Impacts Of Seismic Line Restoration Techniques On Nutrient Biogeochemical Processes In A Boreal Fen

by

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Author's Declaration

This thesis consists of material all of which I 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.

I understand that my thesis may be made electronically available to the public.

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 3 and 4 of this thesis. As a result, repeated information may be included. Chapter 3 reports on data collected from seismic lines in Brazeau County, Alberta from May to August in 2019 and 2020. Chapter 4 reports on data collected from newly restored seismic lines in Brazeau County, Alberta in Brazeau County, Alberta from June to August 2020. M. Schmidt, M. Hunter, and M. McKinnon assisted with sampling in 2019 while M. Schmidt, T. Rachar, A.Allison assisted with sampling in 2020. M. Strack and F. Nwaishi assisted with the study planning and design as well as manuscript revisions. Each manuscript, including figures and tables, was written in its entirety by T. Vodopija and reviewed by M. Strack and F. Nwaishi.

Abstract

Peatlands contain 40 cm or more of partially-decomposed plant matter and sequester carbon and nutrients. The disturbance of peatlands alters these ecological functions. Seismic lines, long cutlines in the forest created for geologic exploration, represent an enormous area of disturbed peatlands in Canada. In Alberta, over 345,000 km of seismic lines intersect peatlands, meaning that the approximately 134,000 km^2 of boreal peatlands in Alberta are covered with an estimated 1,900 km^2 of seismic line disturbance. There is no definitive method on how to restore peatland seismic lines and little research on post-restoration ecosystem function. This thesis aims to better understand the effects of restoration on biogeochemical functioning, particularly the nutrient cycling of nitogen (N) and phosphoous (P), on legacy seismic lines in a Alberta fen. The major themes of this thesis examined (1) quantifying how the restoration of seismic lines using new mounding techniques affected decomposition rates, pore water nutrient concentrations, and net mineralization rates in a fen, and (2) assessing the interactions between restoration treatments and fertilization on pore water nutrient concentrations, net mineralization rates, and plant nutrient supply rates *in-situ* and controlled impacts of an NPK fertilizer on soil processes in preliminary applications.

To evaluate the implications of the different restoration techiques, of mounding and fertilizing, on the ecological functioning of the fen, field and laboratory studies were conducted in 2019 and 2020. The effects of mounding on hydrophysical peat properties were analyzed by peat surface samples. Decomposition was determinered using the Tea Bag Index (TBI) in the field and by the loss of mass in the laboratory experiment. Net mineralization rates of N and P were analyzed using the buried bag method, and pore water samples were collected (0-10 cm) and analyzed for N and P concentrations.

The results from this study suggest that microbial activity increases with the addition of microtopgraphy. However, nutrient cycling effects from mechanical restoration were not clearly seen within two years post-restoration. When examining the effect of NPK fertilizer on nutrient availability, net mineralization rates, and foliar concentrations, results suggest that the use of fertilizer can increase organic matter decomposition in mechanically restored treatments. The addition of fertilizer can increase nutrient availability; however, the fertilizer is more likely to become immobilized in unsaturated conditions. The use of fertilizer resulted in taller trees. However it also increased the cover of graminoids, which may provide increased competition for tree seedlings. More research is needed to confirm the direct effects of fertilizer on tree recovery on restored seismic lines over time, but results suggest fertilizer may assist in providing nutrients needed for faster tree growth over unfertilized lines.

This study provides background concentrations of decomposition rates, N and P pools, and net N and P mineralization rates, which can be used to monitor the progress of the restoration techniques as the peatland recovers. These results also imply that implementation of mechanical restoration techniques, that introduce hummock and hollow microtopography, will increase microbial activity and allow oxidation of N. Additionally, the use of NPK fertilizer will enhance peatland seismic line restoration, by increasing nutrient availability and aiding in tree growth. However, fertilizer should be applied in moderation, as the addition of fertilizer also resulted in increased graminoid cover. These results from this study provide valuable information for improving the success of future restoration projects leading to more reforestation of the seismic lines, which will not only benefit humanity, but will aid in the conservation of wildlife, such as the woodland caribou (*Rangifer tarandus caribou*).

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1.0 Introduction

About 21% of western Canadian landscapes are occupied by a type of wetland known as peatlands (Vitt, Halsey, Bauer, & Campbell, 2000). Peatlands are wetlands that have accumulated partially decomposed plant matter (also referred to as peat), to a depth of 40 cm or more (Glaser, 1987; National Wetlands Working Group, 1997). These specialized landscapes have many important ecological functions that help maintain vital cycles of the biosphere while providing habitat to endangered animals and plants. Peatlands capture and store carbon, preventing it from being released back into the atmosphere, where it can exert a greenhouse effect and exacerbate global warming (Gorham, 1991). Peatlands can filter contaminants like nutrients and metals from terrestrial water sources before discharge to aquatic ecosystems (Coupal, 1976). Most peatland surfaces are characterized by elevated and depressed microforms called hummocks and hollows, respectively, which allows them to support a diverse plant assemblage (Haddad et al, 2015). The functional and structural characteristics of peatlands are products of dominant environmental conditions; thus, peatlands are very sensitive to disturbances that alter environmental processes.

Disturbances that impact peatland structure and functions can be natural (e.g., drought and wildfires) or anthropogenic (e.g., development projects and mining). Canadian peatlands are mainly located in the boreal forest region where intensive resource extraction occurs (Rooney, Bayley, & Schindler, 2012). Therefore, peatlands are often disturbed by methods of exploring, extracting, and transporting these resources. These disturbances alter hydrological conditions, affect ecosystem processes, and alter biological community structures (van Rensen et al., 2015). Following these disturbances, restoration is implemented in some jurisdictions as a regulatory requirement to re-establish the original forms and functions of these disturbed peatlands. For instance, energy exploration companies are required to restore peatland impacted by their anthropogenic disturbances such as open pit mining and construction of well pads and mineral features (Alberta Environment, 2010). However, peatlands impacted by other types of disturbances like seismic lines, a form of linear disturbance created from the exploration for oil and gas, are often left to self-restore through secondary succession (Dabros, Pyper, & Castilla, 2018). Evidence from legacy seismic lines that are over 50 years old suggest that this self-restoration is often ineffective for the reestablishment of plant species found in pre-disturbance community, especially trees, due to a lack of microtopography leading to flooded conditions (van Rensen et al., 2015).

Unlike with other disturbances associated with energy exploration in Canada's boreal region, there are no regulatory requirements to restore peatlands impacts by seismic lines. This results in limited knowledge on an effective way to restore them, so thousands of seismic lines act as corridors fragmenting the ecosystems they intersect (Luizäo & Ribeiro, 2007; van Rensen et al., 2015; Finnegan, Pigeon, & MacNearney, 2019). The fragmentation of boreal peatlands caused by seismic lines negatively alters the structural functions of the peatland, such as the provision of habitat and protection for woodland caribou (Finnegan et al., 2018). However, it is unclear how the edaphic conditions resulting from seismic disturbances impact the nutrient cycling processes that are required to support the peatland biogeochemical functions and re-establishment of desired vegetation assemblages on the seismic lines

Indeed, the uncertainties surrounding the potential of restoring peatland functions on seismic lines in exacerbated by the fact that this is a relative new and untested concept, as past seismic line restoration projects have focused on restoring the structure of boreal peatlands to provide safe habitat for woodland caribou (James and Stuart-Smith, 2000). Thus, there is a knowledge gap in the effectiveness of practices used in seismic line restoration with a specific focus on restoring peatland functions, such as carbon accumulation and nutrient cycling.

Traditionally, peatland restoration practices involve the reconfiguration of the residual peat surface to recreate peatland's natural microtopographic gradient, which comprises hummocks and hollows. This is accomplished by scooping near surface peat to create a mound (hummock) usually flipping the peat pile upside down, so that the deeper peat matter is on top, while the living vegetation is in the bottom (Schneider et al., 2002; Filicetti et al., 2019). This peat inversion method results in a loss of established vegetation, leading to the re-establishment of an undesired peatland plant assemblage (Echiverri et al. 2020). The hummocks created through peat inversion are often very large resulting in the surface exposure of recalcitrant catotelm peat, or sometimes mineral soil, which lack labile substrate required by aerobic microbes to mediate nutrient cycling processes and other biogeochemical functions. As a result, this type of restoration practice may restore the structure of the peatland without restoring the functional attributes that make peatlands unique.

The goal of this research is to assess the effectiveness of novel restoration techniques in restoring the biogeochemical processes of peatlands, while also restoring the structure that provides safe caribou habitat. Peatland restoration to restore ecological function is a novel idea, as there is a lack of research characterizing and studying biogeochemical processes post-restoration in seismic line disturbed peatlands. The research in this thesis aims to characterize effects of novel restoration techniques on peat properties and biogeochemical processes; and to examine if there is a need for additional nutrients to be added to expedite restoration. Using new restoration techniques, biogeochemical functions can be restored to aid in the growth of desirable woody vegetation. These trees will help establish habitat, allowing these peatlands to be able to fully support species affected and endangered by the disturbance of these unrestored and poorly restored seismic lines.

1.1 Research Objectives

The main objective of the restoration applied was to create microsites that will support moderately wet conditions suitable for the revegetation of trees along seismic lines created in peatlands. To better understand how restoration affected nutrient cycling and if this affected tree establishment, two specific research objectives were explored:

1) Quantifying how restoration affects decomposition rates, pore water nutrient concentrations, and net mineralization rates in a fen undergoing restoration of seismic line disturbances using newly modified mounding techniques that are designed to improve the limitations of the traditional mounding technique

2) Assessing the interactions between restoration treatments and fertilization on pore water nutrient concentrations, net mineralization rates, and plant nutrient uptake *in-situ* and controlled impacts of an NPK fertilizer on soil processes in preliminary applications.

Previous studies have shown that restoration can alter nutrient concentrations and net mineralization rates to those more similar to the natural reference sites in peatlands (Hartsock et al., 2016). To achieve this, new restoration treatments of ripping and mounding were used to reconfigure the seismic line. It is hypothesized that if changes to the microtopography are made in the peatland through ground reconfiguration approaches, then the new ecosites will stimulate nutrient cycling through increased rates of net mineralization. The addition of fertilizer was implemented on one of the seismic lines to determine if supplying the system with additional nutrients would enhance nutrient availability and cycling rates. It is hypothesized that if restoration treatments include the addition of fertilizer, then there will be greater availability of nutrients in the peat and water for the plant community to access, reducing nutrient limitations in the peatlands.

1.2 Thesis Structure

This thesis is divided into five chapters. The first chapter presents a general introduction to seismic line disturbances and what is known about the restoration of seismic lines, and it outlines the overall goal and specific objectives of the thesis.

Chapter two provides a literature review. It provides an overview of the ecohydrological characteristics of microtopography on peatlands, and the consequences of seismic lines that eliminate microtopography. It also explores what is known about the restoration of microtopography and identifies a knowledge gap surrounding the impact of seismic line disturbance and new restoration techniques on peatland nutrient cycling.

Chapter three examines the first objective of characterizing the nutrient cycling processes and dynamics of a peatland undergoing restoration on legacy seismic lines.

Chapter four addresses the second objective by evaluating the impact of fertilizer on biogeochemical processes of a peatland one-year post restoration on legacy seismic lines.

Chapter five summarizes conclusions from the two manuscripts, outlining the major contributions to knowledge and recommendations on future research that can further advance the knowledge of biogeochemical functioning of seismic line disturbed peatlands, helping to improve future restoration practices.

2.0 Literature Review

Peatlands are a category of wetland known for their slow decomposition, which causes a build-up of partially decomposed plant matter to a depth of 40 cm or more. Peatlands are the planet's natural storage system, as these special landscapes use their thick layers of peat to store carbon, nutrients, and metals from the atmosphere and water that flows through them (Vitt, 2006). Peatlands function as nutrient filters, and on average over 50% of the total N, total P, phosphate, and NO_3^- inputs into peatlands are retained (Cheng & Basu, 2017). This is due to the ability of peatland flora and microfauna to assimilate inorganic nutrients into stable organic compounds that comprise their cellular structure (Saunders and Kalff, 2001; Reddy et al., 1999). Additionally, the reduced conditions that are dominant in peatlands also facilitate biogeochemical transformations that produce fewer mobile forms of nutrients (Saunders & Kalff, 2001; Reinhardt et al., 2005). Peatland biogeochemical functions are influenced by ecohydrological characteristics of peatland microforms.

2.1 Ecohydrology Characteristics of Microtopography in Peatlands

Most peatland surfaces have small scale variation in elevation. This unique microtopographic gradient consists of microforms known as hummocks and hollows. The vertical relief, ranging from a few centimeters to a meter tall, is created by microforms known as hummocks (Rochefort et al., 1990). Although hummocks are elevated areas which are generally drier, they have varying soil moisture levels caused by the flashy peatland water table, whereas hollows are low-lying saturated depressions (Barreto & Lindo, 2018). Although these microforms are small elevation changes in the landscape, they are important for providing diversity in site conditions that allows for differences in ecosystem processes and productivity. The variation of moisture content between the microforms drives differences in biogeochemical processes. For instance, the waterlogged hollows create an anoxic environment that regulates the slow rate of organic matter decomposition and peat accumulation in peatland. This microtopographic variation allows the peatland to be resilient to climatic and hydrological changes.

Peatland microtopography creates conditions that enable peatlands to support a diverse plant community that require different environmental conditions. The drier hummocks allow for vegetation, such as woody plants and lichens, that are not adapted to high-water table conditions, while hollows create environments suitable for hydrophilic vegetation that are adapted to prolonged saturated conditions (Charman, 2002). The variation of plant community composition caused by hummocks and hollows creates a difference in nutrient demands (Eppinga et al., 2008). These differences of nutrient demands are thought to affect the available nutrient pools (Turetsky, 2003). Peatland plant growth is dictated by the availability of nutrients, especially nitrogen (N) and phosphorus (P) (Bedford et al., 1999, Aerts & Chapin, 1999).

Boreal peatlands are usually N limited; however, peatlands can switch to a P limited system in persistently saturated conditions (Charman, 2002). Vegetation can take up N in the inorganic forms of nitrate (NO_3^-), nitrite (NO_2^+), and ammonium (NH_4^+; Fig. 2.1). In peatlands the dominant concentrations of N in nutrient pools come from N being cycled within the peatland, deposition of NO_3^- and NH_4^+, and fixation of atmospheric nitrogen (N_2; Urban & Eisenreich, 1988; Vile et al., 2014). The stable triple bonded N_2 occurs naturally in peatlands before being fixed by the microbial community. The N_2 is broken down into ammonium where it can be further transformed into plant available forms of N, i.e., NO_2^- and NO_{3^-}. Once N is fixed, it is cycled within the peatland ecosystem, going through processes of ammonification, the conversion of organic N from dead organisms and plant matter into NH_4^+. The microorganisms use organic N to produce energy for self-consumption and their waste product is NH_4^+. The production levels of NH_4^+ are dependent on external influences on the microbial community and dominant redox conditions (Frei et al., 2012). Although NH_4^+ is a bioavailable form of N, most vegetation prefers to uptake N in the form of NO_3^-. In peatlands, NH_4^+ is the dominant N form due to the persistent reduced condition, but when peatlands undergo wet to dry cycles, then NH_4^+ is converted into NO_3^- through the process of nitrification, which is common in the aerobic layers of the peat profile (Robertson & Groffman, 2007). Most peatland plants such as *Sphagnum* mosses have evolved to adapt to the low N environment common in boreal peatlands. Thus, these plants can thrive in a low nutrient peatland environment due to their ability to access N from NH_4^+. The uptake of NH_4^+ by *Sphagnum* dominated peatlands may also reduce the transformation of NH_4^+ to NO_3^- because of the high demand for NH_4^+ (Wang & Moore, 2014, Wood et al., 2016). The progression of N mineralization in peatlands is very sensitive to soil moisture conditions (Bayley et al., 2005; Wood et al., 2016).

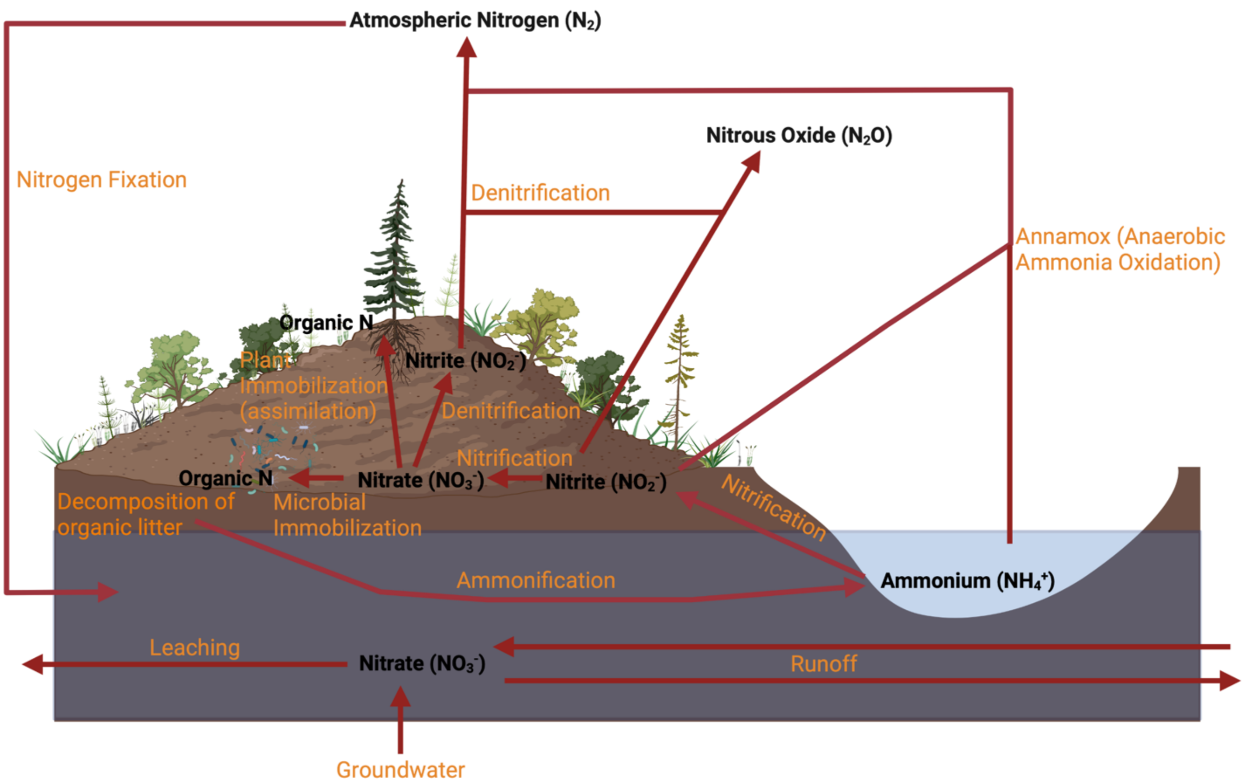

Figure 2.1. The nitrogen cycle in a peatland.

Nitrogen mineralization is strongly influenced by peat moisture conditions, temperature, degree of soil aeration, and abundance and quality of organic matter (Ehrenfeld & Yu, 2012). Study sites with lower water tables and lower soil moisture have higher rates of nutrient mineralization (Wood et al., 2016). Oxic conditions lead to more available oxygen causing increased microbial activity and nutrient mineralization that leads to an increase in nutrient availability (Keller et al., 2004; Strack et al, 2006; Macrae et al, 2013; Bonan & Van Cleve, 1992; Updegraff et al., 1995). Generally, there is a limited amount of decomposing and nitrifying bacteria in areas of peatland under a dominant high-water table. The water table is often above or close to the surface in hollows, which leads to lower N availability and greater denitrification rates relative to hummocks. The anoxic conditions dominant in hollows support the accumulation of NH_4^+ and a limited concentration of NO_3^- in this microform (Jones et al., 2005). However, this will vary depending on the peatland's water table position (Huang and Schoneau, 1998;). Given that NO_3^- is the most mobile form of inorganic N, peatlands that are influenced by geogenous water sources, such as groundwater and surface water, tend to be more nutrient-rich (Wood et al., 2016). Therefore, the supply and availability of NO_3^- in peatlands is strongly influenced by hydrology. Increased concentrations of NO_3^- in peatlands are often correlated with unstable hydrologic dynamics (Jones et al., 2005).

Phosphorus is needed as a macronutrient to maintain vegetation and microbial community functions in peatlands. However, the dynamics of P in boreal peatlands are more complex than N dynamics because of the geochemical reactivity P with other elements (Richardson and Marshall, 1986; Walbridge and Navaratnam, 2006). The dynamics of P in peatlands is influenced by aeration, phosphate ion receptors, and ambient P concentrations (Reddy & DeLaune, 2008). High redox potential in dry hummocks can lead to the release of P. However, this P is inaccessible to microbes and plants because of adsorption by cations (Kooijman et al., 2020). Phosphorous is held in minerals and is released by the process of physical, biological, and chemical weathering of these minerals. The presence of magnesium (Mg) and calcium (Ca), in alkaline environments, and aluminum (Al), iron (Fe), and manganese (Mn), in acidic environments, are indicator of P availability. Phosphorous is frequently bound with these minerals (Walbridge & Navaratnam, 2006). Microorganisms can assimilate inorganic and organic P from soils, with the use of phosphatase enzymes, when there is low P availability in the soil (Vance et al., 2005). Therefore, the aerobic conditions of the hummocks will create favorable conditions for the microbes to mineralize the P.

2.2 Impacts of Seismic Lines on Peatlands

Peatland structure and functions are significantly altered and degraded by linear disturbances. In Alberta, seismic lines accounts for some of the greatest areas of peatland disturbances, with over 345,000 km of seismic lines that intersect peatlands (Strack et al. 2019). This means that the approximately 134,000 km^2 of boreal peatlands in Alberta are covered with an estimated 1,900 km^2 of seismic line disturbance (Strack et al. 2019). Seismic lines are generated at high densities of 10 to 40 km/km^2 in some regions (Filicetti et al., 2019; Lee and Boutin 2006; Schneider, 2002). Given that the Federal government's definition of undisturbed land is considers as any land located 500 m or more away from anthropogenic disturbance, therefore the area affected by seismic line disturbances will be substantially greater than 1,900 km^2 (Strack et al. 2019). This disturbance created by seismic lines fragments the landscape and change the ecological structure and functions of the peatlands they intersect (Dabros et al. 2018).

