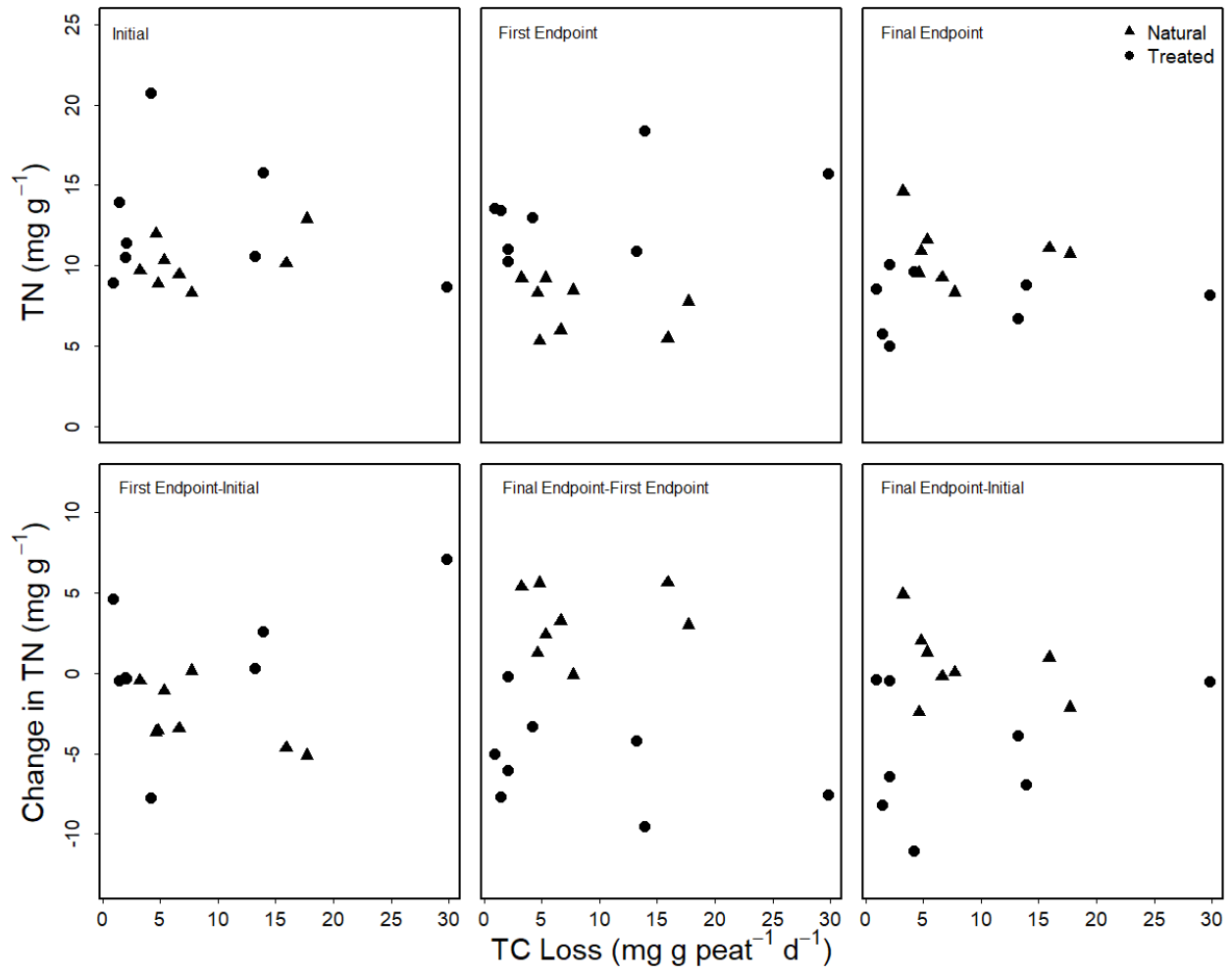


Figure A.3: TC loss vs. TN. Top panels show the relationships between endpoint measurements of TN and TC loss while bottom panels show the relationship between the change between TN endpoints and TC loss. There were no significant linear relationships found.