The creation of seismic lines involves the partial removal of vegetation to create access routes for heavy equipment used in resource exploration, which also compacts the underlying peat substrate (Dabros et al., 2018). Compacted peat conditions created by seismic lines persist for decades post-exploration, leading to inundation of the lines and a lack of microtopographic gradients that control crucial biogeochemical processes in pre-disturbance peatlands (Stevenson et al. 2019; Chen et al., 2017; Williams et al. 2013). For instance, the creation of seismic lines removes trees, and this causes reductions in the amount of water uptake from the peatland as transpiration. This leads to increased flooding in the seismic line and modifies the development and structure of the peat (Caners, 2014). These changes in hydrology caused by the seismic lines alter the types of vegetation present because the absence of elevated microforms limits the survivability of vegetation like trees and lichens on seismic line affected peatlands. Studies have been conducted on the recovery rates of these seismic lines, and even after more than 50 years, there was little recovery of woody vegetation on seismic lines crossing peatlands (van Rensen et al., 2015). Even in cases where some woody plants have tried to re-establish, they are often found to be stunted at 3 m in height (Lee, & Boutin, 2006; van Rensen, 2015; Filicetti et al., 2019). As a result, the vegetation communities that regenerate on legacy lines are different from those in adjacent peatlands (Dabros et al., 2021; Davidson et al., 2020).

2.3 Restoring Microtopography in Peatlands

It is important to bring these disturbed ecosystems back to their original and natural functions, and a way to achieve this is through restoration. Most seismic line restoration work has focused on restoring habitat structure to protect caribou rather than restoring the ecological function of the peatland system (Filicetti et al. 2019; Finnegan et al., 2018). With increasing awareness about the importance of peatland restoration as a nature-based climate solution, the goal of seismic line restoration is now shifting towards restoring the peatland functions including primary productivity that supports the uptake of carbon, cycling of nutrients, and reestablishment of vegetation structure that provide habitat for endangered wildlife and plant biodiversity that strengthens biological resilience in a changing climate. Restoring these peatland functions will help re-establish peatland's ecological values that are currently lacking in legacy seismic lines. Recreating a microtopographic gradient through surface reconfiguration is the first step in restoring seismic line impacts. A common surface reconfiguration technique that has been used is seismic lines restoration is the creation of mounds (2020 Project Summaries, 2020; Dabros et al., 2018) .

Mounding is a technique that digs out a pile of peat, and sometimes mineral soil, from a seismic line to create an elevated area on the surface. The common practice is to invert the excavated peat pile, exposing the peat/mineral substrate at the surface, while the living vegetation is buried underneath, known as mechanical mounding (Schneider et al., 2002; Filicetti et al., 2019). Given that peat is easily compressed, disturbed peatlands are vulnerable to having their microtopography homogenized. Mounds reduce severity of flooding, which helps with the reestablishment and survival of seedlings, ultimately leading to a faster recovery time for the seismic line (Caners, 2014). The creation of mounds on peatland seismic lines has been shown to increase aeration through the creation of thicker oxic zones along with creating warmer microclimates and larger rooting depths for establishment of woody species, as the water table is gradually isolated from their rhizosphere (Pearson et al., 2011). The presence of the different elevation leads to a wide variation of vegetation as it allows for a variation in soil moisture and nutrient gradients (Finnegan et al., 2019).

The structure of these anthropogenically created mechanical mounding hummocks is often different from natural peatland hummocks, which presents some limitation to their ability to support peatland functions. For instance, mechanical mounded hummocks are higher than natural analogues because the primary goal of creating high mounds under current seismic line restoration is to reduce the sightline and movement efficiency of predators, such as wolves (Filicetti et al. 2019; Finnegan et al., 2018). Therefore, created mechanical mounds have been used for functional restoration as a means of reducing predation rates on caribou. The increased height can have consequences on the structural restoration of the seismic lines, as high mounds can lead to the disconnection of the surface from the water table for keystone peatland vegetation, like mosses, that rely on capillary movement to obtain water (Echiverri et al. 2020). It can also result in the mineral soil becoming the medium on the top of the mounds, which is relatively unsuitable for the establishment of peatland plants. These inverted mechanical mounds are also often created at high densities to slow down the movement of predators. The high density of mounds does not mimic the natural density of hummocks in peatlands. Seismic lines are long and narrow, making their restoration expensive. Using this traditional method of mounding is very time consuming and costly.

Novel surface reconfiguration techniques that eliminated the limitations of mechanical mounding techniques are currently being tested on legacy seismic lines (Xu, 2019). These novel techniques, Hummock Transfer, Inline Mounding, and Rip and Lift, are modifications of the mechanical mounding technique that do not invert the mounds to keep the structure of the mounds intact with the roots of the surviving vegetation. Creating mounds with heights that are like those of natural peatland and maintaining soil properties makes it easier for vegetation to access the water table, keeping the hydraulic connectivity that sustains capillary flow of water to mosses. The high cost associated with mechanical mounding technique is eliminated by reducing the density of the mounds to mimic those of natural peatlands.

With the introduction of new seismic line restoration techniques, there is need to assess their effectiveness in restoring the biogeochemical processes that support peatland functions. Pilot field studies on these novel mounding techniques, such as Hummock Transfer, Inline Mounding, and Rip and Lift, also present an opportunity to access the co-benefits of other restoration management practices such as seedling planting and application of slow-release fertilizer to facilitate the establishment of desired vegetation community. Fertilizer application has been used to enhance the restoration of other disturbed peatlands, primarily extracted peatlands (Caisse et al., 2008; Emond et al., 2016; Hytönena and Kaunisto, 1999; Hytönena and Saarsalmi, 2009;

Sottocornola et al., 2007). The addition of common peatland limiting nutrients (i.e., N and P) through fertilization has proven effective in achieving the desired vegetation growth in peatlands (Rochefort et al., 2003), particularly in promoting tree growth with the addition of P fertilizer (Sundström et al, 1995; Caisse et al., 2008). Similarly, other studies have found that N fertilization can lead to increases in vascular plant growth in boreal peatlands (Limpens et al. 2003; Tomassen et al. 2004; Wiedermann et al. 2009; Le at al. 2021). Nishimura and Tsuyuzaki (2015) found that the addition of N can promote the dominance of grasses, resulting in a decrease in cover of mosses and forbs due to increased competition. At the Degerö Stormyr fen in Sweden a long-term study of anthropogenically applied NH_4NO_3 solution of 3g N m^{-2} $year^{-1}$, resulted in a no change in *Sphagnum* cover after 4 years. However, after 8 years there was a 59% reduction in *Sphagnum* cover (Wiedermann, Nordin, Gunnarsson, Nilsson, & Ericson, 2007; Eriksson, Öquist, & Nilsson, 2010). At a bog in Scotland, Levy et al. (2019) observed a 30 percent reduction in *Sphagnum* cover after 14 years of anthropogenically applying a NH_4NO_3 solution of 6.4g N m^{-2} $year^{-1}$. At the Mer Bleue bog in Canada, there was a similar long-term study of anthropogenically applied NH_4NO_3 solution of concentrations higher then 3.2g N m^{-2} $year^{-1}$, resulted in a decrease in *Sphagnum* after 3 years, and an absence of *Sphagnum* completely after 5 years (Juutinen, Bubier, and Moore, 2010). Although the application of a high concentration NH_4NO_3 solution negatively impacted the survival and growth of *Sphagnum*, other vegetation such as dwarf shrubs and other mosses benefitted from the additional N (Juutinen et al., 2016). Increases in growth of one functional group can alter the vegetation composition as a competitive advantage is given to the functional types that can benefit from the nutrient addition the most. This advantage can result in certain functional groups changing the environmental growing conditions. For instance, at the Mer Bleue Bog the positive response of the shrub layer to the nitrogen addition led to increased shading which was had a detrimental effect on *Sphagnum* survival and growth (Chong, Humphreys, & Moore, 2012). Turkington et al. (1998) found that applying an NPK fertilizer to nutrient limited boreal ecosystems resulted in a vegetation community shift, which favored graminoids and some shrubs, while the cover of other shrubs, lichens, and bryophytes declined. In the restoration of a peat extraction area, Sliva and Pfadenhauer (1999) found that the addition of fertilizer with P was effective in increasing the quantity of shoots of graminoids. Additionally, greenhouse studies have shown increasing *Sphagnum* productivity with the addition of N and P fertilizers (Li et al., 2018). However, it is unclear if the nutrient condition in a seismic line contributes to the limited establishment of woody species. Thus, it is not known if fertilization of the tree seedling planted on the modified mounds will plays a significant role in their establishment. Further research needs to determine whether restoring microtopography and planting seedlings alone will it be enough for trees and other woody vegetation to regenerate naturally on the seismic lines or if fertilization is necessary.

3.0 Characterizing Nutrient Dynamics of a Peatland Undergoing Restoration on Legacy Seismic lines in Alberta's Boreal Forest Region

3.1 Introduction

The biogeochemical functions of boreal peatlands support the sequestration of carbon (C) and nutrients, such as nitrogen (N) and phosphorus (P), through a rate of biomass accumulation that is disproportionate to the rate of decomposition (Gorham, 1991). The structure of peatlands and landscape position enable them to regulate hydrology and sustain requisite wetness for anoxic conditions associated with a slow rate of decomposition (Glaser, 1987). One of the key structural features of peatland that support the hydrologic regulatory function and moisture gradient is the variation in microtopography resulting in different microforms known as hummocks and hollows. Hummocks are slightly elevated areas, while hollows are low-lying portions of the peat surface. Moisture and nutrient gradients across a peatland are influenced by these slight changes in elevation. This difference in moisture conditions creates redox gradients that support various rates of biogeochemical processes (Frei et al., 2012). As a result, vegetation assemblages across peatlands reflect the gradients in moisture and nutrient availability across microforms. However, disturbances often remove the microtopographic gradients resulting in changes to the hydrological conditions that impact peatland biogeochemical functions and vegetation assemblage.

Peatlands are heavily disturbed ecosystems in boreal regions of Canada (Rooney, Bayley, & Schindler, 2012; Strack et al., 2019). The disturbance of peatlands alters their biogeochemical and ecohydrological functions, limiting their capacity to regulate major cycles (e.g., carbon cycle) of the earth's biosphere that play a crucial role in mitigating climate change impacts. A major form of peatland disturbance in the western boreal forest region of Alberta is created from the geologic exploration for oil and gas resources. For instance, resource extraction activities in Canadian's boreal peatlands have resulted in an extensive web of linear disturbances (~5-8 m wide), known as seismic lines, with at least 345,000 km of seismic lines intersecting with peatland ecosystems in Alberta (Strack et al. 2019). Seismic lines alter the natural setting of the landscape. When seismic lines are created, the peatland surface is flattened and compacted by the weight of the equipment (Stevenson et al. 2019). This interrupts the flow of water and causes saturated conditions on the seismic line (Dabros et al. 2017). To move the seismic equipment across the landscape, trees and other vegetation are removed.

The landscape fragmentation and leveling associated with seismic lines modifies the microtopographic gradients that support a range of biogeochemical processes and diverse microhabitats found in natural peatlands. Without the microtopographic gradient, some peatland plant species that cannot tolerate saturated conditions, like trees, will have limited growth and survival. Therefore, the impact of seismic lines on peatland structure needs to be removed to restore the structure and functions of peatlands on these lines. However, there was no environmental regulatory requirements for resource exploration companies to restore these seismic lines. Thus, vast portion of peatlands in central Alberta are characterized by legacy seismic lines that have been left for decades to self-regenerate through secondary succession, but tree regrowth on these lines remains poor (Lee and Boutin 2006; van Rensen et al. 2015). In recent years, restoration trials have been implemented on seismic lines within woodland caribou ranges to reduce the negative impact of seismic lines on high-rate mortality of endangered caribou calves through predation by wolves. The restoration approach adopted in these recent projects involves reconfiguration of the seismic line to restore optimal hydrological and biogeochemical conditions that can support the growth of tree species that provide structural habitat support to caribou.

Seismic line surface reconfiguration is achieved through the process of mechanical mounding, which creates elevated landforms along the seismic line by excavation and placement of the inverted peat profile on the line. The formation of these mounds is done at high densities, creating deep depressions and elevated mounds that are high enough to restrict the sightline and movement of predators hunting the endangered woodland caribou (Sutton 1993; Pyper et al., 2014). Although traditional seismic line restoration methods have shown promising results in restoring vegetation structure of boreal forest stands, their soil and vegetation ecological functions are not leading to the recovery of natural peatland conditions (BERA Project Report, 2020; Echiverri, 2020). Potentially, moisture conditions are not the only barrier to peatland tree species reestablishment. Macronutrients, such as N and P, are important for tree establishment and growth (Sundström et al, 1995; Caisse et al., 2008; Kool and Heijman, 2009; Nishimura and Tsuyuzaki, 2015). The addition of P in other disturbed peatlands has led to increased tree growth (Sundström et al, 1995; Caisse et al., 2008). However, the addition of N and P has also been shown to increase other peatland species, such as shrubs and grasses, that could provide competition for tree growth (Kool and Heijman, 2009; Nishimura and Tsuyuzaki, 2015).

The modification of peatland nutrient dynamics by seismic line fragementation is not well understood and nutrient cycling of newly restored seismic lines has not been studied. Changes to nutrient availability have been observed in peatlands post-disturbance because of warmer and more oxic conditions altering microbial activity, which could suggest a change in net mineralization rates (Bradford et al., 2008; Li et al., 2012). Davidson et al. (2020) also found a nearly 40%

reduction in peat organic matter on a seismic line compared to adjacent natural areas, coupled with increased δ13C and δ15N stable isotope signatures on the line, implying increased mineralization rates. With regards to moisture dynamics, previous research indicates that a lowered peatland water table can cause a reduction in the moisture content of the peat surface (Waddington et al. 2010) that can result in increased mineralization rate (Bayley et al. 2005).

Previous research suggests that peat properties are sensitive to disturbance such as those associated with heavy machinery used in restoration civil earth works that can compact the peat and alter physical properties (Laine et al., 2006; Nwaishi et al., 2015; Lepilin et al., 2019; Szajdak et al., 2020). This disturbance results in a decrease of organic matter content and pore size resulting in increased bulk density and decreased specific yield and total porosity (Boelter 1969; Lepilin et al., 2019). Studies that have characterized peat hydrophysical properties of seismic lines restored using mechanical mounding methods suggest that surface reconfiguration re-disturbs the peat resulting in further increases in volumetric water content (VWC) and bulk density, as inversion places the compressed peat and sometimes mineral soil on top, resulting in higher bulk density and VWC in the surface layers (Lieffers et al, 2017; Davidson et al. 2020). Novel surface reconfiguration techniques that have been designed to address the limitations of the traditional mounding technique are currently underway in seismic lines located within boreal forest region of Alberta. This pilot project presents an opportunity to assess the effect of seismic line restoration techniques on peat hydrophysical properties and nutrient cycling.

To address the knowledge gaps surrounding the impact of seismic line disturbance and new restoration techniques on peatland nutrient cycling, this study was conducted with the main aim of characterizing the biogeochemical processes of a fen undergoing restoration of seismic line disturbances using newly modified mounding techniques. The specific objectives of the study are as follows: 1) to characterize the microclimatic conditions of the site and preliminary effects of the new restoration techniques on peat hydrophysical properties; 2) evaluate the effect of restoration treatments on rates of decomposition; 3) assess nutrient pools and net mineralization rates across the microtopographic gradients created through these new surface reconfiguration techniques, relative to natural and unrestored sites. It is hypothesized that the new restoration techniques used to reconfigure the peatland surface will re-disturb peat properties resulting in a modification of peat hydrophysical properties (e.g., specific yield, porosity, bulk density, and volumetric moisture content). Based on the changes in soil properties and moisture variations created by the reintroduction of microtopography, it is hypothesized that the mechanical surface reconfiguration will increase the rate of biogeochemical processes, including decomposition, net mineralization and availability of N and P on the mounds.

3.2 Methods

3.2.1 Site Location

This study was conducted in Brazeau County, Alberta, Canada (Fig. 3.1). The field site is a treed fen located in the boreal transition ecoregion within the boreal plains ecozone (52°53'21.4"N; 115°32'57.0"W). The fen had an average peat depth of 2.9 m and the dominant trees growing on the site are *Picea mariana* (black spruce) and *Larix laricina* (tamarack) with the understory vegetation dominated by shrubs, sedges, *Sphagnum* and true mosses. The treed fen contains both a rich fen section with an average porewater pH of 7.3 and EC of 178.1 $\mu S\ cm^{-1}$; and a poor fen section with a lower pore water pH of 5.9 and EC of 52.6 $\mu S\ cm^{-1}$. There is a moisture gradient between the two fens with the rich fen being wetter than the poor fen, which influences the vegetation, as the poor fen is *Sphagnum* dominated. Both fen types are intersected by legacy seismic lines constructed approximately 40 years prior to this restoration. The plant communities on the seismic line are composed of species also observed in the understory of the adjacent undisturbed peatland; however, the density of trees and ground lichen are very low. The seismic lines are 5 m wide, and the disturbance occupies an area of approximately 8,700 m^2.

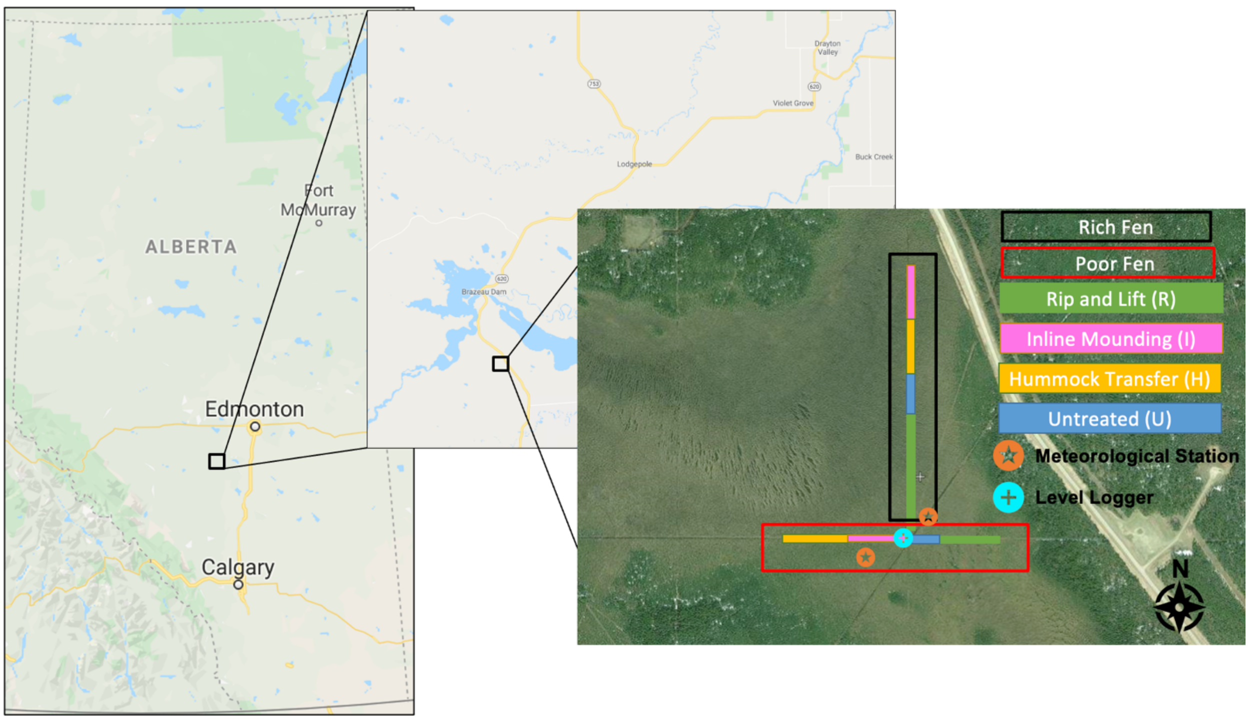

Figure 3.1. Map of the study site location in Brazeau County, Alberta. The portion enclosed in the box indicates the location of the seismic line disturbed peatlands within the Alberta area. The intersecting seismic lines are highlighted with different The intersecting seismic lines are highlighted with different colors to demonstrate the locations of restoration treatments within each fen type.

To restore the seismic lines and create suitable conditions for regrowth of desirable peatland vegetation community, civil earthworks (ground surface reconfiguration) were conducted in March 2019 to create new microsites mimicking those in the natural areas of the peatland.

3.2.2 Ground Reconfiguration Treatments

The ground surface reconfiguration was achieved using three new restoration treatments, which include Hummock Transfer, Inline Mounding, and Rip and Lift (Fig. 3.2). These treatments were implemented on each of the three major seismic lines on the site (Fig. 3.1). Within each treatment the goal was to create some level of microtopographic gradient with hummock and hollow microsites. The hummocks are the lifted regions on the landscape and hollows are low-lying pools. The hummocks and hollows were evenly paired across the seismic lines within each of the treatments at an approximate density of 155 mounds/ha.

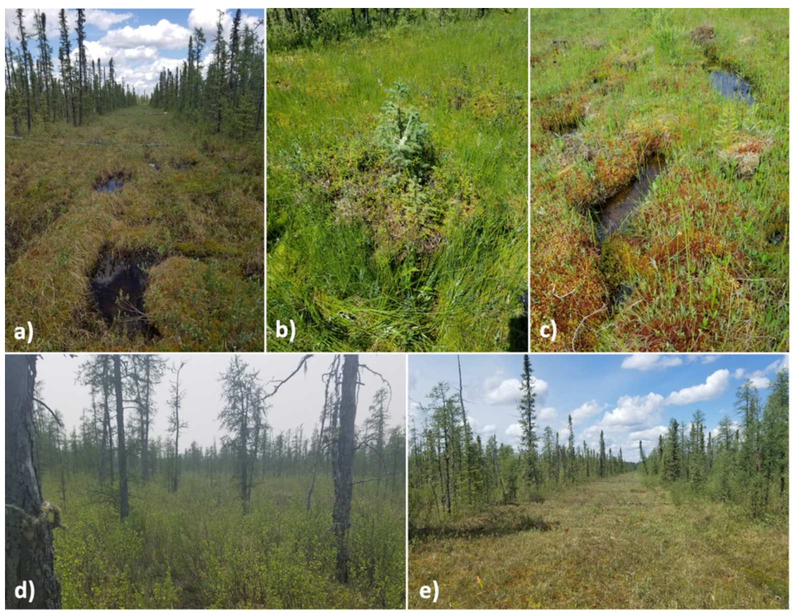

Figure 3.2. Pictures of the different restoration treatments showing (a) Inline Mounding, b) Hummock Transfer, c) Rip and Lift, d) Natural, and e) Untreated. The outcome of how the restoration treatments altered the microtopography on the seismic line (a,b,c). The natural area of the treed fen that was not directly affected by the seismic line disturbance (d). The Untreated portion of the seismic that was left without any groundwork reconfigurations (e).

The Inline Mounding technique is similar to traditional mounds currently used for seismic restoration within caribou habitat. However, in this study, the mounds were not inverted, so vegetation is left right-side-up and the pools created are not as deep as those created with the traditional mounding techniques. The Inline Mounding hummocks were created by the excavation of peat from the line, and placement of the peat next to the pit where it was removed from to create the hummock and hollow microforms. The Hummock Transfer technique created microforms by taking a hummock from an adjacent natural area and placing it on the line with vegetation upright (Xu, 2019). The hummocks were transferred under frozen conditions to ensure that they remained intact. Although this reduces the density of hummocks in the natural areas off the line, it allows for the natural establishment of hummocks with woody vegetation on the line.

The Rip and Lift is a ripping technique that creates 1 m deep rips using a single tooth ripping shank dragged on the ground and lifting the peat at the end of the rip to create the microtopographic gradient. The ripped area forms the hollow, and the material that was ripped and dragged forms a micro-elevated area that is expected to support hummock conditions like those found in patterned fens. These ground reconfiguration treatments were compared against an Untreated portion of the seismic line that had no ground reconfigurations. The Untreated area does not have distinct hummocks and hollows; however, samples were taken from slightly higher areas and lower depressions that exist on the Untreated treatments. Also, the surrounding intact natural treed fen, hummocks and hollows, were used as a reference site against which the structure and functions of the restoration treatments could be compared (Brinson & Rheinhardt, 1996; Pruitt et al., 2012; Wortley et al., 2013).

3.2.3 Site Micrometeorological Conditions and Hydrophysical Properties of Peat

The research occurred during the 2019 and 2020 growing seasons that had very different weather conditions (Fig. 3.4). A meteorological station was setup on the study site to characterise local micrometeorological conditions. The station was located at the intersection of the seismic lines (Fig. 3.1) and it continuously recorded meteorological data (soil moisture, soil temperature, air temperature etc.) every two hours throughout the year. Precipitation was also recorded every two hours with a ECH_2O Rain model ECRN tipping bucket (Meter Environment, Pullman, Washington, USA).

Moisture content and nutrient conditions were measured over the two growing seasons (June-August). The moisture content of hummocks and hollows were measured using Delta Devices HH2 Moisture Meter (Hoskin Scientific Ltd, Burlington, Ontario). During each point measurement, a microform's moisture content was taken in three locations and averaged. Two hummocks and two hollows in the far north line and two hummocks and two hollows in the east to west line in each treatment, Hummock Transfer, Inline Mounding, and Rip and Lift, were measured every one to two weeks. Water table was also measured using level loggers that were installed in the Untreated and Natural areas of the site, and they recorded depth to water table every two hours.

The characteristics of the peat were analyzed by removing intact peat cores from two hummocks and two hollows in the east to west line in each treatment, Hummock Transfer, Inline Mounding, and Rip and Lift, from the fen using cut pieces of metal pipes that measured approximately 15 cm in height and 6.35 cm in diameter. Once the cores were extracted, the top and bottoms of the pipes were wrapped in plastic wrap and secured with duct tape to ensure no water or peat loss during transportation. These cores were taken back to the Mount Royal

University Ecology Laboratory for analysis of hydrophysical parameters (i.e., volumetric soil moisture, bulk density (p_b), specific yield (Sy), and porosity) using standard techniques (Boelter, 1966). To calculate volumetric soil moisture, the volume of water relative to the total volume of soil, from gravimetric moisture data analyzed in the lab, cores were weighed for their field weight. Cores were then placed in Milli-Q water for 72 hours to allow them to saturate from below and weighed to determine the wet-weight that was used to determine porosity (Equation 1). Afterwards, cores were placed on a metal rack and drained for 24 hours to determine the weight of the gravity drained samples that aided in the calculation of specific yield (Equation 2). Lastly, the cores were placed in a drying oven at 80 °C for 2 days to obtain the dry weight, which was used in estimating bulk density and volumetric soil moisture following equations 3-4.

$$Porosity = \left(\frac{\text{wet weight (g)} - \text{dry weight (g)}}{\text{Volume (ml)}}\right) \quad [1]$$

$$\text{Sy} = \left(\frac{\text{wet weight (g)} - \text{gravity drained weight (g)}}{\text{Volume (ml)}}\right) \quad [2]$$

$$\text{Pb} = \left(\frac{\text{dry weight (g)}}{\text{Volume (ml)}}\right) \quad [3]$$

$$\text{Volumetric moisture} = \left(\frac{\text{field weight (g)} - \text{dry weight (g)}}{\text{Volume (ml)}}\right) \quad [4]$$

3.2.4 Biogeochemistry

To assess the biogeochemical processes resulting from the reintroduction of a microtopographic gradient on the seismic lines, decomposition rate, pore water nutrient concentration, peat available nutrient content, and N and P net mineralization rates were measured. Decomposition rates was assessed using the Tea Bag Index method (TBI; Keuskamp et al. 2013). Briefly, four pairs of pre-weighed tetrahedron-shaped Lipton's green tea and rooibos tea bags were buried in each of the restoration treatments in the north line and the east to west line at a depth of 8 cm for a period of 90 days. The tea bags are made of 0.25 mm mesh, so that microorganisms could enter the bags for decomposition (Setala, Marshall & Trofymow 1996). After 90 days of incubation, the tea bags were removed, oven dried at 60 °C for 24 hours and reweighed to determine post-incubation dry weight. The dry weights of the rooibos tea are used to determine the decomposition, while the weight of the green tea is used to determine the stabilization factor because the different kinds of tea decompose at different rates. Relative to the faster decomposing leaves of green tea, the rooibos tea is composed of woodier material, which is harder to decompose. Hence, the green tea reaches a plateau of decomposition after 40 to 60 days while rooibos tea decomposition does not plateau until approximately 90 days. The stabilization factor is computed by dividing the decomposed fraction of green tea (ag) by the hydrolysable fraction of green tea (Hg) and subtracting the product from 1.

$$S = 1 - \left(\frac{ag}{Hg}\right)$$

The green tea's stabilization factor is used to help determine the predicted labile fraction of rooibos tea (*ar*):

$$ar = Hr \times (1 - S)$$

The decomposition rate (k) is calculated per day. It is derived using the equation:

$$k = \ln \frac{\frac{ar}{(WR - 1(1 - ar))}}{t}$$

Where, t is the time (days) spent incubating in the ground and WR is the fraction of rooibos tea remaining.

Extractable N and P in peat were measured within four hummock and hollow pairs in each of the five-treatment types (n = 40). To account for for heterogeneity across the site, two hummock and hollow pairs were sampled in the northern section of the seismic line, and two hummock and hollow pairs were sampled from the east to west seismic line. Peat samples for nutrient extraction and net mineralization studies were collected at the beginning, peak and end of the growing season in 2019, and at the peak of the growing season in 2020. Briefly, grab samples of peat were taken at approximately 10 cm depth within each of the five treatment types on each of the two seismic lines. A pair of peat samples were removed from two different hummocks and hollows resulting in four replicate hummocks and hollows measured in each treatment and a total 80 samples that were removed from the fen. One of the paired samples was taken to the laboratory to be analyzed for pre-mineralization available concentrations of NO_3^-, NH_4^+ and SRP at the time of collection, while the second pair was placed into a polyethylene bag and buried back into the collection location to incubate for 28 days after which they were removed and analyzed for post-mineralization concentrations of NO_3^-, NH_4^+ and SRP (Eno, 1960).

To determine extractable nutrient concentration, two 10 g portions of peat were subsampled from each sample and placed into sterile sample cups. One set of the subsamples from each sample was mixed with 50 ml of milli-Q water to determine SRP, while the other set of subsamples were mixed with 50 ml of 2 M KCl to extract the NO_3^- and NH_4^+ (Binkley and Hart, 1989). Samples were sealed and shaken for 1 hour on a Heavy Duty Orbital Shaker (OHAUS CORPORATION, Model SHHD1619AL, Parsippany, New Jersey, USA). Once the samples were well mixed, they were filtered through Whatman No. 42 filter paper (pore size of 2.5 μm). A portion of the filtrate was poured into a 15 ml centrifuge tube and frozen until they were analyzed using standard colorimetric methods on a Bran-Luebbe Autoanalyzer III (Seal Analytical) at the Biogeochemistry

Laboratory, University of Waterloo in 2019. Due to COVID-19 lockdowns, 2020 samples were analyzed at the Natural Resources Analytical Laboratory (NRAL) at the University of Alberta using standard colorimetric methods (Thermo Gallery Beermaster Autoanalyzer).

Pre-mineralization sample results were used to compare changes in available nutrient concentrations throughout the growing season. Calculations of the net mineralization rates were determined by the differences in concentrations between the pre-mineralization and post-mineralization peat samples. Concentrations above zero indicated net mineralization whereas concentrations below zero indicated net immobilization. The rate was determined by dividing the change in nutrient concentration by the number of days the peat samples were incubated in the ground. Subsamples of peat were taken at the time of analysis to determine soil moisture content, as the values of available nutrient and net mineralization rates are presented per dry weight of peat.

Pore water samples were simultaneously collected with the peat samples for nutrient concentration analysis. The pore water samplers were approximately 30 cm long plastic PVC pipe with small holes and a geosock sediment screen placed in the lower 10 cm of the pipe. Samplers were sealed at the top and bottom with holes drilled into the top of the sampler to attach a plastic tube with a three-way valve at the end that was used to access the pore water when sampling. Pore water samplers were installed at 10 cm depth in hummocks and hollows within each treatment, and samples were extracted using a syringe that was triple rinsed with deionized water between each sample. The pore water was collected in 50 ml centrifuge tubes, filtered in the laboratory, and frozen until they were ready to be analyzed for NO_3^-, NH_4^+ and SRP at the Biogeochemistry Laboratory at the University of Waterloo in 2019 and the Natural Resources Analytical Laboratory at the University of Alberta in 2020.

3.2.5 Statistical Analysis

An analysis of variance (ANOVA) was used to determine the calculated probability (p-values) of variation in hydrophysical properties, decomposition rate (k), pore water chemistry, pore water nutrient concentrations of macronutrients (µg/l), net mineralization rates (µg g^{-1} dry peat day^{-1}) among treatments (Natural, Untreated, Hummock Transfer, Inline Mounding, and Rip and Lift), microforms, and years (2019 and 2020) as fixed factors. Pairwise comparisons were conducted on significant relationships ($p<0.05$) using post-hoc tests between subsets by means of the emmeans function (Lenth, 2021). Pore water chemistry and nutrient concentrations and net mineralization rates were not normally distributed, so they were log transformed to be normally disturbuted prior to analysis. All statistical data analysis was calculated in R studio (R Studio, version 1.2.5042; RStudio Team, 2020).

3.3 Results

3.3.1 Site Micrometeorological Conditions and Hydrophysical Properties of Peat

The micrometeorological conditions over the two growing seasons varied considerably, providing an opportunity to contrast restoration nutrient dynamics under wet and dry conditions (Fig. 3.3). There was significantly more ($F_{1,75} = 8.511$, $p = 0.004$) precipitation in the 2019 growing season than during the same period in 2020, with a mean (± standard deviation) of 0.4 (± 0.7) mm of average daily precipitation compared to 2020 which had 0.16 (± 0.3) mm. The fluctuations in the water table were the same in all the treatments. Although the water table at the beginning of the growing season was not significantly different ($F_{2,602}= 15.420$, $p=0.9126$) in 2019 and 2020, there was a significant difference ($F_{2,602}= 15.420$, $p<0.001$) in the water table in July and August between the years, amounting to a difference of 1.3 cm and 6.4 cm, respectively. Similarly, to the water table, there was a continuous decrease in VWC in 2020 as the growing season progressed;

however, the average VWC in 2020 (0.751 $m^3/m^3 \pm 0.12$), was still higher than in 2019 (0.648 $m^3/m^3 \pm 0.04$), despite all the precipitation in 2019 (Fig. 3.4). The VWC measured at the micrometeorological station and the manual soil moisture readings showed little difference between 2019 and 2020. However, the Untreated areas had very similar average percent moisture content between the hummocks and hollows, whereas the treated areas resemble the Natural area's drier hummocks and wetter hollows (Table 1). There was a significant difference ($F_{2,545} = 3.632$, $p=0.0271$) between the soil moisture in the hummocks of the treatments, as Rip and Lift hummocks had significantly higher ($F_{2,545} = 3.632$, $p<0.001$) soil moisture than Hummock Transfer and Inline Mounding hummocks. Higher average daily soil temperatures were also warmer in 2019 (15.4 °C ± 2.0), compared to those in 2020 (14.8 °C ± 1.6). Although soil temperatures were higher in 2019, the average daily air temperature was higher in 2020 (14.0 °C ± 3.1), than in 2019 (13.2 °C ± 3.2).

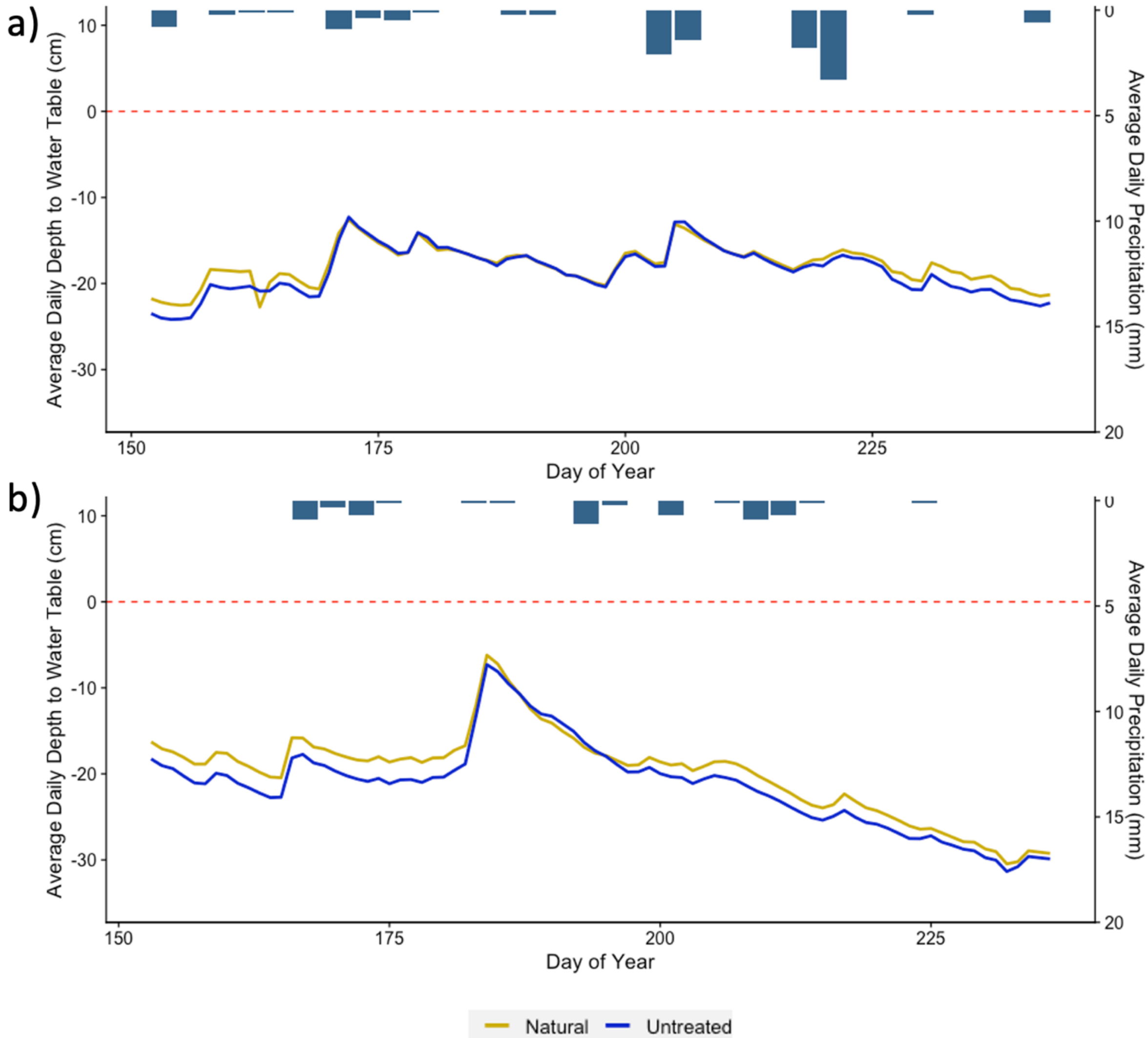

Figure 3.3. Seasonal trends, between June 1 and August 22, of the average daily precipitation and the daily average water table fluctuations in a) 2019 and b) 2020 from the growing season.

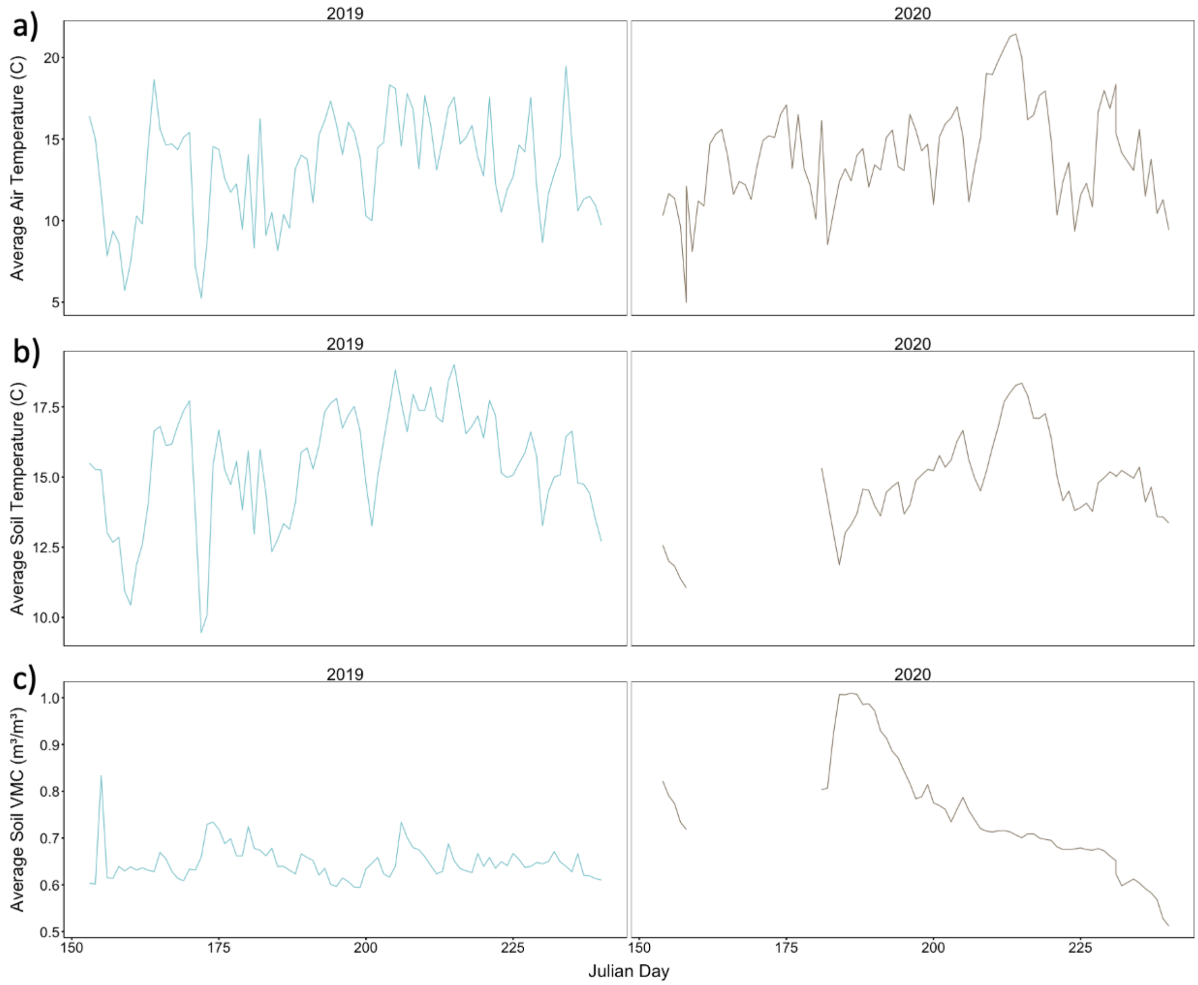

Figure 3.4. Meteorological Data of a) average air temperature, b) average soil temperature, and c) average soil volumetric water content (VWC e from the 2019 and 2020 growing season (June 1 to August 27).

Peat hydrophysical data was collected at the fen, and although different restoration techniques created different size and shape of hummocks, following resettling, the hummocks in all the treatments were of similar height and similar to those in the Natural area. The peatland has an average of 91.6% organic matter in the top 15 cm of peat, and no treatment effect was observed. Similarities were also seen between the treatment's hydrophysical properties, as there was no significant difference ($F_{4,31} = 1.99$, $p = 0.121$) in bulk density, specific yield, and porosity among the treatments. Although there were no significant differences, Table 2 shows a trend of the

Untreated section having a lower average bulk density (0.06 ± 0.02 g/cm^3) and higher specific yield (0.11 ± 0.01) than the other treatments. This inverse relationship between bulk density and specific yield is also seen in the other treatments. There is a trend of the restored treatments having a higher bulk density and lower specific yield compared to the Untreated portion of the seismic line. The average specific yield of the peat samples ranged from 0.09 to 0.11. The average porosity was similar across samples ranging between 0.76 - 0.79 across all treatments.