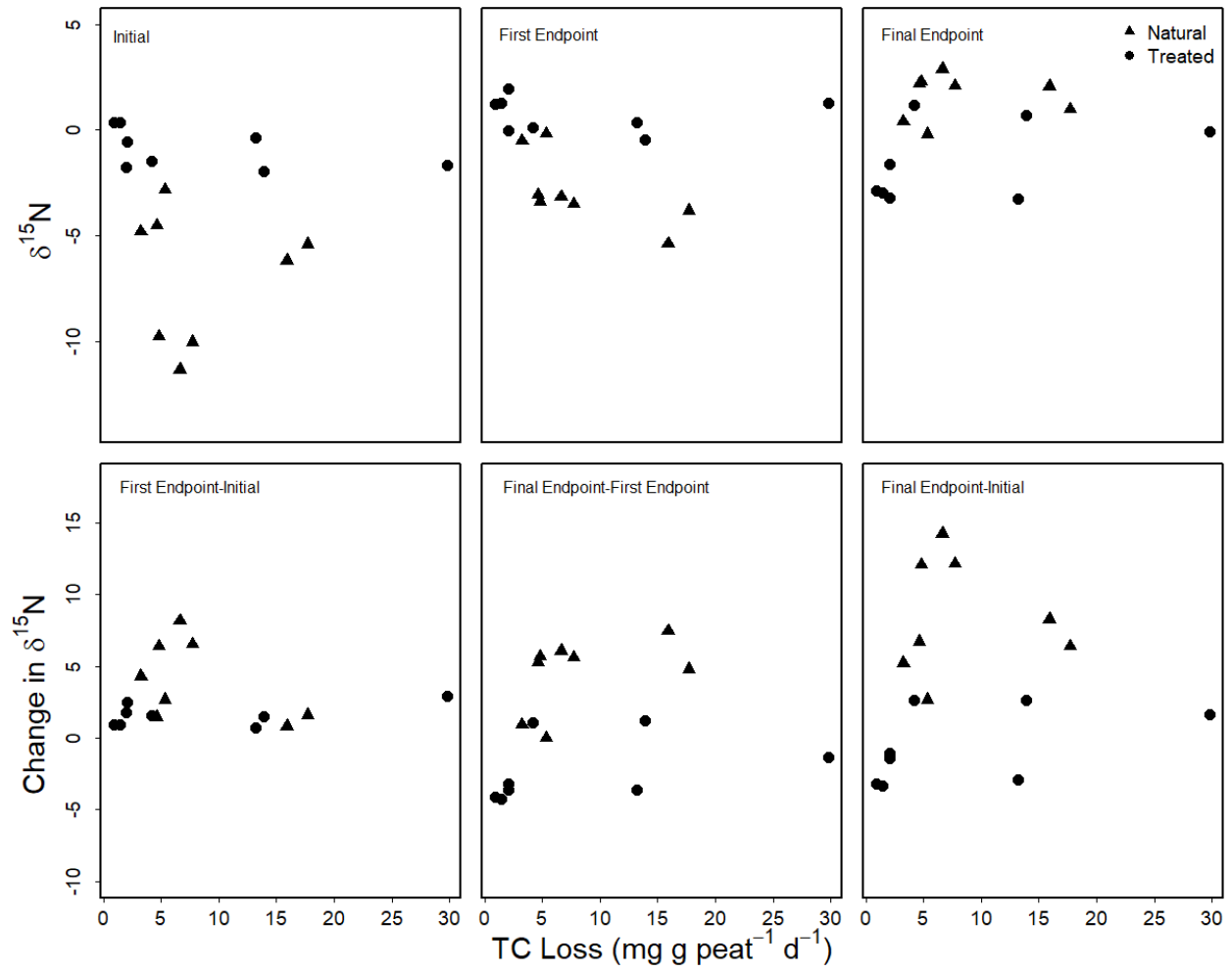


Figure A.4: TC loss vs. $\delta^{15}\text{N}$. Top panels show the relationships between endpoint measurements of $\delta^{15}\text{N}$ and TC loss while bottom panels show the relationship between the change between $\delta^{15}\text{N}$ endpoints and TC loss. There were no significant linear relationships found.