Table 3.1. Percent soil moisture content of the microtopography in 2019 and 2020 within each of the restoration treatments.

Treatments	Soil Moisture Content (%)							
	2019				2020			
	Hummock		Hollow		Hummock		Hollow	
Hummock Transfer	40	(±30)	100	(±0)	33	(±23)	100	(±2)
Inline Mounding	34	(±10)	100	(±0)	37	(±12)	100	(±0)
Rip and Lift	64	(±33)	83	(±26)	48	(±24)	93	(±14)
Natural	38	(±34)	92	(±14)	39	(±37)	71	(±38)
Untreated	60	(±44)	66	(±39)	55	(±37)	64	(±39)

Table 3.2. Similarities in hydrophysical properties of the peat within the different restoration treatments in 2020 and pore water chemistry for 2019 and 2020

Variables	Hydrophysical										Pore Water Chemistry			
Treatments	Hummock Height (cm)		Organic Matter-LOI (% wt. loss)		Bulk Density (g/cm3)		Porosity		Specific Yield		pH		EC µs	
Hummock Transfer	20.8	(±9.0)	90.8	(±4.2)	0.07	(±0.016)	0.76	(±0.066)	0.10	(±0.090)	6.8	(±0.83)	144	(±90.2)
Inline Mounding	18.6	(±7.2)	91.6	(±4.7)	0.08	(±0.023)	0.77	(±0.050)	0.10	(±0.024)	6.4	(±0.72)	`126	(±110)
Rip and Lift	22.5	(±8.7)	91.7	(±4.8)	0.09	(±0.023)	0.78	(±0.034)	0.09	(±0.025)	6.4	(±0.72)	120	(±128)
Natural	22.8	(±8.6)	91.4	(±4.3)	0.08	(±0.010)	0.77	(±0.055)	0.09	(±0.019)	6.5	(±0.92)	139	(±129)
Untreated	NA		92.3	(±4.7)	0.06	(±0.016)	0.79	(±0.043)	0.11	(±0.011)	6.6	(±0.77)	134	(±93.1)

Pore water chemistry was also analyzed throughout the growing seasons in 2019 and 2020. The electrical conductivity of the fen had a large variation, as the site consist of a rich (224.55 ± 75.99 µS cm^{-1}) and poor fen (71.75 ± 86.90 µS cm^{-1}). However, since each of the treatments are located within both the rich and poor fen, there is no significant difference ($F_{4,120}$=0.186, p=0.945) in EC between the treatments. Like the EC, the pH varied greatly between the rich (7.16 ± 0.52) and poor fen (5.96 ± 0.50); however, the average pH of the site was neutral (6.50 ±0.79), with a pH ranging from 4.60 to 7.93, with no significant difference ($F_{4,155}$ p=0.229) in pH between the treatments.

3.3.2 Decomposition Rates

Rates of decomposition were significantly higher ($F_{1,62}$=4.535, p<0.0372) in 2020 than in 2019 (Fig. 3.5). Although decomposition rates were higher in 2020, the deviation between the restored treatments in the hollows was also less, and their rates of decomposition were similar to Natural. In 2020, the hummocks created by the Hummock Transfer and Rip and Lift resulted in a higher decomposition rate relative to that of the Inline Mounding. Yet, the rate of decomposition in the Hummock Transfer was lowest in 2019 (0.01 ± 0.005), while in 2020 Hummock Transfer had the highest average rate of decomposition in its hummocks. However, between the years, no significant ($F_{4,44}$ =0.547, p=0.7022) treatment effects were observed in the rate of decomposition.

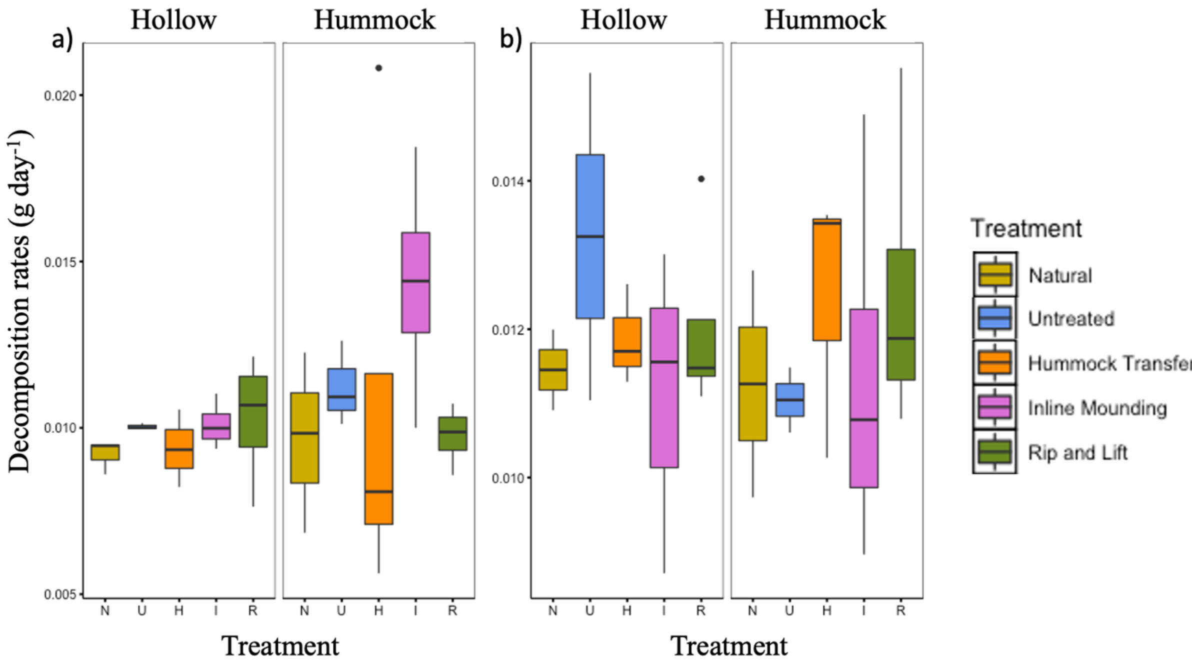

Figure 3.5. The elevated decomposition rates in b) 2020 compared to a) 2019, and the differences in decomposition rates between the restoration treatments during the growing seasons.

3.3.3 Nutrient Pools and Net Mineralization Rates

Nutrient concentration varied over the season. For instance, at the peak of the growing season in 2019, there is a large variation in concentration of SRP in the hummocks of the Natural and Inline Mounding, and this is not seen on the other seismic line treatments (Fig. 3.6b). However, the average SRP concentrations are similar between all the treatments ($F_{4,27}$ =2.074, p=0.112). Although microforms were added to the seismic line, none of the porewater SRP concentration trends observed are significant ($F_{1,30}$ =0.496, p=0.487) between the hummocks and hollows. The pore water TIN concentrations of the Untreated and Natural fluctuated depending on the microtopography (Fig. 3.6a). For instance, the hollows of the Natural had greater pore water TIN concentrations than the Untreated, whereas the Untreated had greater pore water TIN concentrations than the Natural in the hummocks. The restored areas, although microtopography was reintroduced, had similar low concentrations in the hummocks and hollows. The trends observed between treatments for the TIN were not significant ($F_{4,24}$= 0.845, p= 0.511), and they were primarily driven by the concentration of NH_4^+ in the pore water, while the pore water NO_3^- concentrations were lower (Fig. 3.6c and d). Therefore, the trends observed for the pore water concentrations of NO_3^- are different from the TIN and NH_4^+. Instead, the highest average concentrations of NO_3^- were present in the Untreated. Although there was a slightly higher average concentration of NO_3^- in the pore water of the Rip and Lift treatment compared to the others, the NO_3^- concentrations were very similar between all the treatments.

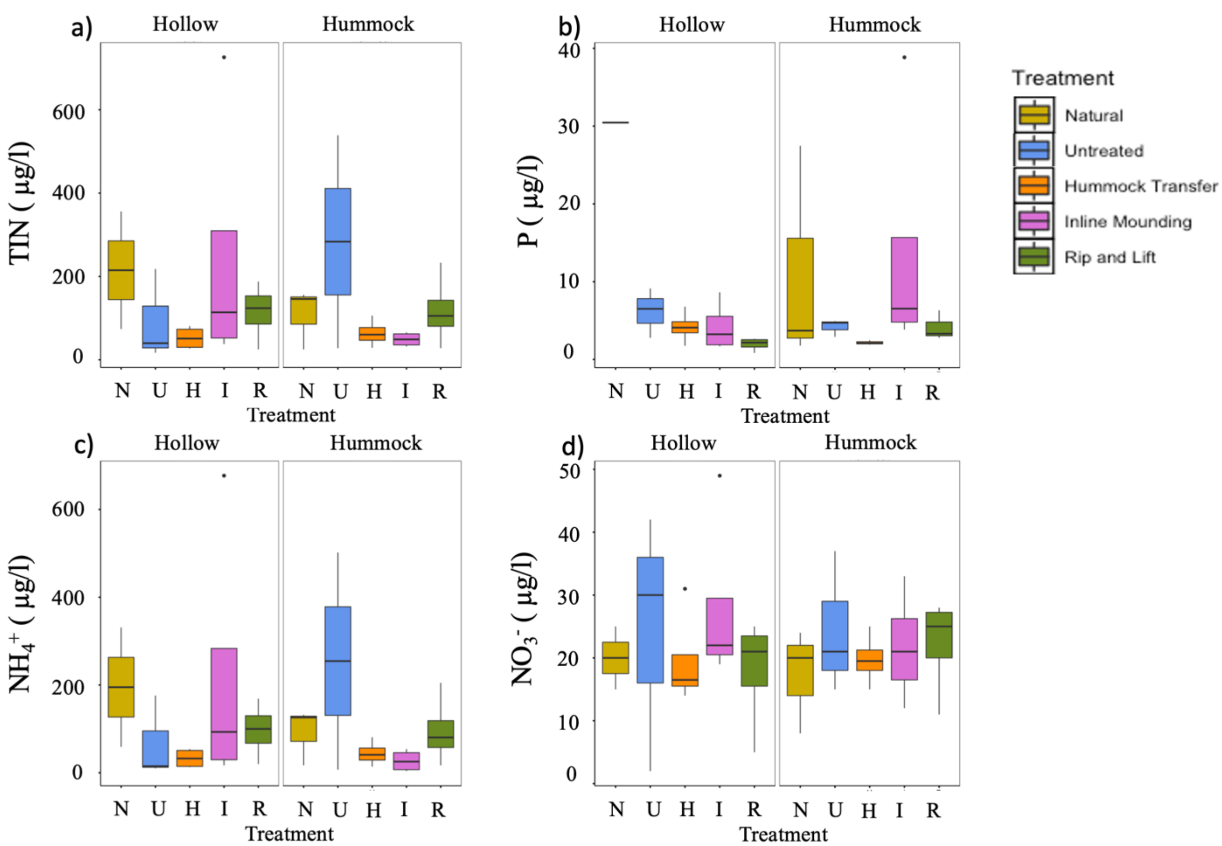

Figure 3.6. Pore water a) Total inorganic nitrogen (TIN) and b) SRP concentrations present at the peak growing season (July) of 2019 within each of the treatments. Pore water TIN concentrations are composed of mostly c) ammonium (NH_4^+) compared to d) Nitrate (NO_3^-).

Concentrations of SRP in pore water were also analyzed throughout the 2019 growing season, and no significant ($F_{4,64}$= 1.109, p=0.3601) SRP treatment effect was observed (Fig. 3.7).

Over the growing season, the concentration of pore water SRP fluctuated, but the concentrations between the months were not significantly different ($F_{2,96}$= 1.641, p=0.199). Concentrations of SRP were generally similar or lower at the peak of the season compared to June and August (Fig. 3.9). A microtopographic effect was seen in Inline Mounding, as the porewater in the hummocks had elevated concentrations of SRP compared to the hollows.

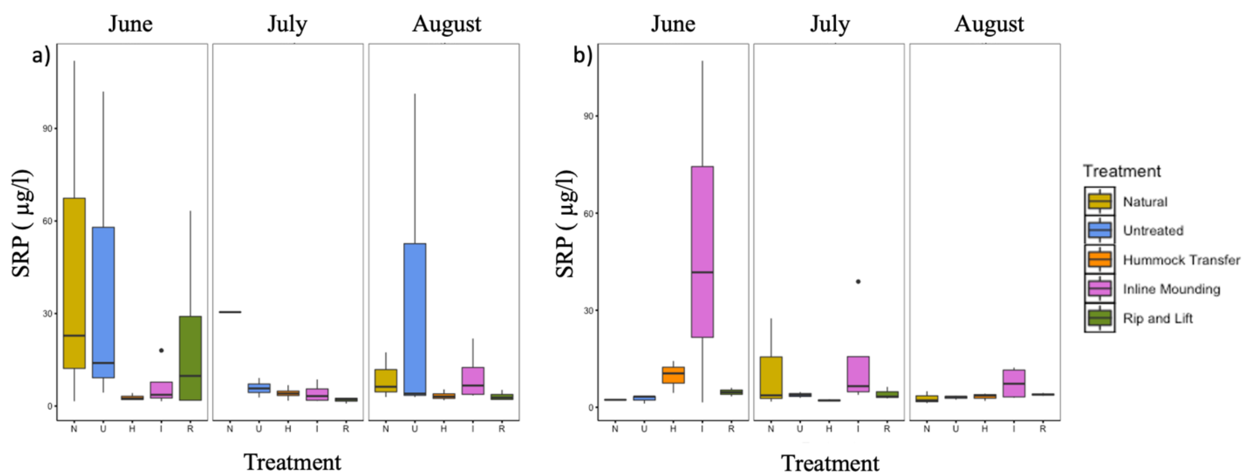

Figure 3.7. Patterns of pore water SRP concentrations throughout the growing season of 2019 across the treatments in a) hollows and b) hummocks

The net mineralization rates of NH_4^+ were higher than those of NO_3^- throughout the growing season (Fig. 3.8). In the hollows, the Hummock Transfer net NH_4^+ mineralization rates of were higher than the other treatments (Fig. 3.8a). However, this increased rate of net mineralization for the Hummock Transfer was not observed in the hummocks. Instead, the average net mineralization rate of the Untreated in the hummocks was higher than the other treatments (Fig. 3.8b). On average, throughout the season, NH_4^+ was being mineralized; however, at the peak of the growing season, NH_4^+ was immobilized in the hummocks of the Natural, Inline Mounding, and Rip and Lift. NO_3^- was being immobilized in the hummocks of the Natural throughout the growing season. At the peak of the growing season all the restoration treatments expect for in Rip and Lift had an average net NO_3^- mineralization rate below zero, in the hollows. In the hummocks in August, the restoration treatments and the Untreated had net NO_3^- mineralization, while NO_3^- was still being immobilized in the Natural site. Although there were slight fluctuations between the treatments in the rates of NO_3^- being mineralized, there was no significant difference.

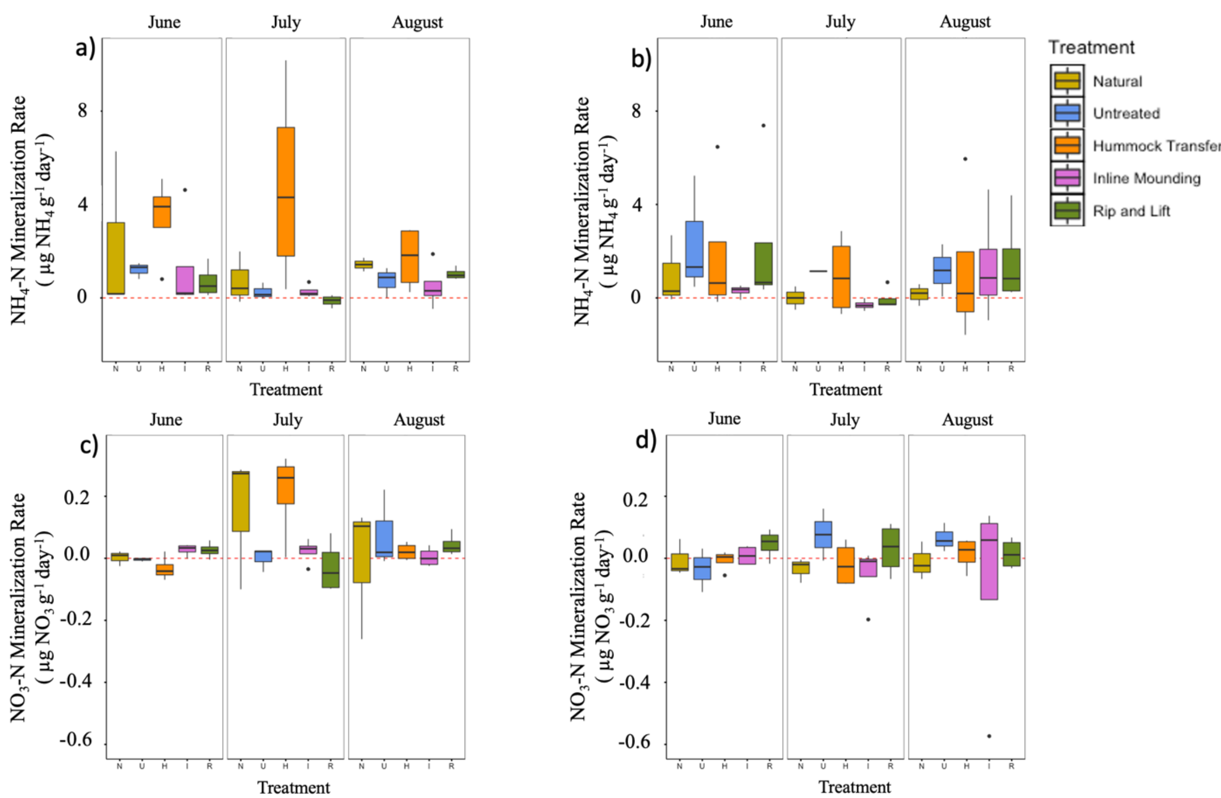

Figure 3.8. Growing season dynamics of net ammonium mineralization rates in a) hollows and b) hummocks and net nitrate mineralization rates in c) hollows and d) hummocks in 2019.

Although decomposition rates were higher in 2020 than 2019, overall, this did not lead to higher concentrations of nutrients in the pore water in 2020 (Fig. 3.9). The highest pore water SRP concentrations were observed in the Untreated site in 2020, whereas the Untreated concentrations were lower and similar to those of the restoration treatments in 2019 (Fig. 3.9a). NO_3^- concentration in 2019 were low, and in 2020 almost all the NO_3^- pore water concentrations were below detectable limits. However, NH_4^+ concentrations were detectable, and there was no treatment effect observed in 2020 (Fig. 3.9b). Inline Mounding had a higher average NH_4^+ concentration compared to the other treatments, but it also had the widest range of NH_4^+ concentrations. Although, the NH_4^+ concentrations varied in 2019 and 2020, there was no treatment effect observed between the two years ($F_{4,82} = 2.166$, $p=0.080$).

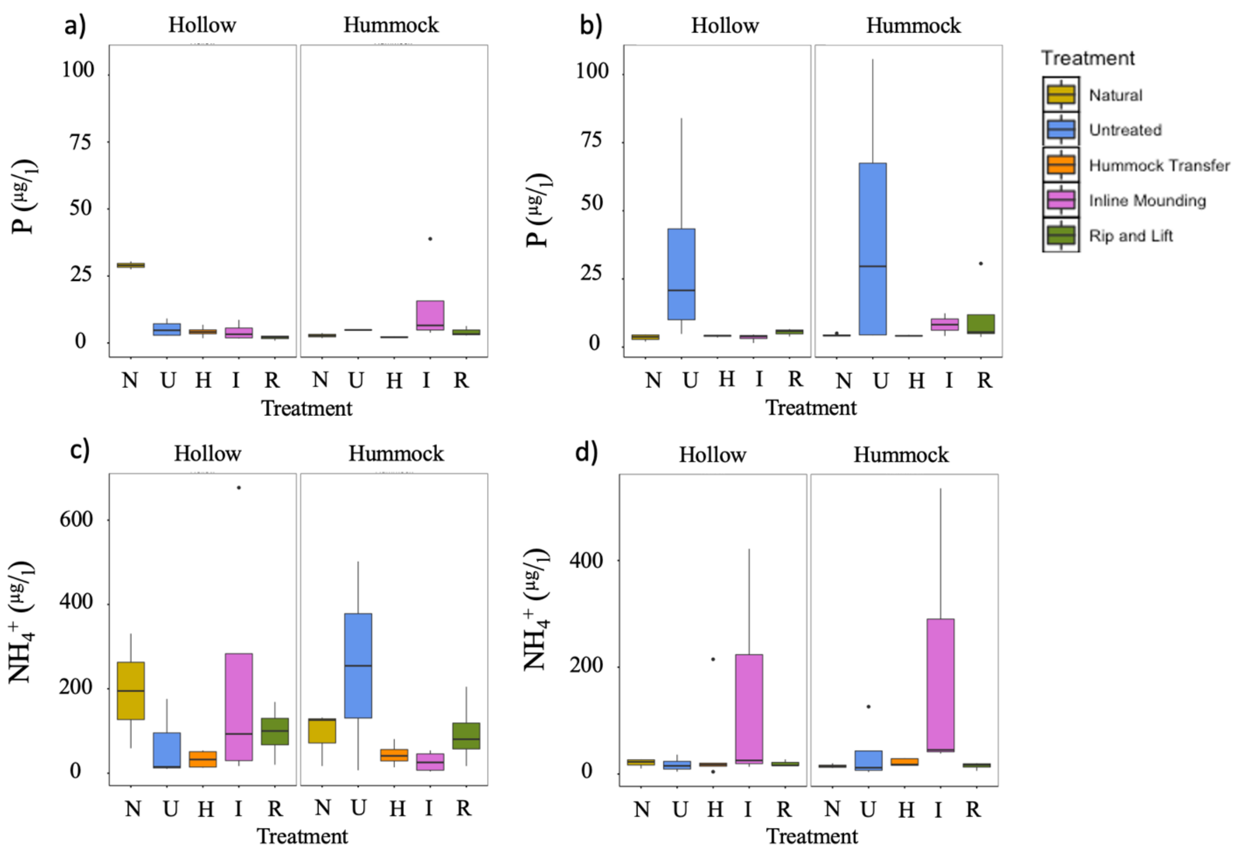

Figure 3.9. Temporal changes in peak growing season Pore water SRP in a) 2019 and b) 2020 and pore water NH_4 in c) 2019 and d) 2020 across the treatments

Figure 3.10 is comparing the mid-growing season, July, net mineralization rates of nitrogen in 2020 to 2019. In 2019, Hummock Transfer had high net mineralization rates for both NH_4^+ and

NO_3^-, nonetheless this trend was not observed in 2020. Instead in 2020, the rate of net NH_4^+ and NO_3^- mineralization was more unified across the different treatments, and like 2019 there are higher rates of net NH_4^+ mineralization then of NO_3^-. However, there is no significant difference ($F_{(4,67)}$= 0.983, p=0.423) in the net mineralization rate of NO_3^- in July between the years and treatments, nor is there a significant difference ($F_{(4,67)}$=0.983, p=0.423) in the rate of net NH_4^+ mineralization between the treatments amongst the two years. However, there was significantly more ($F_{(1,74)}$=5.02, p<0.0281) NH_4^+ mineralized in 2019 compared to 2020.

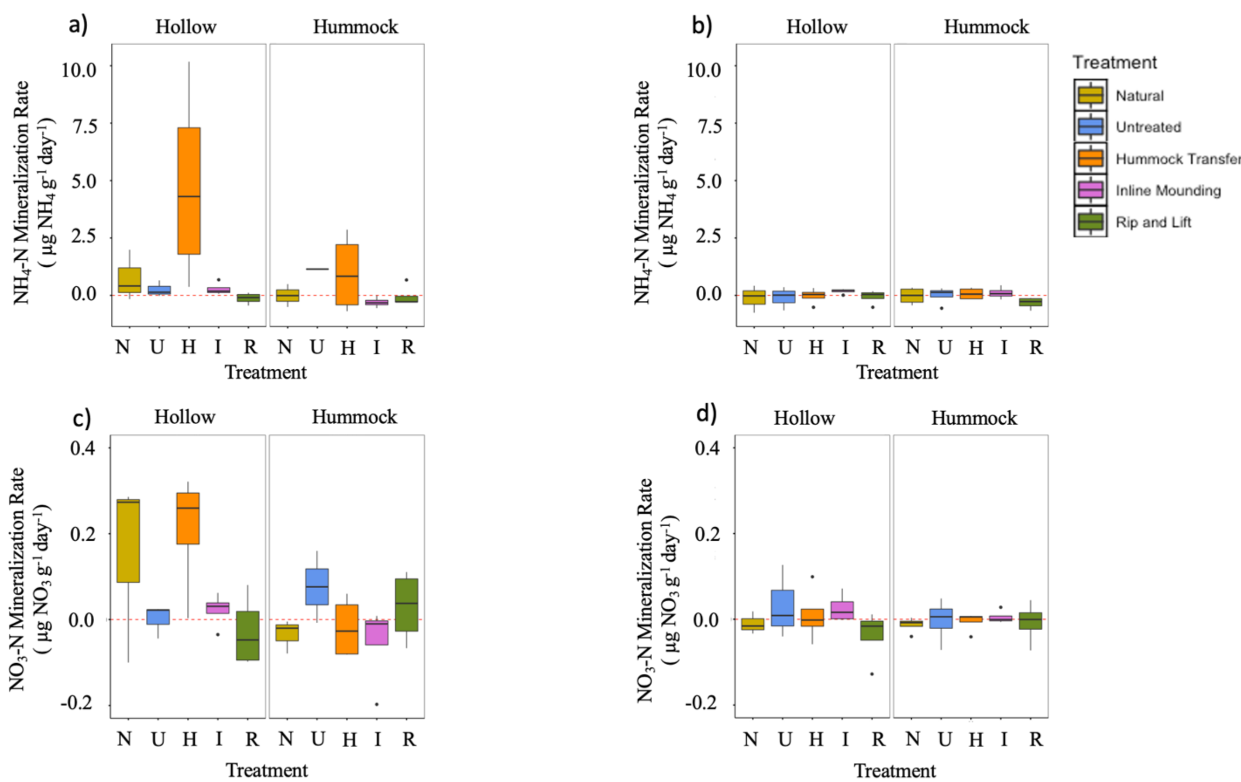

Figure 3.10. Net nitrogen mineralization rates of ammonium in a)2019 compared to b)2020 and nitrate during July of c)2019 and b)2020 across treatments

3.4 Discussion

3.4.1 Site Micrometeorological Conditions and Hydrophysical Properties of Peat

The micrometeorological conditions of the site varied over the 2 year study period. There was significantly ($p < 0.005$) more precipitation during the 2019 growing season, which increased soil moisture conditions, with potential feedback on nutrient cycling processes (Macrae et al., 2013). Even with a significant decrease in the water table in July and August from 2019 to 2020 with a difference in depth of 1.3 cm and 6.4 cm, there was not any major impact in the rates of nutrient cycling processes. Similarly, previous studies have shown that a 20 cm lowering of a peatland's water table is not sufficient to cause a significant difference in nutrient dynamics because of the ability of peat to sustain a thick capillary fringe that can maintain sufficient soil moisture contents for the microbial community (Macrae et al., 2013). There was no significant difference in soil moisture between the years. However, there was a significant difference in soil moisture between the hummocks in different treatments in 2019 (Table 1). Soil moisture is often influenced by the microtopography of a peatland, so the heights of the artificially formed hummocks are important for the reestablishment of biogeochemical processes and vegetation (Filicetti and Nielsen, 2020).

Hummock heights are especially important for the reestablishment and growth of tree seedlings (Kangas et al., 2016). A study by Lieffers et al. (2017) showed that the tree seedling density in restored mounded areas was 20 % higher than un-mounded areas four- or five-years post-restoration. There were no significant differences in heights among the restoration treatments of the newly formed hummocks in the present study; however, these artificially formed hummocks are similar in height to the natural hummocks in the adjacent area and higher than at Untreated where no clear hummocks exist. This is beneficial for the reestablishment of peatland processes because the delicate balance of microform heights influences not only the establishment of trees but can also alter understory vegetation community structure (Echiverri et al., 2020). The growth of understory vegetation, like bryophytes, can be inhibited by hummocks that are too elevated from the water table (Price et al., 1988; Caners et al., 2019), whereas hummocks that are too low are unable to sustain tree growth (Dabros et al., 2017; Lieffers et al., 2017).

Organic matter content was similar throughout the site, which is consistent with previous studies. For instance, Davidson et al. (2020) also did not find any significant difference in the OM content between the Natural, Untreated, and treatment areas on a seismic line undergoing restoration, with OM content similarly in the 90% range. This study also observed a slightly lower average organic matter on the line compared to the natural area of the site, although not significant (Davidson et al. 2020). The average porosity at the site is within the range (0.71 to 0.95) reported for fen peatlands (Rezanezhad et al., 2016). However, Boelter (1966) and Radforth and Brawner (1977) suggested that it is unusual that peat porosity is less than 0.8. Increased porosity is an indicator of decreased density of peat (Rezanezhad et al., 2016). A trend of the Untreated section having a lower average bulk density and higher average specific yield suggests less compaction in the Untreated compared to the treatments and Natural. This higher bulk density in the treatments and Natural area could indicate increased decomposition (Quinton et al., 2000). The creation of microforms creates drier microsites, which result in increased decomposition that increases the mass of dry material per volume of peat increasing bulk density (Quinton et al., 2000; Rezanezhad et al., 2016). Field and laboratory studies have shown that bulk density of peat can range from 0.02

to 0.25 g/cm^3, so the bulk density at the fen is within this range. However, it is on the lower end of the scale (0.06-0.09 g/cm^{-3}), which is similar to the bulk density of another disturbed peatland (0.04-0.16 g/cm^{-3}) that was impacted by compaction through construction of winter road (Strack et al., 2018). This lower bulk density would support the theory of decreased decomposition due to compaction causing potentially increased anaerobic conditions. Although the bulk density estimates for the study site resembles those of other disturbed sites, the mounded area started to show slightly higher bulk density than unmounded areas one-year post restoration. This was comparable to the trends observed by Davidison et al. (2020), which showed that three years post restoration, treed fens impacted by seismic lines had a higher bulk density on mounded lines (0.06 ± 0.04 g/cm^{-3}) compared to un-mounded lines (0.03 ± 0.02 g/cm^{-3}). This would suggest that there is increased decomposition occurring in the mounded areas in 2020, which was observed as the untreated site had a lower decomposition rate compared to the mounded sites. On the other hand, the bulk density increase can be due to the compaction and settling in the treated areas where excavation may have disturbed the peat structure allowing compaction of the mounds. The specific yield had the contrasting results to the bulk density, as decreased bulk density resulted in increased specific yield (Whittington and Price, 2006). However, like the bulk density, the specific yield of the peat samples collected was in the expected range of 0.048 to 0.45 as reported in other studies (Rezanezhad et al., 2016).

3.4.2 Biogeochemical Processes

Although all the hydrophysical properties are within the ranges found in other disturbed and restored fen peatlands, restoring peatland ecosystem functions requires not only re-establishing hydrological conditions but also a suitable environment for tree establishment and development, which includes microbial and biogeochemical functioning found in natural analogues (Nwaishi et al., 2015; Wood et al., 2015). Decomposition is an indicator of microbial activity, and the decomposition rate in 2020 was the lowest in the Untreated area compared to all the other treatments. Therefore, peat decomposition was higher in mounded areas, which is expected, as microbial decomposition is predicted to increase with the creation of microforms because of deeper water table, lower soil moisture saturation and hence a thicker profile with oxic conditions that enhance decomposition (Waddington et al., 2010). Frei et al. (2012) observed high nitrification rates in areas were ground water rich in ammonium came up into contact with anoxic zones where these interactions can result in biogeochemical zones of high reactivity (hotspots) in wetland hummock microtopography. Davidson et al. (2020) also found that artificially created hummocks on seismic lines had more decomposed peat and suggested that mounding was creating these biogeochemical hotspots.

There was no difference in decomposition between treatments during 2019, likely because it was during a year of high precipitation. With these water saturated, likely anoxic conditions and low decomposition rates, the observed dominance of NH_4^+ in TIN concentrations in the pore water were expected and these higher concentrations of NH_4^+ than NO_3^- have been seen in many other peatland studies (Macrae et al., 2006; Bayley et al., 2005; Westbrook and Devito, 2004). It was expected that there would be higher pore water NO_3^- concentrations found in the mounded treatments, as the NH_4^+ would be converted to NO_3^- in the presence of oxygen with the hummocks being elevated from the flooded areas. However, there is not much difference in the pore water nutrients between treatments and microforms (Fig. 3.6), and this could be explained by water movement through the fen that could homogenize pore water chemistry between treatment areas.

Net mineralization showed that more NH_4^+ was mineralized than NO_3^-. Other studies also found net nitrification rates that were close to zero in peatlands (Mewhort, 2000; Bayley et al., 2005). These low net nitrogen mineralization rates may indicate that microbes are rapidly immobilizing mineralized nitrogen or nitrate is being lost through denitrification (Andersen et al., 2013). Phosphorus net mineralization was also low, so low that even the Natural sites had P concentrations that were below detectable levels. This indicates that phosphorus is a limiting nutrient in these systems, as reported in other peatlands (Boeye et al., 1999; Andersen et al., 2013). Since trees will need phosphorus to grow (Alban, 1981), this lack of phosphorus could be inhibiting tree growth. The addition of phosphorus in peatland restoration has been used to enhance tree growth (Haveraaean, 1967; Watt, 1966; Caisse et al., 2008), and this might be a consideration for seismic line restoration.

When comparing the nutrient dynamics of 2019 to 2020, it was thought that the increased precipitation would lead to soil moisture content differences between the years. However, the soil moisture content between the restoration treatments in 2019 and 2020 are not significantly different. Soil moisture is a factor that can influence microbial activity and the biogeochemical processes this contributes to, such as decomposition. The drier year, of 2020, did have higher decomposition rates compared to 2019, which is an indicator of more microbial activity. The higher rate of decomposition in 2020 would be expected to lead to greater amounts of mineralized nutrients resulting in an increase of available nutrients in the pore water. However, the opposite trend was observed at the fen between 2020 and 2019, as despite significantly higher decomposition rate in 2020 than in 2019, the N net mineralization rate was lower in 2020 compared to 2019, although the difference was not significant. This could be because mineralization has an optimal water holding capacity from 60 to 75 percent (Yin et al., 2019; Wickland and Neff, 2008), and the average soil moisture of the newly formed hummocks was 39.2% in 2020 which is slightly lower moisture than 2019 when the average soil moisture was 50.1%. This inverse relationship was also seen at the treatment level in 2020 with the Untreated having the highest average decomposition and the lowest daily net mineralization rate. This may be because net mineralization rates are the difference between the gross mineralization and gross immobilization. At the site, the low net mineralization rates might be a result of high immobilization rates of the mineralized N, resulting in a low daily net mineralization rate (Anderson et al., 2013; Macrae et al, 2013; Westbrook and Devito, 2004). The mineralized N might be taken up by the microbial or plant community. This theory is further supported by the low concentrations of N in the pore water indicating that there is a high demand for N at the site.

3.5 Conclusion and Implications for Restoration

This study evaluated the effect of modified mounding techniques on a fen disturbed by seismic lines by characterizing the biogeochemical processes of decomposition and net nutrient mineralization immediately after restoration and one-year post restoration. Results indicate that the difference in biogeochemical processes between the years is being driven by micrometeorological differences and not effects from the different restoration treatments. No significant trends were observed in biogeochemical processes among the treatments immediately after restoration. However, one-year post restoration, bulk density and decomposition slightly increased in the mounded areas. Higher decomposition at the mounded sites suggests greater microbial activity, indicating that the use of microtopographic gradients is effective in creating new microsite conditions. Additionally, the soil moisture between the hummocks and hollows varied in the Hummock Transfer, Inline Mounding, and Rip and Lift, whereas the soil moisture was similar in the hummocks and hollows of the Untreated. This demonstrates that the application of these new restoration techniques, Hummock Transfer, Inline Mounding, and Rip and Lift, work in providing drier microsites that may be able to support desired vegetation. Overall, pore water nutrient concentrations and daily net mineralization rates were lower in 2020 than in 2019, which could be an artifact of seasonal variability between the first 2 years of the study. The low net mineralization rate could also suggest that nutrients were being immobilized by the microbial community to build microbial biomass and stabilize metabolic functions. A high demand for N and P is not uncommon at the early stages of ecosystem restoration, especially in peatlands, which are nutrient poor ecosystems with a vegetation assemblage that is adapted to nutrient limited conditions. This research study suggests that seismic restoration could benefit from the addition of nutrients to meet the N and P demand of reintroduced vegetation on the restored microsites. Further research should be conducted to examine the impact of fertilization on restoration and revegetation of seismic lines with desired plant species.

4.0 Evaluating the Impact of Fertilizer on Biogeochemical Processes of a Peatland Undergoing Restoration on Legacy Seismic lines in Canada's Boreal Forest Region

4.1 Introduction

Restoration of peatlands is new and evolving, as research advancements have only started since the 1990s (Rochefort et al., 2003). The restoration of seismic lines did not begin until the mid 2010s, as it was initially thought that these linear features would self-restore through the ecological process of secondary succession (Chimner et al., 2017). To develop new restoration strategies, knowledge and techniques are often adopted from successful existing restoration practices used in forestry, agricultural land conservation, and restoration of other types of disturbed peatlands. For instance, the moss layer transfer technique that is used in the restoration of extracted peatlands was adapted as a technique for seismic line restoration known as the Hummock Transfer technique (Xu, 2019). This Hummock Transfer technique has been successfully implemented in recent restoration projects, with the goal of recreating the moisture conditions required to re-establish desired vegetation communities on legacy seismic lines in Canada's boreal forest regions (Chapter 2). This study investigates how the application of fertilizer, in addition to mounding techniques, during seismic line restoration affects the recovering of key peatland function.

Restoring moisture conditions alone is not often sufficient to achieve the restoration goals, because the targeted vegetation varies depending on the region. For instance, in Ontario and Quebec, the focus of restoration is on *Sphagnum* moss recolonization, which requires very moist conditions (McNeil and Waddington, 2003) compared to treed boreal peatlands in Alberta where the focus of seismic line restoration is on tree re-establishment (Echiverri et al., 2020). Trees are necessary in Alberta's boreal peatlands for habitat function, as the trees support and protect species at risk such as the *Rangifer tarandus caribou* (woodland caribou; James et al., 2000; Benthlam and Coupal, 2015). To re-establish trees on Alberta's boreal peatlands, both hydrology and nutrient conditions are likely important. Restoring biogeochemical processes in disturbed ecosystems takes longer than re-establishing appropriate moisture conditions (Basiliko et al., 2007; Andersen et al., 2006), and in nutrient limited environments, it may require the addition of fertilizer to boost primary productivity at the initial stage of vegetation community re-establishment. Like with most new strategies used for peatland restoration, fertilization is borrowed from agriculture and forestry practices to enhance the recovery of the desired vegetation. Many different fertilizers using a N, P, and/or K have been used in the restoration of disturbed peatlands, primarily following peat extraction (Caisse et al., 2008; Emond et al., 2016; Hytönena and Kaunisto, 1999; Hytönena and Saarsalmi, 2009; Sottocornola et al., 2007).

Although fertilizers have been used to enhance the re-establishment of peatland vegetation communities in extracted peatlands (Rochefort et al., 2003), it has not been used in the restoration of treed peatland vegetation communities on seismic lines. Indeed, the existing body of knowledge suggests that applying fertilizer to newly restored seismic lines on peatlands could enhance the growth of trees on the line (Hökkä et al., 2008), allowing for the faster return of the site to desired vegetation community structure (Alban, 1981; Caisse et al., 2008; Pacé et al. 2018). Particularly, the addition of phosphorus (P) fertilizer has been shown to have the greatest influence on tree growth in peatland ecosystems undergoing restoration (Sundström et al, 1995; Caisse et al., 2008). Similarly, P fertilizer has been shown to increase restoration success by accelerating the establishment of desired bog vegetation community in restoration trials (Rochefort et al., 2003). However, Nishimura and Tsuyuzaki (2015) found that the addition of N can promote the dominance of grasses, resulting in a decrease of mosses and forbs. The finding by Kool and Heijman (2009) suggest that an increased nutrient availability of both N and P can result in shrubs being the dominant vegetation type over graminoids.

While these previous studies have shown that the use of fertilizer in peatland restoration enhances vegetation establishment, the effect of fertilizer on the re-establishment of biogeochemical processes in restored seismic lines are still unknown. Previous studies have identified that the addition of fertilizer can result in a decreased pH (Shi et al., 2021; Lv et al., 2017). Fertilizer releases nitogen in the form of NH_4^+, which releases hydrogen ions when nitrification, the conversion of NH_4^+ to NO_3^-, occurs. A decrease in pH can hinder soil activity affecting decomposition and net mineralization; however, studies found that the addition of nutrients did not significantly impact peat microbial productivity (Chapin et al., 2003; Keller et al., 2005). In contrast, other studies have found that the addition of fertilizer may result in increased decomposition rates (Shi et al., 2021), linked to higher decomposition rates in plant litter with higher N concentrations (Bragazza et al., 2012). This suggests that nutrient cycling can be altered by fertilization as higher nutrient availability may result in higher litter decomposition rates and thus increase mineralization of nutrients from that litter. Most peatland fertilization studies focus on bogs, which are more acidic and less nutrient rich than fens, but Chapin et al. (2003) compared N and P mineralization responses to the addition of nutrients in bogs and fens. The results showed that although bogs had increased cumulative N and P mineralization, rates were unaffected in fens (Chapin et al., 2003).

To address the knowledge gaps surrounding the impact of fertilization on nutrient cycling of a newly restored peatland seismic line, this study was conducted with the main goal of assessing the interacting effect between restoration treatments and fertilization on soil processes and plant nutrient uptake *in-situ,*as well as the controlled impacts of an NPK fertilizer on soil processes in preliminary applications in a greenhouse trial. Therefore, the objectives of this study are to: 1) assess the effect of NPK fertilization on peat soil processes including decomposition, pore water chemistry, and net mineralization rates under controlled and field conditions, 2) characterize the foliar nutrient content of various plant functional types present at the study site and changes in response to fertilization, and 3) evaluate the effect of restoration treatments (i.e., mounding and hummock transfer) on the nutrient uptake efficiency of the target plant species.

Previous studies have shown that the application of fertilizer in peatlands could enhance biogeochemical processes, such as decomposition and mineralization (Shi et al., 2021; Ojanen et al., 2019; Moilanen et al., 2002). Thus, it was hypothesized that fertilization of seismic lines undergoing restoration would lead to increased rates of decomposition and mineralization. Increases in the soil's ability to supply nutrients, through increased rates of mineralization, to the vegetation can increase the foliar nutrient concentrations. However, earlier investigations have shown that the addition of NPK fertilizer may have the ability to increase the growth of certain plant functional groups while others are unaffected (Rochefort et al., 2003; Nishimura and Tsuyuzaki, 2015). For instance, the addition of high concentrations of N can promote the dominance of grasses or shrubs while deterring the growth of mosses (Wiedermann, Nordin, Gunnarsson, Nilsson, & Ericson, 2007; Eriksson, Öquist, & Nilsson, 2010; Juutinen, Bubier, and Moore, 2010; Nishimura and Tsuyuzaki, 2015; Juutinen et al., 2016). Therefore, it is predicted that there will be a difference in foliar nutrient content between plant functional groups. Prior learning suggests that drainage of saturated conditions improves the growing conditions which increases tree growth (Hökkä et al., 2008). So, it is hypothesized that the restored sites with newly added microtopography will allow trees to better access nutrients from the fertilizer given that.