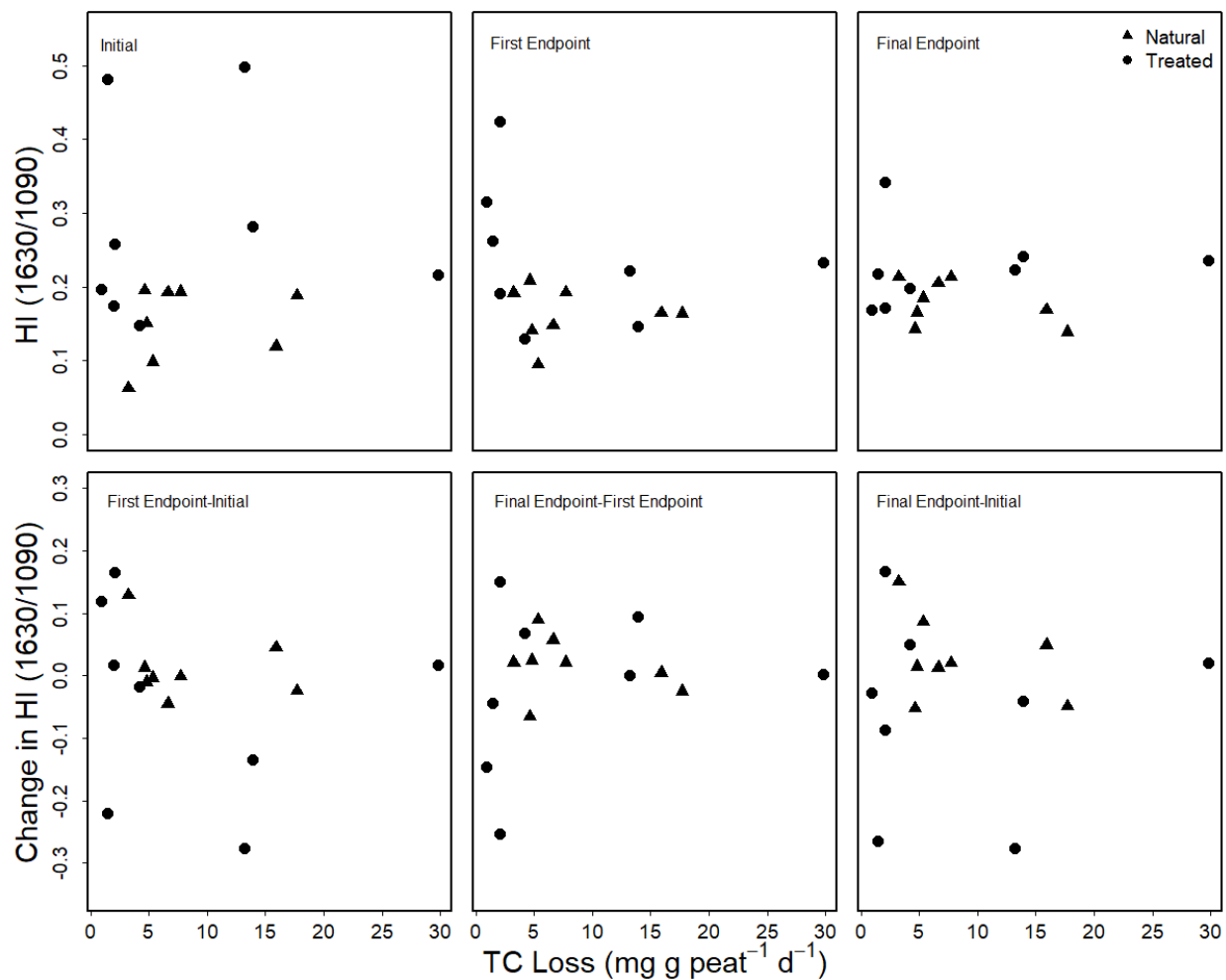


Figure A.5: TC loss vs. humification indices of aromatics (1630/1090). Top panels show the relationships between endpoint measurements of HI and TC loss while bottom panels show the relationship between the change between HI endpoints and TC loss. There were no significant linear relationships found.

Appendix B: Statistical output to support Chapter 3 results

Table B.1: Tukey post hoc table for bulk density of SC3 low-lying cores ($F_{14,50} = 5.24$, $p < 0.001$). Asterisks indicate a significant difference (at $\alpha=0.05$).

cm	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100	100-110	110-120	120-130	130-140	140-150
0-10	1.00	0.52	0.12	0.058	0.075	0.10	0.0039*	0.0015*	<0.001*	<0.001*	<0.001*	0.18	0.096	0.084
10-20		0.98	0.67	0.48	0.51	0.58	0.066	0.031	0.080	0.011*	<0.001*	0.48	1.00	0.28
20-30			1.00	1.00	1.00	1.00	0.82	0.65	0.86	0.36	0.035*	0.94	0.31	0.80
30-40				1.00	1.00	1.00	0.99	0.93	0.99	0.70	0.11	0.99	0.83	0.94
40-50					1.00	1.00	1.00	0.98	1.00	0.85	0.20	1.00	0.95	0.97
50-60						1.00	1.00	0.99	1.00	0.90	0.28	1.00	0.98	0.98
60-70							1.00	0.99	1.00	0.87	0.23	1.00	0.99	0.97
70-80								1.00	1.00	1.00	0.86	1.00	0.98	1.00
80-90									1.00	1.00	0.95	1.00	1.00	1.00
90-100										1.00	0.82	1.00	1.00	1.00
100-110											1.00	1.00	1.00	1.00
110-120												1.00	1.00	1.00
120-130													1.00	1.00
130-140														1.00

Table B.2: Tukey post hoc table for bulk density of SC3 natural cores ($F_{14,61} = 3.86$, $p = 0.00012$). Asterisks indicate a significant difference (at $\alpha=0.05$).

cm	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100	100-110	110-120	120-130	130-140	140-150
0-10	1	1.00	0.93	0.68	0.25	0.27	0.14	0.057	0.21	0.11	<0.001*	0.028 *	0.80	0.76
10-20		1.00	0.98	0.80	0.35	0.38	0.22	0.09	0.30	0.16	<0.001*	0.045*	0.87	0.84
20-30			1.00	0.99	0.78	0.81	0.62	0.38	0.71	0.51	0.0043*	0.20	0.98	0.97
30-40				1.00	1.00	1.00	0.98	0.88	0.99	0.94	0.04	0.63	1.00	1.00
40-50					1.00	1.00	1.00	0.99	1.00	1.00	0.12	0.89	1.00	1.00
50-60						1.00	1.00	1.00	1.00	1.00	0.44	1.00	1.00	1.00
60-70							1.00	1.00	1.00	1.00	0.41	1.00	1.00	1.00
70-80								1.00	1.00	1.00	0.60	1.00	1.00	1.00
80-90									1.00	1.00	0.83	1.00	1.00	1.00
90-100										1.00	0.65	1.00	1.00	1.00
100-110											0.83	1.00	1.00	1.00
110-120												1.00	0.86	0.89
120-130													1.00	1.00
130-140														1.00

Table B.3: Tukey post hoc table for bulk density of BR1 natural cores ($F_{4,15} = 3.52$, $p = 0.032$). Asterisks indicate a significant difference (at $\alpha=0.05$).

cm	10-20	20-30	30-40	40-50
0-10	0.77	0.69	0.22	0.021*
10-20		1.00	0.82	0.17
20-30			0.88	0.22
30-40				0.69

Table B.4: Tukey post hoc table for bulk density of BR1 low-lying cores ($F_{4,5} = 6.87$, $p = 0.029$). Asterisks indicate a significant difference (at $\alpha=0.05$).

cm	10-20	20-30	30-40	40-50
0-10	0.20	0.041*	0.028*	0.077
10-20		0.56	0.37	0.88
20-30			0.99	0.96
30-40				0.80

Table B.5: Tukey post hoc table for organic matter content of SC3 natural cores ($F_{14,34} = 4.17$, $p = 0.00033$). Asterisks indicate a significant difference (at $\alpha=0.05$).

cm	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100	100-110	110-120	120-130	130-140	140-150
0-10	0.96	0.84	0.31	0.11	0.039*	0.0089*	0.016*	0.021*	0.015*	<0.001*	0.0089*	0.018*	0.065	0.023*
10-20		1.00	0.96	0.89	0.64	0.29	0.41	0.47	0.40	0.0017*	0.29	0.28	0.60	0.33
20-30			1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.68	1.00	1.00	1.00	1.00
30-40				1.00	1.00	1.00	1.00	1.00	1.00	0.48	1.00	1.00	1.00	1.00
40-50					1.00	1.00	1.00	1.00	1.00	0.15	1.00	0.99	1.00	0.99
50-60						1.00	1.00	1.00	1.00	0.35	1.00	1.00	1.00	1.00
60-70							1.00	1.00	1.00	0.72	1.00	1.00	1.00	1.00
70-80								1.00	1.00	0.57	1.00	1.00	1.00	1.00
80-90									1.00	0.51	1.00	1.00	1.00	1.00
90-100										0.59	1.00	1.00	1.00	1.00
100-110											0.72	1.00	0.91	0.99
110-120												1.00	1.00	1.00
120-130													1.00	1.00
130-140														1.00

Table B.6: Tukey post hoc table for organic matter content of BR1 natural cores ($F_{9,30} = 5.10$, $p = 0.00033$). Asterisks indicate a significant difference (at $\alpha=0.05$).

cm	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100
0-10	0.89	0.18	0.089	0.044*	0.0089*	0.0046*	0.0066*	<0.001*	0.0042*
10-20		0.94	0.80	0.61	0.24	0.15	0.20	0.010*	0.14
20-30			1.00	1.00	0.95	0.86	0.91	0.26	0.84
30-40				1.00	0.99	0.96	0.98	0.43	0.96
40-50					1.00	1.00	1.00	0.63	0.99
50-60						1.00	1.00	0.94	1.00
60-70							1.00	0.99	1.00
70-80								0.97	1.00
80-90									0.99

Table B.7: Tukey post hoc table for organic matter content of BR1 low-lying cores ($F_{9,29} = 15.1$, $p < 0.001$). Asterisks indicate a significant difference (at $\alpha=0.05$).

cm	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-90	90-100
0-10	0.93	0.025*	0.0081*	<0.001*	<0.001*	<0.001*	<0.001*	<0.001*	<0.001*
10-20		0.33	0.18	0.027*	<0.001*	<0.001*	<0.001*	<0.001*	<0.001*
20-30			1.00	0.99	0.48	0.48	0.041*	0.12	0.011*
30-40				1.00	0.47	0.47	0.031*	0.10	0.008*
40-50					0.93	0.93	0.19	0.44	0.060
50-60						1.00	0.91	1.00	0.62
60-70							0.91	1.00	0.62
70-80								1.00	1.00
80-90									0.98

Table B.8: Tukey post hoc table for total nitrogen of BR1 hummock transfer cores ($F_{9,17} = 15.84$, $p < 0.001$). Asterisks indicate a significant difference (at $\alpha=0.05$).

cm	10-20	20-30	30-40	50-60	60-70	70-80	90-100	110-120	140-150
0-10	0.81	0.0074*	<0.001*	<0.001*	<0.001*	<0.001*	<0.001*	0.008*	0.045*
10-20		0.057	0.0019*	<0.001*	0.0033*	<0.001*	0.0049*	0.11	0.42
20-30			1.00	0.95	0.97	1.00	1.00	0.99	0.84
30-40				0.99	1.00	1.00	0.92	0.73	0.31
50-60					1.00	0.95	0.27	0.18	0.041*
60-70						0.99	0.64	0.44	0.18
70-80							0.88	0.65	0.21
90-100								1.00	0.84
110-120									1.00