Microtopography creates hummocks, which support fluctuations in the water table, allowing optimal microbial activity and subsequently increase decomposition and nutrients mineralization rates.

4.2 Methods and Materials

4.2.1 Site Description and Field Experimental Design

Field research for this study was conducted on legacy seismic lines in a treed fen located within the boreal transition ecoregion of the boreal plains ecozone (52°53'21.4"N; 115°32'57.0"W) near Brazeau County, Alberta, Canada. The fen consisted of two seismic lines that were restored in March 2019. Each seismic line had three types of ground surface reconfiguration treatments comprised of Inline Mounding, Hummock Transfer, and Rip and Liftwhich have been previously described in Chapter 2 (Fig. 4.1). There was also a portion of the seismic line left as unrestored, so that the structure and functions of the restoration treatments could be compared to the untreated and natural areas of the poor fen. In the natural poor fen, the trees are dominantly *Picea mariana* (black spruce) and *Larix laricina* (tamarack), so black spruce and tamarack seedling were planted in pairs on hummocks on the seismic lines in August 2019. These trees were measured using a tape measure in July 2020, almost one-year post planting, to see how the tree heights varied between the fertilized (n=21) and unfertilized (n=40) treatments. On the seismic line running south to north (Fig.4.1), a slow release NPK fertilizer was buried alongside each of the pairs of seedlings. The fertilizer was in 10 g tea bags that were comprised of 20% total N, of which 17.64% is urea N and 2.36% is ammoniacal N, 10% P, and 8% K, with a slow-release coating and contained in a tea bag that was buried in the same whole as the seedling. This fertilizer also contains trace amounts of Zinc (Zn), 0.10%, Copper (Cu), 0.20%, and Boron (B), 0.20% (Reforestration Technologies International, Gilroy, California).

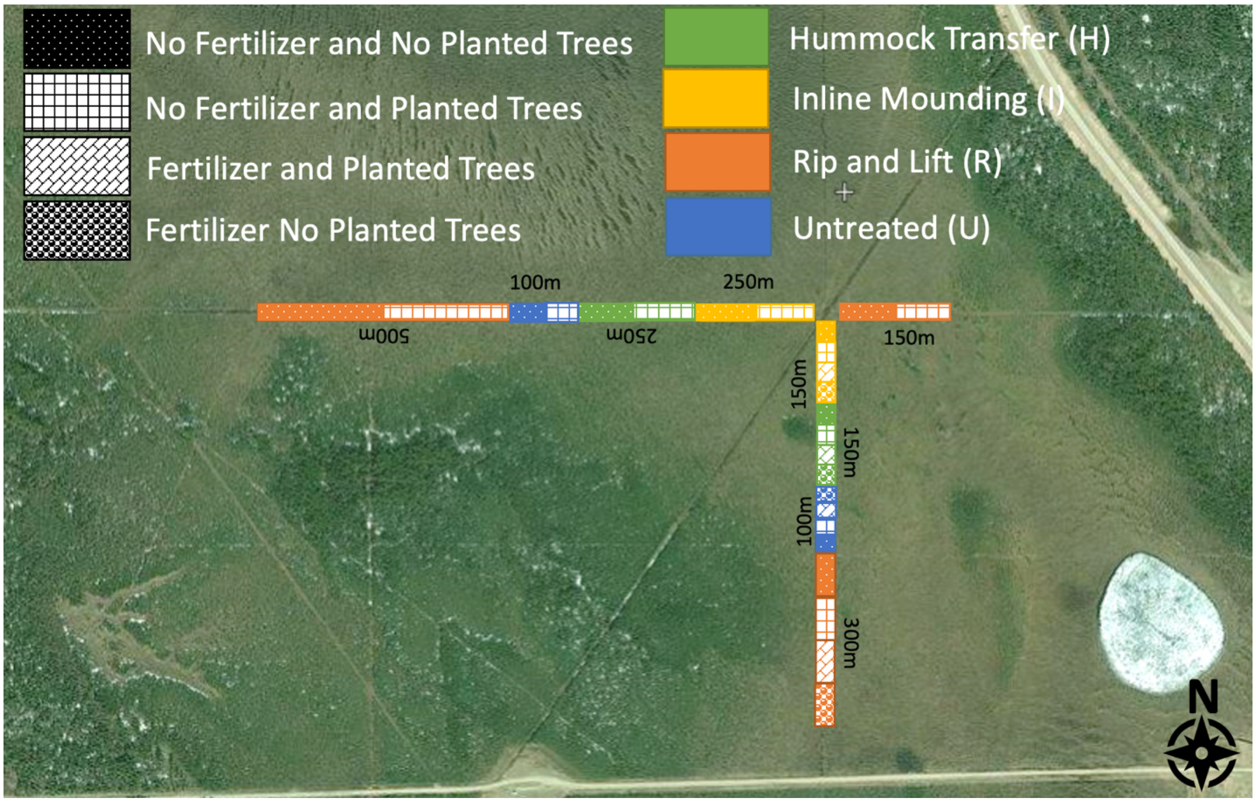

Figure 4.1. Site map of the two seismic lines that were restored using three different restoration methods, Hummock Transfer, Inline Mounding, and Rip and Lift, and part of each treatment was planted with Black spruce and Tamarack seedlings. The North to South line also had an NPK fertilizer applied to part of each treatment, whereas the East to West line was left as a control. Distances represent the length of the mechanical treatments which was equally divided into fertilizer and planted tree treatments.

4.2.2 Effect of Fertilizer on Biogeochemical Processes

To evaluate the effect of NPK fertilizer application on biogeochemical processes under field conditions, decomposition, pore water chemistry, and net mineralization rates were measured. The Tea Bag Index method (TBI) was used to determine the decomposition rates in the fertilized and unfertilized portions of the poor fen (Keuskamp et al. 2013). Pore water collected in July 2019 and 2020 from rhizon samplers (n=32) installed at 10 cm depth in 2 hummocks and 2 hollows in each of the 4 treatments were analyzed by for NO_3^-, NH_4^+ and Soluble Reactive Phosphorus (SRP). The samples were filtered through Whatman No. 42 filter paper (pore size of 2.5 µm) before sending them in frozen condition to the Natural Resources Analytical Laboratory (NRAL) at the University of Alberta for analysis using the Thermo Gallery Plus Beermaster Autoanalyzer (Thermo Fisher Scientific, Vantaa, Finland, 2017) to determine the concentration of NO_3^-, NH_4^+, and SRP by the colorimetric autoanalyzer. Peat net nutrient mineralization rates were also analyzed using the buried bag method described by Eno (1960). One round of field mineralization (n=32) was conducted with 4 replicates in each treatment in both the fertilized and unfertilized during July 2019 and 2020. Following the field mineralization incubation period of 28 day, the nutrient extraction from the peat samples followed the method described by Binkley and Hart's (1989). Briefly, two subsamples of 10 g of peat were removed from the extracted peat and 50 ml of milli-Q water was added to one of the subsamples for the extraction of SRP, while 50 ml of 2M KCl was added to the second subsample for extraction of NO_3^- and NH_4^+. The extraction process involved using an Heavy Duty Orbital Shaker (OHAUS CORPORATION, Model SHHD1619AL, Parsippany, New Jersey, USA) to homogenize the sample for an hour, followed by filtration through a Whatman 42 filter paper. The filtrates from each sample were then frozen to be shipped to NRAL for analysis of inorganic N and SRP.

To evaluate the effects of fertilizer on soil processes under controlled conditions, a greenhouse experiment was conducted at the Mount Royal University Greenhouse in August 2020. Peat cores (n=12) were taken in buckets (with a volume of 6804 cm^3, 24 cm in height, and 19 cm in diameter) from the untreated section of the Brazeau field site and transported to the greenhouse, where they received 16 hours of light a day to mimic growing season conditions in the study site. After they were transported, they were given time to settle, from August to October, and during this time there moisture content was maintained with water taken from the collection site. The water added to the peat cores was analyzed for pre-experimental pore water nutrients. The 12 buckets were divided into four treatment types, each measured in triplicate: 1) unsaturated/unfertilized, 2) saturated/unfertilized, 3) unsaturated/fertilized, 4) saturated/fertilized. Saturated volumetric moisture content was kept at 90 - 100% and water was maintained above the surface of the peat, compared to the unsaturated moisture treatments, which were kept between 10 to 30 % volumetric moisture content. The fertilizer treatments had one 10 g slow release NPK fertilizer packet (as described above) placed at approximately 12 cm depth inside the peat bucket. The experiment was conducted for three months, from October to January. Peat moisture and temperature was measured every 1 – 2 days throughout the study period while conducting measurements to determine litter decomposition, pore water nutrient dynamics, plant available nutrients, and net mineralization rates. The litter decomposition experiment used three tetrahedron-shaped Lipton's rooibos tea bags, which were inserted 8 cm deep into each peat bucket over 85 days. The tea bags were removed and dried in an oven at 60 °C for 24 hours. The dried mass of the tea bag was weighed before and after burial and decomposition was estimated as the mass lost over the incubation period.

To determine nutrient dynamics, the pore water pH and EC was measured using a Hanna HI9811-5 portable pH/EC/TDS/temperature meter (HANNA Instruments, Smithfield, Rhode Island). Peat porewater extracts from the incubation buckets were sent to NRAL for inorganic N and SRP measurements, at the beginning and at the end of the experiment. Pore water samples were collected at approximately 10 cm depth and processed using a similar procedure described for the field peat samples. To determine the net mineralization rates, two grab samples of peat were taken at approximately 10 cm depth from the replicate pots within each of the four treatment types (n=12). One grab sample was analyzed for pre-mineralization available concentrations of NO_3^-, NH_4^+ and SRP while the other was placed into a polyethylene bag and incubated in the peat for 28 days after which it was analyzed for post-mineralization available concentrations of NO_3^-, NH_4^+ and SRP (Eno, 1960). In order observe the impact of the slow-release fertilizer on net mineralization rates, two rounds were conducted a month apart from one another. The peat cores moisture content and nutrients was altered 2 weeks before the mineralization study began. Peat samples were collected for the net mineralization study at the beginning, in October, and at the end of the experiment, in January. To determine these concentrations, the samples were processed using similar procedures described earlier for the net mineralization experiment under field condition.

Plant Root Simulator (PRS) probes (Western Ag. Innovations, Saskatoon, Canada) were used to obtain the exchangeable nutrient supply rate in the soil solution over a period of three days. Two sets of PRS were inserted at a forty-five-degree angle in each peat bucket and incubated for three days. The first set were installed on November 27th 2020 and removed November 30th 2020, and the second set were incrubated in the peat cores from January 18th to the 21st of 2021. Once removed, the PRS probes were immediately triple rinsed with Milli-Q water and placed into a cooler for shipping to Western Ag. Innovations, Saskatoon for analysis. The nutrient supply rate results from the two sets of incubations were averaged.

4.2.3 Foliar Nutrient Composition of Plant Functional Types and Effect of Restoration Treatments

To determine differences in vegetation cover, of shrubs, trees, and graminoids, between the fertilized and unfertilized treatments vegetation surveys (n=145) were conducted. The percent cover was determined visually by randomly sampling using a 1 m x 1 m quadrats. To characterize nutrient uptake efficiency of various plant functional groups, foliar samples were collected from three different functional groups (graminoids, shrubs, and trees) at the peak of the growing season in mid-July during a vegetation survey. A composite sample was taken from each functional type at 11 to 15 different hummocks in the fertilized and unfertilized areas of the seismic line from the 13th to the 15th of July 2020. Although both black spruce and tamarack were collected, only the tamarack nutrient content was analyzed. Before analyses, the foliar samples were placed in an oven at 60 °C for 24 to 48 hours or until dry. Once dry, the samples were ground into a fine granular form using a coffee grinder. The processed samples were sent to the Natural Resources Analytical Laboratory (NRAL) at the University of Alberta for elemental analysis. The concentration of P and K in the foliar samples were determined using an Inductively Coupled Plasma-Optical Emission Spectrometer (ICP-OES) (Thermo Fisher Corporation, Cambridge, United Kingdom) and N concentration was determined by flash combustion using a Thermo FLASH 2000 Organic Elemental Analyzer (Thermo Fisher Scientific Incorporated, Bremen, Germany).

4.2.4 Statistical Analysis

The statistical program R studio (R Studio, version 1.2.5042; RStudio Team, 2020) was used for all statistical analysis, and a calculated probability of $p < 0.05$ was needed to deem results significant. The normality of the results was tested by Shapiro-Wilk tests and Q-Q normality plots; however, samples were found to not be normal although small sample sizes limited a full assessment of data distribution. A linear model (lm) was used and the normality of the residuals was checked. An analysis of variance (ANOVA) was used to compare the effects of treatments and fertilizer in the field and fertilizer and moisture in the laboratory on decomposition, pore water, net mineralization rates, and nutrient supply rates. When differences were significant, post-hoc tests were used between subsets by means of the "emmeans" function (Lenth, 2021).

4.3 Results

4.3.1 Effect of Fertilizer on Biogeochemical Processes

In the fertilized area of the seismic line, the treated sections (i.e., Hummock Transfer, Inline Mounding, and Rip and Lift) showed higher decomposition rates, compared to the Untreated, which had the lowest decomposition rate (Fig. 4.2). Although not significant ($F_{3,18}$ =1.3629, p=0.2859), a fertilizer effect was seen in the treated areas, since the rate of decomposition was higher in the fertilized area compared to the unfertilized section. However, the inverse relationship occurred in the Untreated, where the fertilized section had a lower decomposition rate than that of the unfertilized.

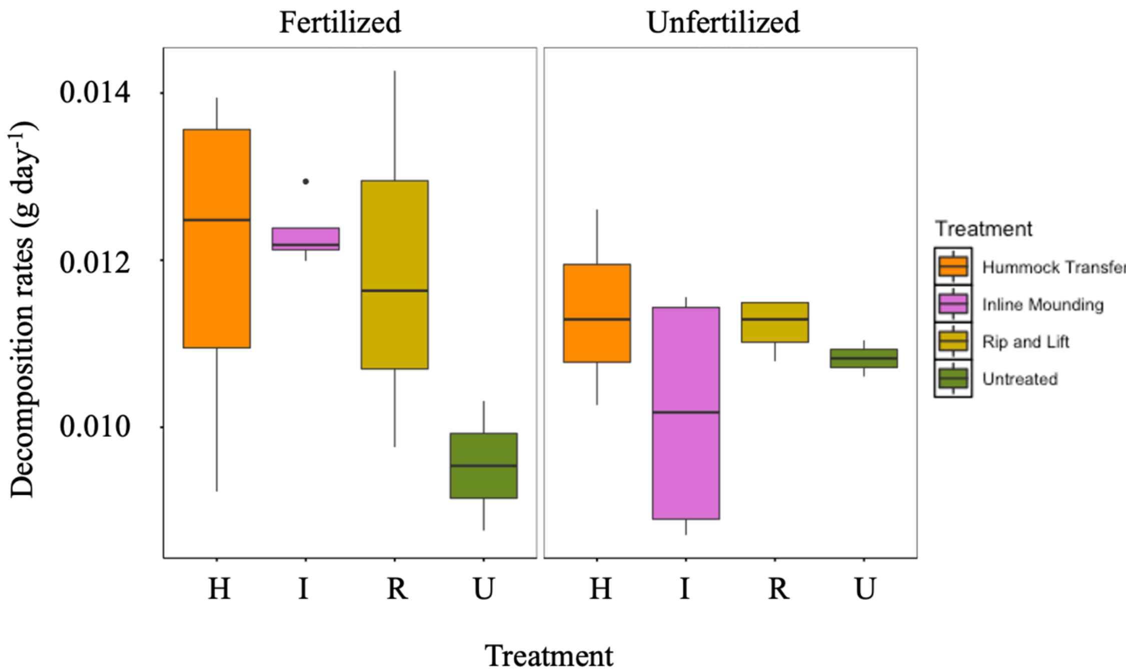

Figure 4.2. Decomposition rates (g day^{-1}) in the treated areas, Hummock Transfer, Inline Mounding, and Rip and Lift, of the seismic line increased compared to the Untreated in the fertilized treatments.

The average NH_4^+ pore water concentrations within the fertilized treatments had similar trends to the decomposition rate, as the average of the Untreated was lower than the restored treatments (Fig. 4.2 and 4.3a). However, unlike decomposition, Inline Mounding had the highest NH_4^+ pore water concentrations compared to the other treatments, and in the unfertilized treatments, Inline Mounding was significantly different from both Rip and Lift ($F_{3,21}$ =3.3412, p=0.0422) and Untreated ($F_{3,21}$ =3.3412, p=0.0497). Since the ranges of the NH_4^+ pore water concentrations were large, none of the differences between the fertilized and unfertilized treatments were significant (Table 4.1). Even though they were not significant, the average NH_4^+ pore water concentrations were higher in the fertilized areas compared to the unfertilized areas in both the Hummock Transfer and Rip and Lift. Although the pore water P concentrations did not follow the same trends as the NH_4^+, there was still no significant difference in the pore water P concentrations between the treatments (Table 4.1; Fig. 4.3). The Hummock Transfer had significantly lower P concentrations than the Untreated overall, but the difference was not significant when factoring in the fertilizer effect. For P, the Untreated had the highest average concentrations for both the fertilized and unfertilized (Fig. 4.3b). While they were not significantly lower, the unfertilized treatments had lower average P concentrations than the fertilized restored treatments. While the porewater concetrations of NH_4^+ and P were able to be detected, the concentrations of NO_3^- were below 4.3 µg l^{-1} making them undetectable.

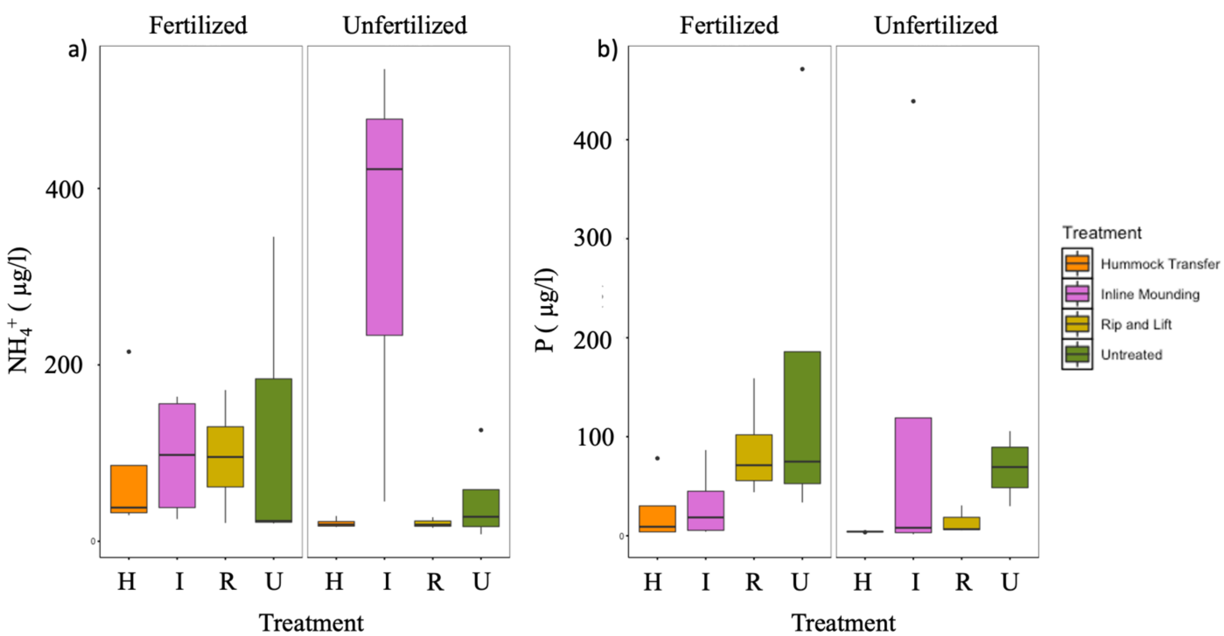

Figure 4.3. Pore water a) NH_4^+ and b) P concentrations in fertilized and unfertilized areas within the different treatments.These results indicate that fertilizer did not cause a significant difference in concentrations of NH_4 and P between treatments.

There were similar rates of net NH_4^+ mineralization between the fertilized and unfertilized treatments (Fig. 4.4; Table 4.1). In contrast, the treated sections (i.e., Hummock Transfer, Inline Mounding, and Rip and Lift) of the seismic line had a variation in net mineralization rates of NO_3^-. In the fertilized area of the Hummock Transfer the NO_3^- was immobilized whereas it was being mineralized in the unfertilized section. The trend of more immobilization in the fertilized area was not seen in the other treatments. Instead, Inline Mounding and Rip and Lift had higher net mineralization rates in the fertilized area. Although the overall net mineralization of P was similar between the fertilized and unfertilized area, a treatment effect was observed, as the net P mineralization rates in Hummock Transfer and Inline Mounding were higher in the fertilized area compared to that of the unfertilized although the difference was not statistically significant.

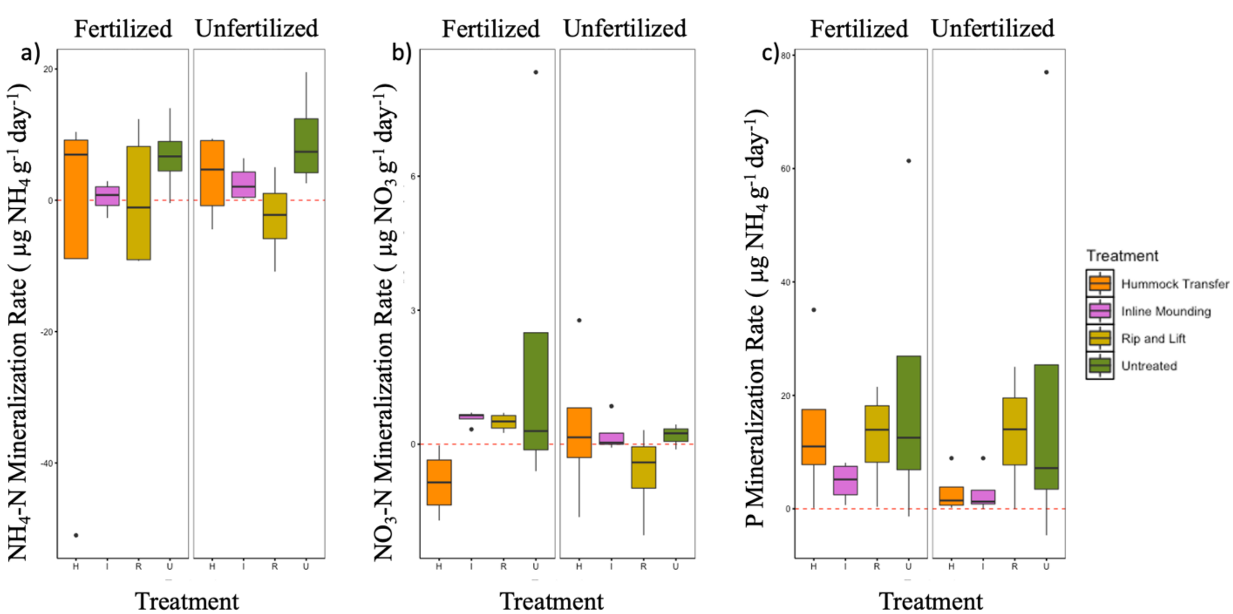

Figure 4.4. Net mineralization rates of a) NH_4^+, b) NO_3^-, and c) P at the peak of the growing season in 2020 for treatments in the fertilized and non-fertilized area. These results showed that the addition of NPK fertilizer did not significantly effect the net mineralization rate of NH_4^+, NO_3^-, and P.

Table 4.1. Linear mixed-effects ANOVA F and p values for the fixed effects of moisture and fertilizer on P, TIN, NH4, and NO3 availability for pore water and mineralization rates

Effect	df	P		NH_4-N		NO_3-N	
		F	p	F	p	F	p
Pore Water Nutrients (µg/l)							
Treatment	2, 25	1.1578	0.344	2.1107	0.1243	NA	NA
Fertilizer	2, 25	0.3543	0.5563	0.0038	0.9514	NA	NA
Treatment x Fertilizer	3, 23	0.9741	0.4220	3.3412	0.03878	NA	NA
Net Nutrient mineralization rate (µg $g^{-1}day^{-1}$)							
Treatment	3, 28	1.5466	0.2244	1.1317	0.3552	1.1383	0.3513
Fertilizer	1, 30	0.2297	0.6352	0.5241	0.4747	0.7756	0.3857
Treatment x Fertilizer	3, 24	0.1956	0.8984	0.3881	0.7626	1.1281	0.3584

NA stands for not applicable as most data point were below detectable limits (<4.3 µg/l)

In the laboratory experiment, saturating the peat cores without the addition of fertilizer resulted in a slightly lower pH and EC (Table 4.2). However, the fertilized and saturated treatment pH was greater than the pH in the other treatments. While the unsaturated/fertilized and unsaturated/unfertilized cores had very similar pH. The addition of fertilized resulted in a higher EC than cores that were not fertilized.

Table 4.2. Laboratory experiment water chemistry results indicate that there was a highest pH in saturated/fertilized treatments.

Treatments	pH	EC (µs)	Temperature (°C)
saturated/fertilized	6.7 (±0.2)	1070.0 (±79.4)	18.6 (±1.9)
saturated/unfertilized	4.9 (±0.1)	186.7 (±186.7)	18.8 (±1.8)
unsaturated/fertilized	5.1 (±0.6)	3143.3 (±719.3)	20.0 (±1.8)
unsaturated/unfertilized	5.3 (±0.2)	640.0 (±246.4)	19.8 (±1.7)

The decomposition rate estimated in the laboratory experiment showed that the decomposition only varied slightly ($F_{3,32}=0.722$, $p=0.546$) between the different treatments. The saturated and fertilized cores had slightly higher decomposition, although saturating and fertilizing alone resulted in a slightly lower decomposition.

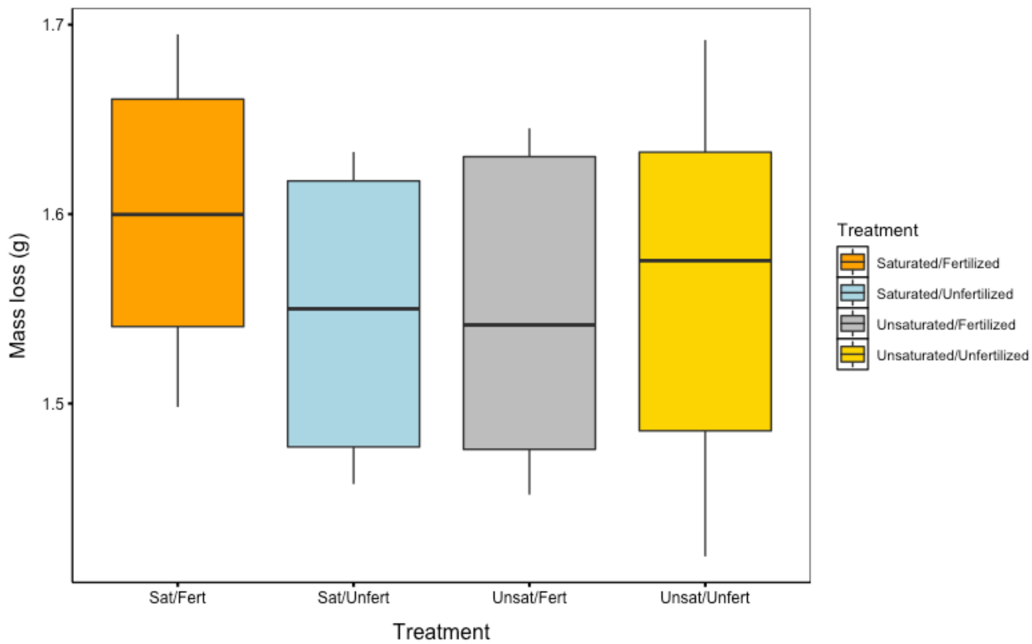

Figure 4.5. The impact of fertilization and saturation changes in the laboratory experiment peat cores mass loss. These results indicate that there is the most mass loss occurring in the saturated/fertilized treatments.

The addition of NPK fertilizer influenced the pore water concentrations of NH_4^+, with the greatest increase from pre-experimental concentrations oberserved in the pore water NH_4^+ concentrations of the unsaturated/fertilized treatment ($F_{4,12}=47.96$, $p=0.0017$; Fig. 4.6a). The unfertilized treatments (saturated/unfertilized: $F_{4,12}=47.96$, $p<0.0001$; unsaturated/unfertilized: $F_{4,12}=47.96$, $p=0.0259$) had significantly lower NH_4^+ concentrations relative to the pre-experimental concentrations. This decrease in pore water nutrient concentration from pre-experimental concentrations was also seen for the P concentrations in the unfertilized treatments ($F_{2,14}=17.39$, $p=0.00016$ Fig. 4.6b). In contrast, the fertilized treatments had elevated pore water P concentrations that were significantly different from the unfertilized concentrations ($F_{2,14}$ =17.39, p=0.0173). The fertilizer addition resulted in higher NH_4^+ and P concentrations under unsaturated conditions. Although the increase in nutrient concentration was less prominent in the unfertilized treatments, the same trend of greater pore water nutrients in the unsaturated cores was observed in the absence of fertilizer.

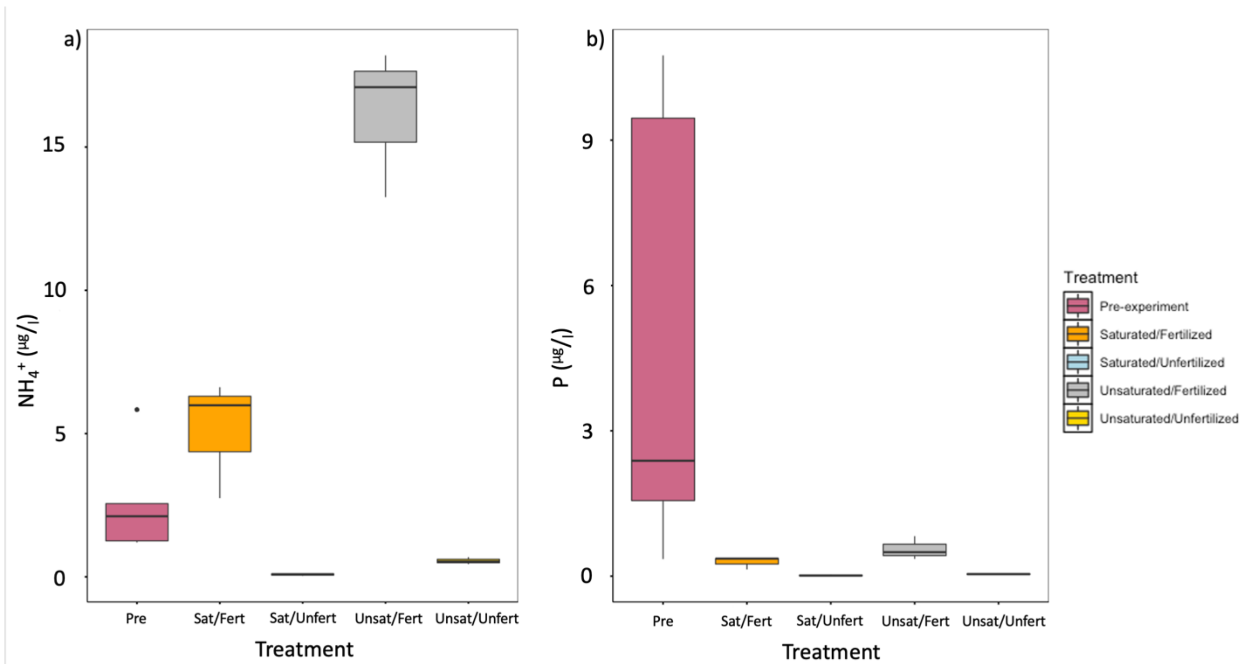

Figure 4.6. Pore water a) NH_4^+ and b) P changes due to changes in moisture and nutrients. Pore water nutrients were highest in the fertilized treatments at the end of the experiment, with the largest concentrations of NH_4^+ and P in the unsaturated/fertilized treatment.

PRS probe results show that there were greater concentrations of P and TIN available for plant uptake in treatments that were fertilized, and that this effect was enhanced when treatments were saturated (Fig. 4.7). Although unfertilized treatments had lower P and TIN supply rates, these rates were also greater in saturated conditions,. TIN supply rate was mostly comprised of NH_4^+.

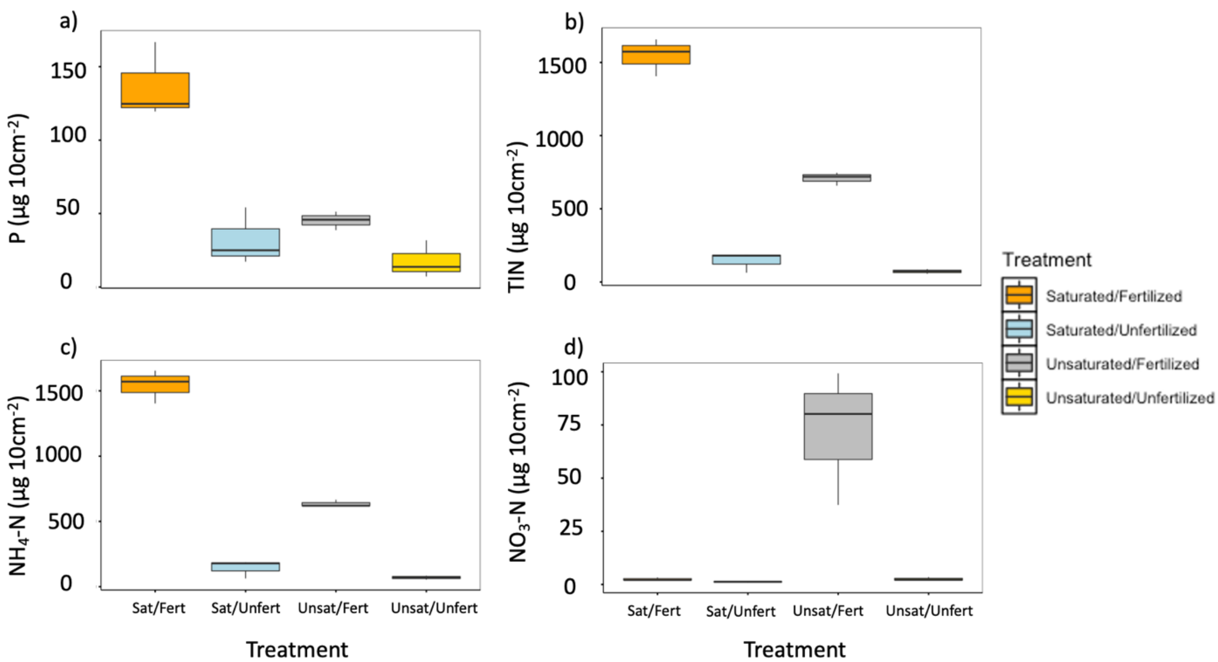

Figure 4.7. PRS probes a) P, b) TIN, c) NH_4^+, d) NO_3^- available for plant uptake in treatments in the laboratory experiment peat cores. Although these results show the highest supply rates of P and TIN in the saturated/fertilized treatments, the highest NO_3^- supply rate is in the unsaturated/fertilized.

In the laboratory experiment, the net NH_4^+ mineralization rates significantly varied ($F_{1,19}$ =5.0255, p=0.03711; Fig. 4.8) among the moisture and fertilizer treatments, unlike the net NO_3^- mineralization rates that were not significantly different with means values ranging from 0.08 to 0.43 µg NO_3^- g^{-1} day^{-1} (Table. 4.3). However, unfertilized treatments, whether saturated or unsaturated, had similar net NH_4^+ mineralization rates and these rates did not significantly fluctuate over time. The moisture content strongly influenced the net mineralization rate of NH_4^+ when fertilizer had been applied (Fig. 4.8a). When fertilized, the saturated treatment had a greater rate of net NH_4^+ mineralized. In the second round of nutrient extraction, the net mineralization rate of the saturated/fertilized treatment increased while in the unsaturated/fertilized, NH_4^+ was being immobilized. The opposite trend was seen for the net mineralization of P, as the unsaturated and fertilized treatments had an increased net mineralization rate of P over time. These results also show that saturated/fertilized conditions resulted in high net P mineralization rates (Fig. 4.8b), although, over time the saturated conditions did not increase the net mineralization rate of P. Fertilized and unsaturated conditions led to an increase in net P mineralization.

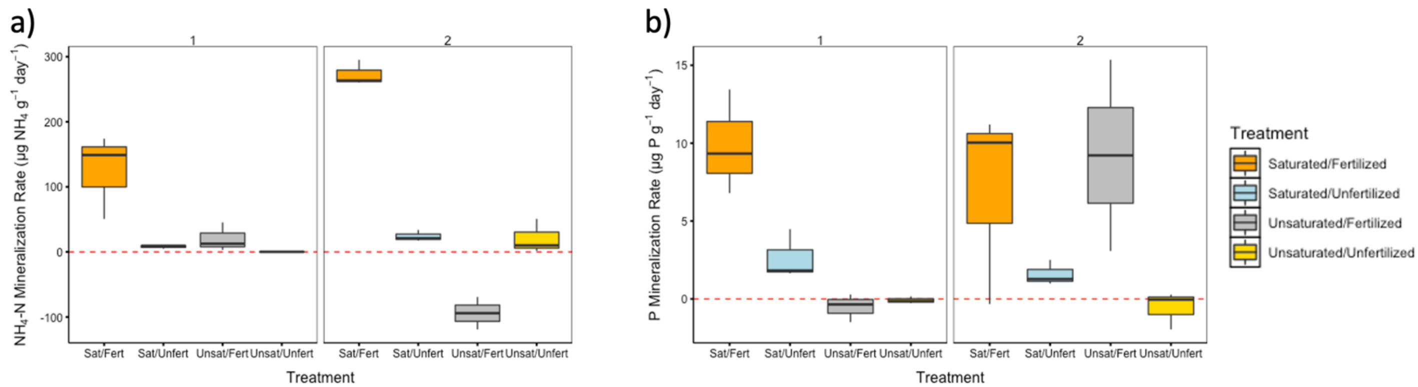

Figure 4.8. The changes in treatment effect of net mineralization rates of a) NH_4^+ and b) P over two rounds, at the beginning of implementing moisture and nutrient treatments and two months post implementation. These results indicate that the net mineralization rates of NH_4^+ and P change in the unsaturated/fertilized treatment as more fertilizer is released over time.

Table 4.3. Linear effects ANOVA F and p values within and between the fixed effects of soil moisture content, saturated and unsaturated, and NKP fertilizer, fertilized amd unfertilized, on P, TIN, NH4, and NO3 availability for pore water, nutrient supply rates, and net mineralization rates.

Effect	df	P		TIN		NH_4-N		NO_3-N	
		F	p	F	p	F	p	F	p
Pore Water Nutrients (mg/l)									
Moisture	1, 14	5.7586	0.01496	2.4701	0.1232	2.50542	0.1651	3.9132	0.04674
Fertilizer	1, 14	5.7892	0.01472	1.9389	0.1833	2.6911	0.1026	1.2992	0.3059
Moisture x Fertilizer	1, 12	0.0024	0.96202	2.5734	0.13698	1.2670	0.28234	7.4729	0.019450
Nutrient supply rate (µg 10 cm^{-2})									
Moisture	1,10	4.205	0.06744	1.7208	0.2189	2.0777	0.18	4.07	0.07128
Fertilizer	1,10	8.1534	0.01527	28.117	<0.001	22.529	<0.001	4.0593	0.0716
Moisture x Fertilizer	1, 8	14.249	0.0054285	74.924	<0.001	94.723	<0.001	13.993	0.005699
Nutrient mineralization rate (µg $g^{-1}$$day^{-1}$)									
Moisture	1, 21	1.4974	0.2346	3.4307	0.0781	3.4846	0.07597	0.0016	0.9682
Fertilizer	1, 21	11.069	0.003201	5.3519	0.03092	5.4752	0.02924	$1x10^{-04}$	0.9936
Moisture x Fertilizer	1, 19	<0.001	0.986527	4.8318	0.04053	5.0255	0.03711	0.0028	0.9585

4.3.2 Foliar Nutrient Content among Plant functional Types

In the field, the foliar nutrient content showed that the uptake of total NPK varied between different vegetation functional types (Fig. 4.9). Vegetation functional types significantly varied in total nitrogen concentrations with shrubs having the highest total N content, while graminoid and tree foliar nutrient contents were not significantly different. The concentrations of P were similar in shrubs and trees, while P content was significantly lower in graminoids compared to trees. However, the opposite pattern between graminoid and tree foliar nutrients was seen for K. Potassium content was significantly different between all the functional types, with graminoids retaining the most K. There was no significant difference in the NPK foliar nutrient concentrations of the larch tree between the restoration treatments. The P foliar content of the fertilized larch trees was almost significantly greater ($F_{1,23}$ =3.541, p=0.073) than those that were not ferilized. However, there was a significantly higher ($F_{1,23}$ =12.24, p =0.002) foliar N content and almost significantly greater foliar P content for fertilized trees than those of unfertilized trees.

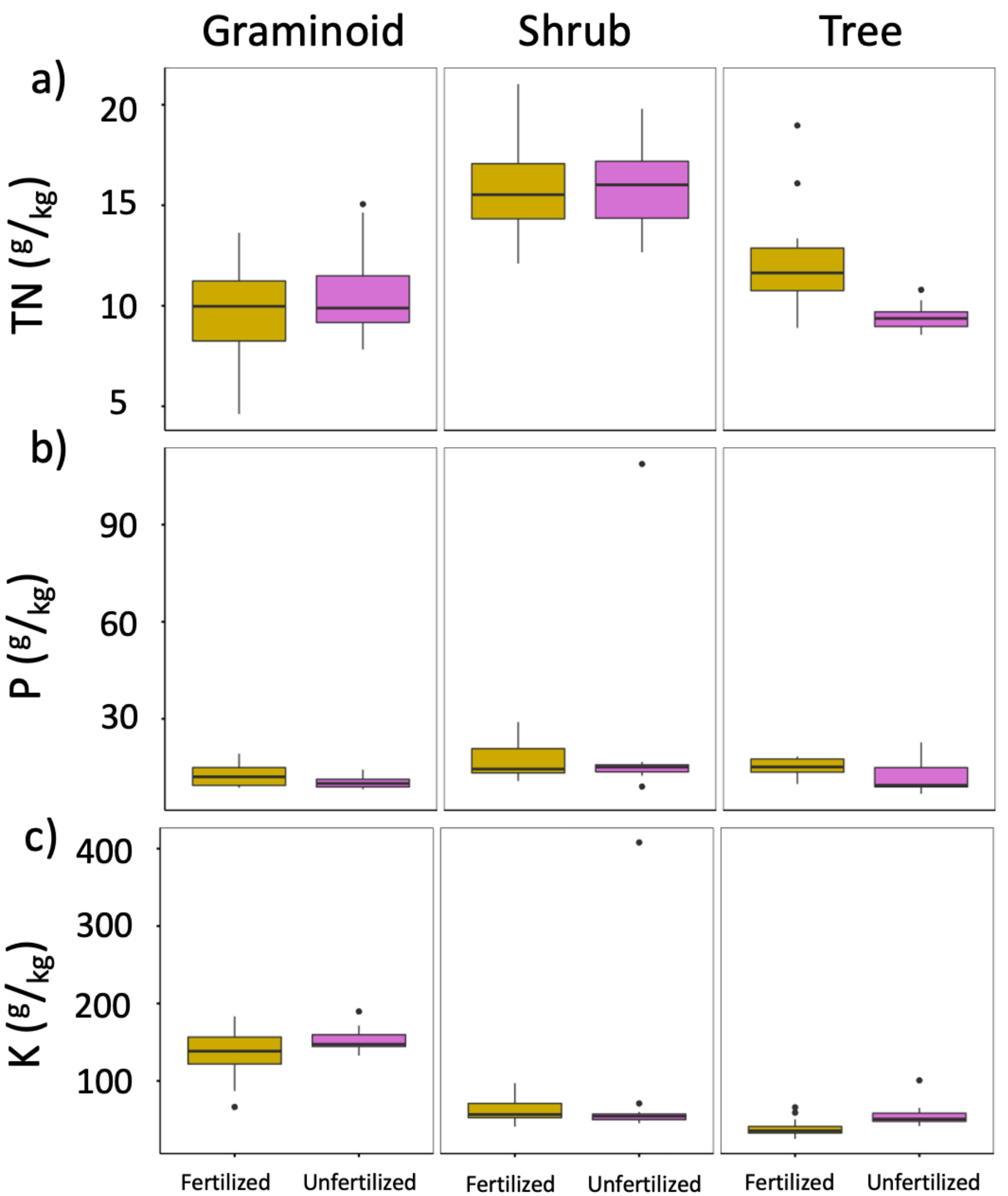

Figure 4.9. NPK foliar nutrient concentrations of the graminoids, shrubs, and larch trees between the fertilized treatments.