Table B.9: Tukey post hoc table for total nitrogen of BR1 upright mound cores ($F_{8,20} = 14.02$, $p < 0.001$). Asterisks indicate a significant difference (at $\alpha=0.05$).

cm	10-20	20-30	30-40	40-50	50-60	70-80	90-100	140-150
0-10	0.91	<0.001*	<0.001*	<0.001*	0.016*	0.0032*	0.0020*	1.00
10-20		0.010*	0.0016*	<0.001*	0.13	0.11	0.077	1.00
20-30			0.99	0.97	1.00	0.87	0.94	0.0013*
30-40				1.00	1.00	0.35	0.46	<0.001*
40-50					1.00	0.24	0.33	<0.001*
50-60						0.98	0.99	0.042*
70-80							1.00	0.015*
90-100								0.0098*

Table B.10: Tukey post hoc table for total nitrogen of SC3 low-lying cores ($F_{8,29} = 3.48$, $p = 0.0062$)

cm	10-20	20-30	30-40	40-50	70-80	90-100	110-120	140-150
0-10	0.87	0.089	0.011*	0.24	0.034*	0.038*	0.11	0.33
10-20		0.74	0.26	0.69	0.48	0.50	0.68	0.79
20-30			1.00	1.00	1.00	1.00	1.00	1.00
30-40				1.00	1.00	1.00	1.00	1.00
40-50					1.00	1.00	1.00	1.00
70-80						1.00	1.00	1.00
90-100							1.00	1.00
110-120								1.00

Table B.11: Tukey post hoc table for total nitrogen of BR1 natural cores ($F_{5,18} = 10.61$, $p < 0.001$). Asterisks indicate a significant difference (at $\alpha=0.05$).

cm	10-20	20-30	30-40	70-80	90-100
0-10	1.00	0.0015*	<0.001*	0.0059*	0.014*
10-20		0.004*	0.0013*	0.016*	0.038*
20-30			1.00	0.98	0.88
30-40				0.85	0.61
70-80					1.00

Table B.12: Tukey post hoc table for total nitrogen of SC3 natural cores ($F_{9,29} = 10.55$, $p < 0.001$). Asterisks indicate a significant difference (at $\alpha=0.05$).

cm	10-20	20-30	30-40	70-80	80-90	90-100	110-120	120-130	140-150
0-10	0.99	0.11	0.0011*	<0.001*	0.026*	<0.001*	0.75	0.011*	<0.001*
10-20		0.48	0.014*	<0.001*	0.086	<0.001*	0.96	0.057	0.0035*
20-30			0.94	0.16	0.73	0.086	1.00	0.87	0.26
30-40				0.78	0.98	0.55	1.00	1.00	0.78
70-80					1.00	1.00	0.73	1.00	1.00
80-90						1.00	0.89	1.00	1.00
90-100							0.60	0.99	1.00
110-120								0.97	0.67
120-130									0.99

Table B.13: Tukey post hoc table for total nitrogen of BR1 low-lying cores ($F_{5,18} = 17.12$, $p < 0.001$). Asterisks indicate a significant difference (at $\alpha=0.05$).

cm	10-20	20-30	30-40	70-80	90-100
0-10	1.00	<0.001*	<0.001*	0.0030*	0.016*
10-20		0.00016	<0.001*	0.0073*	0.038*
20-30			0.99	0.47	0.14
30-40				0.20	0.047*
70-80					0.97

Table B.14: Tukey post hoc table for C/N of BR1 hummock transfer cores ($F_{9,17} = 12.1$, $p < 0.001$). Asterisks indicate a significant difference (at $\alpha=0.05$).

cm	10-20	20-30	30-40	50-60	60-70	70-80	90-100	110-120	140-150
0-10	0.076	0.0044*	<0.001*	<0.001*	0.0027*	<0.001*	<0.001*	<0.001	0.0037*
10-20		0.25	0.048*	0.012*	0.16	0.012*	0.025*	0.17	0.52
20-30			1.00	1.00	1.00	1.00	1.00	1.00	0.99
30-40				1.00	1.00	1.00	1.00	1.00	0.95
50-60					1.00	1.00	1.00	1.00	0.84
60-70						1.00	1.00	1.00	0.97
70-80							1.00	1.00	0.92
90-100								1.00	0.98
110-120									1.00

Table B.15: Tukey post hoc table for C/N of BR1 upright mound cores ($F_{8,20} = 8.37, p < 0.001$). Asterisks indicate a significant difference (at $\alpha=0.05$).

cm	10-20	20-30	30-40	40-50	50-60	70-80	90-100	140-150
0-10	0.75	0.0027*	<0.001*	<0.001*	0.050	0.0027*	0.0024*	0.92
10-20		0.14	0.056	0.055	0.42	0.18	0.17	1.00
20-30			1.00	1.00	1.00	1.00	1.00	0.036*
30-40				1.00	1.00	0.99	0.99	0.012*
40-50					1.00	0.99	0.99	0.012*
50-60						1.00	1.00	0.23
70-80							1.00	0.044*
90-100								0.040*

Table B.16: Tukey post hoc table for C/N of SC3 low-lying cores ($F_{8,29} = 2.52, p = 0.033$). Asterisks indicate a significant difference (at $\alpha=0.05$).

cm	10-20	20-30	30-40	40-50	70-80	90-100	110-120	140-150
0-10	0.65	0.097	0.043*	0.47	0.094	0.048*	0.18	0.59
10-20		0.93	0.82	0.96	0.93	0.80	0.94	0.99
20-30			1.00	1.00	1.00	1.00	1.00	1.00
30-40				1.00	1.00	1.00	1.00	1.00
40-50					1.00	1.00	1.00	1.00
70-80						1.00	1.00	1.00
90-100							1.00	1.00
110-120								1.00

Table B.17: Tukey post hoc table for C/N of SC3 natural cores ($F_{9,29} = 9.11$, $p < 0.001$). Asterisks indicate a significant difference (at $\alpha=0.05$).

cm	10-20	20-30	30-40	70-80	80-90	90-100	110-120	120-130	140-150
0-10	0.26	0.0088*	<0.001*	<0.001*	0.039*	<0.001*	0.024*	0.0011*	0.0021*
10-20		0.73	0.041*	0.0085*	0.52	0.011*	0.39	0.10	0.17
20-30			0.94	0.67	0.99	0.65	0.96	0.86	0.94
30-40				1.00	1.00	1.00	1.00	1.00	1.00
70-80					1.00	1.00	1.00	1.00	1.00
80-90						1.00	1.00	1.00	1.00
90-100							1.00	1.00	1.00
110-120								1.00	1.00
120-130									1.00

Table B.18: Tukey post hoc table for C/N of BR1 natural cores ($F_{5,18} = 16.19$, $p < 0.001$). Asterisks indicate a significant difference (at $\alpha=0.05$).

cm	10-20	20-30	30-40	70-80	90-100
0-10	0.21	<0.001*	<0.001*	<0.001*	<0.001*
10-20		0.0094*	0.0035*	0.0071*	0.013*
20-30			1.00	1.00	1.00
30-40				1.00	0.99
70-80					1.00

Table B.19: Tukey post hoc table for C/N of BR1 low-lying cores ($F_{5,18} = 59.52$, $p < 0.001$). Asterisks indicate a significant difference (at $\alpha=0.05$).

cm	10-20	20-30	30-40	70-80	90-100
0-10	0.010*	<0.001*	<0.001*	<0.001*	<0.001*
10-20		<0.001*	<0.001*	<0.001*	<0.001*
20-30			1.00	0.66	0.49
30-40				0.53	0.37
70-80					1.00

Table B.20: Tukey post hoc table for $\delta^{15}\text{N}$ of BR1 hummock transfer cores ($F_{9,17} = 19.72$, $p < 0.001$). Asterisks indicate a significant difference (at $\alpha=0.05$).

cm	10-20	20-30	30-40	50-60	60-70	70-80	90-100	110-120	140-150
0-10	0.14	<0.001*	<0.001*	<0.001*	0.0017*	<0.001*	<0.001*	0.0020*	0.0062*
10-20		0.020*	<0.001*	<0.001*	0.073	<0.001*	0.013*	0.23	0.50
20-30			1.00	1.00	1.00	1.00	0.92	0.74	0.50
30-40				1.00	0.98	1.00	0.36	0.22	0.097
50-60					0.92	0.99	0.13	0.088	0.032*
60-70						1.00	1.00	0.97	0.85
70-80							0.44	0.28	0.11
90-100								1.00	0.94
110-120									1.00

Table B.21: Tukey post hoc table for $\delta^{15}\text{N}$ of BR1 upright mound cores ($F_{8,20} = 8.87$, $p < 0.001$). Asterisks indicate a significant difference (at $\alpha=0.05$).

cm	10-20	20-30	30-40	40-50	50-60	70-80	90-100	140-150
0-10	0.31	<0.001*	<0.001*	<0.001*	0.017*	0.0016*	0.010*	0.75
10-20		0.19	0.10	0.087	0.42	0.43	0.86	0.99
20-30			1.00	1.00	1.00	1.00	0.84	0.022*
30-40				1.00	1.00	0.97	0.65	0.011*
40-50					1.00	0.95	0.59	0.0086*
50-60						1.00	0.91	0.14
70-80							0.99	0.060
90-100								0.28

Table B.22: Tukey post hoc table for $\delta^{15}\text{N}$ of SC3 low-lying cores ($F_{8,29} = 4.79$, $p = 0.00079$). Asterisks indicate a significant difference (at $\alpha=0.05$).

cm	10-20	20-30	30-40	40-50	70-80	90-100	110-120	140-150
0-10	0.66	0.018*	<0.001*	0.064	0.0062*	0.015*	0.33	0.47
10-20		0.53	0.074	0.40	0.30	0.49	0.99	0.96
20-30			0.98	0.97	1.00	1.00	0.99	1.00
30-40				1.00	1.00	0.99	0.74	1.00
40-50					1.00	0.98	0.81	1.00
70-80						1.00	0.95	1.00
90-100							1.00	1.00
110-120								1.00

Table B.23: Tukey post hoc table for $\delta^{15}\text{N}$ of SC3 natural cores ($F_{9,29} = 14.75$, $p < 0.001$). Asterisks indicate a significant difference (at $\alpha=0.05$).

cm	10-20	20-30	30-40	70-80	80-90	90-100	110-120	120-130	140-150
0-10	0.28	<0.001*	<0.001*	<0.001*	0.0012*	<0.001*	0.018*	<0.001*	<0.001*
10-20		0.068	0.0027*	<0.001*	0.038*	<0.001*	0.31	0.039*	0.033*
20-30			1.00	0.41	0.87	0.54	1.00	1.00	0.99
30-40				0.80	0.98	0.90	1.00	1.00	1.00
70-80					1.00	1.00	1.00	1.00	1.00
80-90						1.00	1.00	1.00	1.00
90-100							1.00	1.00	1.00
110-120								1.00	1.00
120-130									1.00

Table B.24: Tukey post hoc table for $\delta^{15}\text{N}$ of BR1 natural cores ($F_{5,18} = 32.68$, $p < 0.001$). Asterisks indicate a significant difference (at $\alpha=0.05$).

cm	10-20	20-30	30-40	70-80	90-100
0-10	0.26	<0.001*	<0.001*	<0.001*	<0.001*
10-20		<0.001*	<0.001*	<0.001*	<0.001*
20-30			1.00	0.28	0.19
30-40				0.36	0.25
70-80					1.00

Table B.25: Tukey post hoc table for $\delta^{15}\text{N}$ of BR1 low-lying cores ($F_{5,18} = 18.17$, $p < 0.001$). Asterisks indicate a significant difference (at $\alpha=0.05$).

cm	10-20	20-30	30-40	70-80	90-100
0-10	0.13	<0.001*	<0.001*	<0.001*	<0.001*
10-20		0.0032*	0.0009*	0.019*	0.040*
20-30			0.99	0.95	0.83
30-40				0.70	0.48
70-80					1.00

Table B.26: Tukey post hoc table for $\delta^{13}\text{C}$ of BR1 hummock transfer cores ($F_{5,18} = 18.17$, $p < 0.001$). Asterisks indicate a significant difference (at $\alpha=0.05$).

cm	10-20	20-30	30-40	50-60	60-70	70-80	90-100	110-120	140-150
0-10	1.00	0.19	0.029*	0.021*	0.85	<0.001*	<0.001*	<0.001*	0.0011*
10-20		0.43	0.11	0.099	0.99	0.0040*	0.0011*	0.0014*	0.0046*
20-30			1.00	1.00	0.99	1.00	0.96	0.77	0.94
30-40				1.00	0.93	1.00	0.93	0.65	0.90
50-60					0.97	0.94	0.68	0.37	0.69
60-70						0.55	0.33	0.17	0.33
70-80							1.00	0.90	1.00
90-100								0.99	1.00
110-120									1.00

Table B.27: Tukey post hoc table for $\delta^{13}\text{C}$ of SC3 low-lying cores ($F_{8,29} = 3.33$, $p = 0.0080$). Asterisks indicate a significant difference (at $\alpha=0.05$).

cm	10-20	20-30	30-40	40-50	70-80	90-100	110-120	140-150
0-10	0.13	0.046*	0.0078*	0.51	0.016*	0.017*	0.023*	0.55
10-20		1.00	0.95	1.00	0.97	0.98	0.92	1.00
20-30			1.00	1.00	1.00	1.00	1.00	1.00
30-40				1.00	1.00	1.00	1.00	1.00
40-50					1.00	1.00	1.00	1.00
70-80						1.00	1.00	1.00
90-100							1.00	1.00
110-120								1.00

Table B.28: Tukey post hoc table for $\delta^{13}\text{C}$ of SC3 natural cores ($F_{9,29} = 3.85$, $p = 0.0027$). Asterisks indicate a significant difference (at $\alpha=0.05$).

cm	10-20	20-30	30-40	70-80	80-90	90-100	110-120	120-130	140-150
0-10	1.00	0.20	0.030*	0.068	0.98	0.010*	0.30	0.43	0.23
10-20		0.33	0.065	0.14	0.99	0.022*	0.39	0.57	0.34
20-30			1.00	1.00	1.00	0.99	1.00	1.00	1.00
30-40				1.00	1.00	1.00	1.00	1.00	1.00
70-80					1.00	0.99	1.00	1.00	1.00
80-90						0.98	0.98	1.00	1.00
90-100							1.00	1.00	1.00
110-120								1.00	1.00
120-130									1.00

Table B.29: Tukey post hoc table for $\delta^{13}\text{C}$ of BR1 natural cores ($F_{5,18} = 3.20$, $p = 0.031$). Asterisks indicate a significant difference (at $\alpha=0.05$).

cm	10-20	20-30	30-40	70-80	90-100
0-10	0.79	0.031*	0.41	0.29	0.048*
10-20		0.31	0.98	0.94	0.42
20-30			0.68	0.82	1.00
30-40				1.00	0.80
70-80					0.91

Table B.30: Tukey post hoc table for $\delta^{13}\text{C}$ of BR1 low-lying cores ($F_{5,18} = 9.78$, $p = 0.00012$). Asterisks indicate a significant difference (at $\alpha=0.05$).

cm	10-20	20-30	30-40	70-80	90-100
0-10	0.62	<0.001*	<0.001*	0.0073*	0.0059*
10-20		0.0093*	0.016*	0.17	0.14
20-30			1.00	0.68	0.74
30-40				0.83	0.87
70-80					1.00

Table B.31: Tukey post hoc table for humification indices of BR1 hummock transfer cores ($F_{9,17} = 3.79, p = 0.0087$). Asterisks indicate a significant difference (at $\alpha=0.05$).

cm	10-20	20-30	30-40	50-60	60-70	70-80	90-100	110-120	140-150
0-10	0.018*	0.11	0.70	0.85	0.27	1.00	0.99	0.11	0.52
10-20		1.00	0.86	0.45	1.00	0.062	0.11	1.00	0.96
20-30			0.84	0.59	1.00	0.23	0.31	1.00	0.92
30-40				1.00	0.98	0.93	0.98	0.97	1.00
50-60					0.86	0.99	1.00	0.77	1.00
60-70						0.47	0.59	1.00	0.99
70-80							1.00	0.26	0.81
90-100								0.38	0.92
110-120									0.99

Table B.32: Tukey post hoc table for humification indices of SC3 low-lying cores ($F_{8,29} = 3.19, p = 0.010$). Asterisks indicate a significant difference (at $\alpha=0.05$).

cm	10-20	20-30	30-40	40-50	70-80	90-100	110-120	140-150
0-10	0.94	0.88	0.75	0.31	0.61	0.15	0.050	0.026*
10-20		1.00	1.00	0.70	1.00	0.77	0.36	0.11
20-30			1.00	0.80	1.00	0.91	0.52	0.16
30-40				0.83	1.00	0.94	0.57	0.18
40-50					0.91	1.00	1.00	0.99
70-80						0.99	0.77	0.26
90-100							0.99	0.55
110-120								0.91

Table B.33: Tukey post hoc table for humification indices of BR1 upright mound cores ($F_{8,20} = 9.16$, $p = 0.000031$). Asterisks indicate a significant difference (at $\alpha=0.05$).

cm	10-20	20-30	30-40	40-50	50-60	70-80	90-100	140-150
0-10	0.0010*	0.0064*	1.00	0.0034*	0.13	0.57	0.0083*	<0.001*
10-20		1.00	0.0019*	1.00	1.00	0.051	0.92	1.00
20-30			0.011	1.00	1.00	0.25	1.00	0.99
30-40				0.0062*	0.15	0.64	0.015*	<0.001*
40-50					1.00	0.15	1.00	1.00
50-60						0.73	1.00	1.00
70-80							0.37	0.028*
90-100								0.88

Table B.34: Tukey post hoc table for humification indices of SC3 natural cores ($F_{9,29} = 3.65$, $p = 0.0037$). Asterisks indicate a significant difference (at $\alpha=0.05$).

cm	10-20	20-30	30-40	70-80	80-90	90-100	110-120	120-130	140-150
0-10	1.00	0.94	0.79	0.045*	0.050	0.067	1.00	0.98	0.065
10-20		1.00	1.00	0.25	0.13	0.32	1.00	1.00	0.22
20-30			1.00	0.75	0.29	0.80	0.97	1.00	0.53
30-40				0.75	0.30	0.80	0.94	1.00	0.54
70-80					0.85	1.00	0.44	0.94	1.00
80-90						0.86	0.15	0.44	1.00
90-100							0.47	0.95	1.00
110-120								0.98	0.28
120-130									0.75

Table B.35: Tukey post hoc table for humification indices of BR1 natural cores ($F_{5,18} = 7.28$, $p = 0.00069$). Asterisks indicate a significant difference (at $\alpha=0.05$).

cm	10-20	20-30	30-40	70-80	90-100
0-10	0.0013*	0.99	0.37	0.16	0.0099*
10-20		0.0041*	0.085	0.22	0.93
20-30			0.68	0.36	0.030*
30-40				0.99	0.41
70-80					0.72

Table B.36: Tukey post hoc table for humification indices of BR1 low-lying cores ($F_{5,18} = 11.56$, $p = 0.000041$). Asterisks indicate a significant difference (at $\alpha=0.05$).

cm	10-20	20-30	30-40	70-80	90-100
0-10	<0.001*	1.00	0.50	0.30	0.0046*
10-20		<0.001*	0.0037*	0.0082*	0.44
20-30			0.67	0.45	0.0085*
30-40				1.00	0.16
70-80					0.30