In both the fertilized and unfertilized seismic lines there was a low abundance of natural trees that had established ($F_{2,448}$ =16.1169, p =1.00; Fig. 4.10). The percent cover of this targeted vegetation was lower than that of the graminoids and shrub ($F_{2,448}$ =16.1169, p <0.0001). There were significantly more shrubs compared to graminoids within the unfertilized area ($F_{2,448}$ =15.960, p<0.0001) and fertilized area. Although, the fertilized areas did have a significantly lower ($F_{2,448}$ =15.960, p=0.0365) percent cover of shrub than the unfertilized treatments. The increase in graminoid cover was significant ($F_{2,448}$ =15.960, p<0.0001) in the fertilized areas relative to the unfertilized areas.

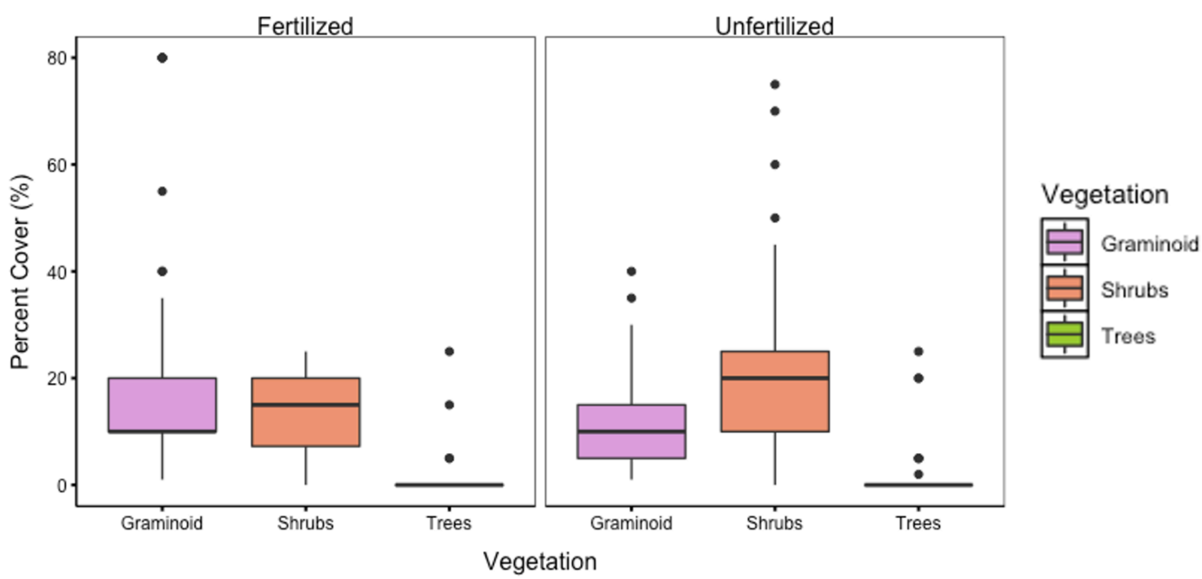

Figure 4.10. The percent cover of graminoids, shrubs, and trees on the fertilized and unfertilized seismic lines. These results indicate that shrubs are more dominate on the seismic line than graminoids, however graminoids cover increases with the application of NPK fertilizer.

Trees planted on the seismic lines in 2019 showed that one year post planting there was significantly taller ($F_{1,59}$ =18.338, p=0.0001) trees in the fertilized treatment than the unfertilized treatments (Fig. 4.11). The greatest average tree height was seen in the Hummock Transfer, while the inverse is true for the unfertilized Hummock Transfer ($F_{3,53}$ =2.2782, p=0.0051). Seedlings had a similar tree height responses in the Inline Mounding, Rip and Lift, and Untreated unfertilized areas, while Inline Mounding and Untreated trees had the poorest growth among the fertilized treatments.

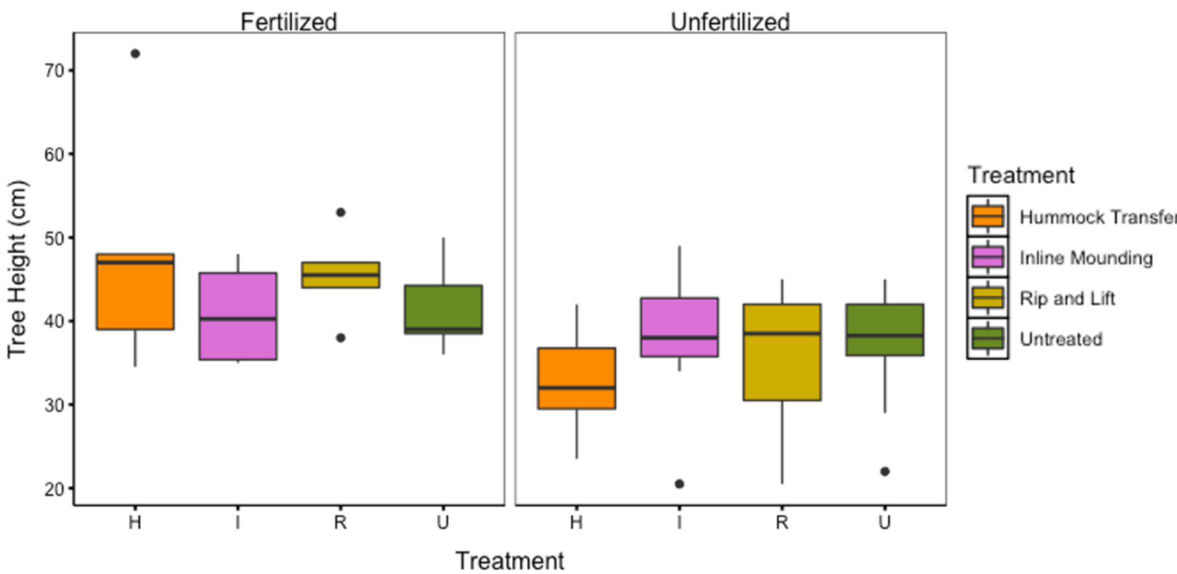

Figure 4.11. The slight increase in seedling growth in the fertilized treatments compared to treatments in unfertilized lines

4.4 Discussion

4.4.1 Effect of Fertilizer on Biogeochemical Processes

There were differences in biogeochemical processes between the fertilized and unfertilized sections of the study site. The addition of nutrients in the restored areas resulted in higher decomposition rates (Fig. 4.2). This is expected as the application of other types of fertilizer, such as ash-fertilizer, has been observed to increase the rate of decomposition on restored peatland sites that were previously disturbed (Moilanen et al. 2002). However, the additional nutrients in the untreated area resulted in a lower rate of decomposition, showing that without mechanical reconfiguration of the peatland surface, the application of fertilizer is unlikely to increase microbial activity. This limited effect on decomposition can be a result of poor aeration as a result of a lack of microtopography in the Untreated, as decomposition is a process that is influenced by the moisture content of the site. As the waterlogged soils are elevated and likely drained by the addition of hummocks in the treated areas, there is more oxygen available to facilitate decomposition. Additionally, nutrients from the addition of the fertilizer may be lost from the system before they can be accessed by the microbial community, particularly in the saturated soils of the untreated line where loss of nutrients with moving water is more likely.

A laboratory experiment was conducted to see how the addition of fertilizer would influence peatland processes under controlled conditions. Environmental conditions such as pH can alter nutrient cycling. Inthe lab experiment, saturated/fertilized cores had the highest pH, while the unsaturated/ fertilized and unsaturated/ unfertilized cores had very similar pH. This suggests that the fertilizer did not have as strong of an effect in the unsaturated cores, as the pH has been seen to increase in peatlands with the addition of fertilizer due to increased rates of nitrification (Shi et al., 2021). As microbes prefer neutral environments, pH has been shown in other studies to be a major environmental factor in influencing the rate of N mineralization, with N mineralization rates increasing as pH increases from 4 to 8 (Shi et al., 2021; Högberg et al., 2007; Rousk et al., 2009; Cheng et al., 2013; Kader et al., 2013; Jiang et al., 2015; Lin et al., 2016). Shi et al. (2021) report that in a peatland with N inputs, the increased soil pH stimulated higher rates of nitrification (43% higher than control), which contributed to the increases in pH and NH_4^+ concentrations. Other studies have also demonstrated that nitrifiers prefer more alkaline soils where higher pH lead to increased nitrification rates resulting in increases on NO_3^- concentrations (He et al., 2007; Xu et al., 2012; Jiang et al., 2015; Tang et al., 2016).

In the laboratory experiment, fertilization greatly increased pore water NH_4^+ concentration; however, this is not seen for P in the pore water. Even though the fertilized buckets had higher P pore water concentrations than the unfertilized, the P concentrations at the end of the experiment for the fertilized treatments were still lower than the pre-experimental concentrations. P is geochemically reactive, so its concentration in soil is influenced by a lot of factors, like iron (Fe), aluminium (Al), magnesium (Mg), and calcium (Ca), that can immobilize the fertilizer (Walbridge & Navaratnam, 2006). In many ecosystems, including peatlands, P is highly conserved (Bridgham et al., 1996), so P from the fertilizer might be immobilized as it is being released. Therefore, when an NPK fertilizer is applied, most of the plants that do very well with NH_4^+ are going to have access to enough nutrients however, if the targeted plants need more P to aid in the plants growth then a phosphate fertilizer would need to be applied instead of an NPK fertilizer. Particularly, tree growth is known to be strongly influenced by the addition of P in peatland ecosystem undergoing restoration (Sundström et al, 1995; Caisse et al., 2008). Investigations, primarily in extracted peatlands, regarding the addition of nutrients have shown that P-fertilization can promote tree grow in disturbed peatlands (Bussières et al., 2008; Caisse et al., 2008). Although previous studies on post-harvested peatlands found that K and N did not enhance growth, this study examined the potential of NPK fertilizer to enhance vegetation growth on newly restored seismic lines. Seismic lines may have different nutrient requirements as the restored seismic lines do not have a layer of straw mulch, which supplies high concentrations of K to the restored post-harvested peatlands as it decays (Boudreau, 1999; Rochefort et al., 2003), while peat drainage, subsidence, and oxidation increase available N concentrations in post harvested peatlands (Piispanen and Lahdesmaki, 1983;

Wind-Mulder and Vitt, 2000; Andersen et al., 2006). However, the addition of N can promote the dominance of grasses (Nishimura and Tsuyuzaki, 2015). Therefore, increased nutrient concentration is not always beneficial for all fen species. For instance, optimal growth occurs for *Sphagnum* moss when in environments with low concentrations of N and P (Press et al., 1986; Clymo, 1987), and high inputs of N have been seen to decrease *Sphagnum* cover in peatlands (Wiedermann, Nordin, Gunnarsson, Nilsson, & Ericson, 2007; Eriksson, Öquist, & Nilsson, 2010; Juutinen, Bubier, and Moore, 2010; Juutinen et al., 2016; Levy et al., 2019).

Based on the results obtained from the controlled conditions in the laboratory, it was clear that the saturated treatments had a higher net ammonification rate than the unsaturated, as would be expected since anoxic conditions are needed for ammonification. The addition of NPK fertilizer elevated the net NH_4^+ mineralization rates further in the saturated treatments resulting in higher concentration of NH_4^+ in the pore water and supply rates of NH_4^+ in saturated/fertilized conditions. Even though the unsaturated/fertilized conditions do not show an increase in mineralization, these are net mineralization rates, which represents the deviation in gross mineralization and immobilization (Anderson et al., 2013; Macrae et al, 2013; Westbrook and Devito, 2004). Therefore, in the unsaturated/fertilized treatment, higher immobilization might be due to a higher microbial biomass growth rate. Although the highest concentrations of NH_4^+ were observed in the pore water of the unsaturated/fertilized treatment, the NH_4^+ supply rate was lower in the unsaturated than the saturated in the fertilized treatments. When given the opportunity to be oxidized, the NO_3^- concentrations and supply rates were higher in the unsaturated/fertilized than all the other treatments. These results suggest that treatments with the addition of microforms, that have unsaturated zones, will lead to higher supply rates of available NO_3^- for plants to access. These increases in plant available nutrients can lead to increased foliar nutrient concentrations

(Munir et al., 2017). As seedlings are planted on the hummocks of the newly restored treatments, the addition of fertilizer would increase N and P availability for the trees. Further, the PRS probes showed that the addition of fertilizer does increase the nutrients available for plant uptake, specifically the N and P, regardless of saturation.

4.4.2 Plant Functional Type Foliar Nutrient Content

The larch seedlings planted in the different restoration treatments (i.e., Hummock transfer, Rip and lift, Inline mounding) did not have significantly different concentrations of NPK foliar nutrients; however, there was a significant difference in N foliar content in the larch trees in response to fertilization. Overall, the average foliar N, even in the fertilized larch trees (12.4 ± 2.6 g kg^{-1}) was lower than in other peatland restoration projects. For instance, Choi et al. (2007) found that larch trees in undrained (20.7 ± 0.2 g kg^{-1}) and drained (33.17 ± 0.6 g kg^{-1}) minerotrophic peatland in west-central Alberta had higher foliar N concentrations. Similarly, Tilton (1977) saw larch tree in Minnesota fens have average foliar N contentations of 19.1 g kg^{-1} and average foliar P concentrations of 2.7 g kg^{-1}, which is lower than the larch P foliar concentration in the unfertilized (12.1 ± 4.7 5g kg^{-1}) and fertilized (15.0 ± 2.81 g kg^{-1}) treatments. The increase in N and P in the fertilized seedlings resulted in taller trees than those that were planted in unfertilized treatments. Other fertilizers, such as wood-ash that are low in N and high in P and K, have been reported to have positive effects on tree growth in the restoration of post-extracted peatlands (Silfverberg and Huikari 1985; Silfverberg 1996; Hytönen 1995; Hytönen and Kaunisto 1999; Moilanen et al. 2002). Although the growth of other types of trees and fertilizers have been studied for extracted peatlands, there has only been a few studies conducted in North America for the effect of NPK fertilizer on larch trees. For instance, Bussières et al. (2008) showed that the addition of NPK fertilizer resulted in similar growth rates of larch seedlings on restored cut-over peatland as on conventional forestry areas. Another study conducted by Caisse et al. (2008), also demonstrated that NPK fertilizer improves larch growth, and it increased larch survival by 11 to 17 percent compared to unfertilized larch trees. Caisse et al. (2008) also concluded that the re-application of fertilizer is important, after 4 to 6 years, as a shortage of P was the most limiting nutrients for the larch trees growth. P has also been seen to be the limiting growth nutrients for other trees, such as the Scots pine (Sundström, 1995). However, Caisse et al. (2008) also noted that a complementary application of potassium stimulated additional growth in the larch. The application of either N or K without P resulted in limited increases in larch growth (Caisse et al., 2008). The most effective dose of NPK found by Caisse et al. (2008) was 10 g 3.2N-3P-5K per tree or 10 g 7N-3P-5K per tree, whereas Bussières et al. (2008) noted that benefits of tree growth plateaus on dosages greater than 122.5 g of 3.4N-8.3P-24.2K per tree. The dose applied to the seismic line was 10 g of 18N-10P-8K g per tree, hence a higher dosage of fertilizer may have yielded stronger effects. A higher dosage of fertilizer may also have led to increases in graminoid or other unwanted vegetation growth.

Although foliar N concentrations were the lowest for graminoids, there was a significant shift in graminoid cover between fertilized and unfertilized sites. Similarly, other studies have found that N fertilization can lead to increases in vascular plant growth in boreal peatlands (Limpens et al. 2003; Tomassen et al. 2004; Wiedermann et al. 2009; Le at al. 2021). Although the application of a high concentration NH_4NO_3 solution have been seen to negatively impacted the survival and growth of *Sphagnum* (Wiedermann et al., 2009; Eriksson, Öquist, & Nilsson, 2010; Juutinen, Bubier, and Moore, 2010; Levy et al., 2019), other vegetation such as dwarf shrubs, forbs, and other mosses benefitted from the additional N (Juutinen et al., 2016; Nishimura and

Tsuyuzaki, 2015). Increases in growth of one functional group can alter the vegetation composition as a competitive advantage is given to the functional types that can benefit from the nutrient addition the most, and the different functional groups can change the environmental growing conditions (Turkington et al., 1998; Chong, Humphreys, & Moore, 2012). The addition of NPK fertilizer to nutrient limited boreal ecosystems often results in a vegetation community shift, which favors graminoids and shrubs (Turkington et al., 1998; Sliva and Pfadenhauer, 1999). The increased cover of tall graminoids can create competition and inhibit the growth of the larch seedlings planted in the fertilized treatments, as larch trees are known to be shade intolerant (Duncan, 1954). It was observed that graminoids had a lower P foliar nutrient concentration than the other functional types (Fig. 4.9). This suggests that the graminoids are using the N and P provided by the fertilizer to increase their biomass instead of holding onto high concentrations of nutrients in leaf tissue. Contrary to studies done by Turkington et al. (1998) and Sliva and Pfadenhauer (1999), other research experiments have found that increased nutrient availability is more likely to result in shrub dominated ecosystems than grass dominated ecosystems (Kool and Heijmans, 2009).

4.4.3 Conclusions and Implications for Restoration

The addition of fertilizer to restored peatlands may be a critical factor to bringing back desired vegetation and increasing nutrient availability. Our results indicate that fertilizer can support higher rates of decomposition in mechanically restored seismic lines. These increased rates of decomposition can lead to increases in microbial activity, which result in greater nutrient supply to the vegetation.

The laboratory experiment further emphasized the importance of fertilizer to supply additional nutrients to vegetation. Particularly, the addition of NPK fertilizer in unsaturated zones, such as hummocks led to increased nitrification. In the field, the fertilizer application resulted in greater total foliar N nutrient concentrations in the larch trees.

Preliminary data showed that in the first year post-planting, there were taller trees in fertilized areas compared to unfertilized areas, although further monitoring of the site is needed to determine the magnitude of the fertilizer's influence on the tree growth. The application of fertilizer also seems to be leading to an increase in graminoid cover, which can create competition for the seedlings. Longer term monitoring is needed to determine if the graminoids will outcompete the seedlings, and if the use of fertilizer will permanently alter the vegetation composition from that of the surrounding natural areas.

5.0 Summary and Conclusions

This thesis reported biogeochemical processes in a newly restored fen with the main goal of understanding how restoration affects nitrogen (N) and phosphorus (P) nutrient cycling. It focused on how different restoration techniques, mounding and fertilization, can influence nutrient availability. The first chapter of the thesis provided a general introduction to the background and motivation of this study. To better understand the research that has been conducted previously a synthesis of literature was compiled in chapter 2. Chapters 3 and 4 focused on the specific objectives that were addressed by the field and laboratory research.

Chapter 3 quantified how the newly implemented restoration treatments affected the biogeochemical processes in the fen. Specifically, how the decomposition rates, pore water nutrient concentrations, and net mineralization rates were influenced by the modified mounding techniques that are designed to improve the limitations of the traditional mounding technique. The results indicate that microtopography may have little effect on, or might be slow to specifically change, the nutrient dynamics, as a difference in biogeochemical activity was not observed immediately after restoration. However, one-year post restoration higher decomposition at the mounded sites suggested greater microbial activity. Pore water nutrient concentrations and daily net mineralization rates were lower in the first year post restoration relative to measurements taken immediately after restoration, which may be indicating that mineralized nutrients may be directly immobilized due to high microbial biomass demand for N and P. This study suggests that restoration could benefit from the addition of nutrients to supply the N and P demand of vegetation on the site. Further research was conducted in chapter 4 to examine how the supply of N and P from fertilization would impact the biogeochemical processes and influence the vegetation community.

Chapter 4 focused on assessing the effect of NPK fertilizer addition on restoration. The study examined the interactions between the restoration treatments and the preliminary application of fertilizer on pore water nutrient concentrations, net mineralization rates, and foliar nutrient concentrations in-situ. All the restoration treatments' nutrient dynamics responded similarly to the addition of nutrients. However, the laboratory study showed that with the addition of nutrients, there was an increase in ammonification in the saturated treatments and an increase in nitrification in the unsaturated treatments. In the field, the effect of fertilizer was seen to increase plant nutrient foliar nutrients and the tree height. As the height of the trees in the fertilized treatments were taller only one-year post planting, this emphasizes the importance of nutrients addition to kickstart tree recovery on legacy seismic lines. However, the observed increase in graminoid cover also suggested that high dosage of N-rich fertilizer could lead to increased competition and the elimination of important peatland vegetation, such as larch trees that are shade intolerant. Controlled impacts of the addition of NPK fertilizer were also assessed on soil processes highlighting the importance of site conditions and microforms to provide the conditions for efficientoxidation.

In conclusion the major findings of this study are: (1) The addition of microforms microforms increased microbial mediated processes such as decomposition (Fig. 5.1). (2) The addition of fertilizer can increase N minerialization rates depending on the moisture condition, as seen in the laboratory experiment. However in the field applications of fertilizer, more time is needed to let the nutrient cycling processes stabilize (Fig. 5.1). (3) Fertilizer addition in the laboratory experiment resulted in increased nutrient supply rates (4) Applying fertilizer aided in producing taller trees in just one year post-planting (Fig. 5.1). (5) The addition of fertilizer also resulted in higher graminoid cover.

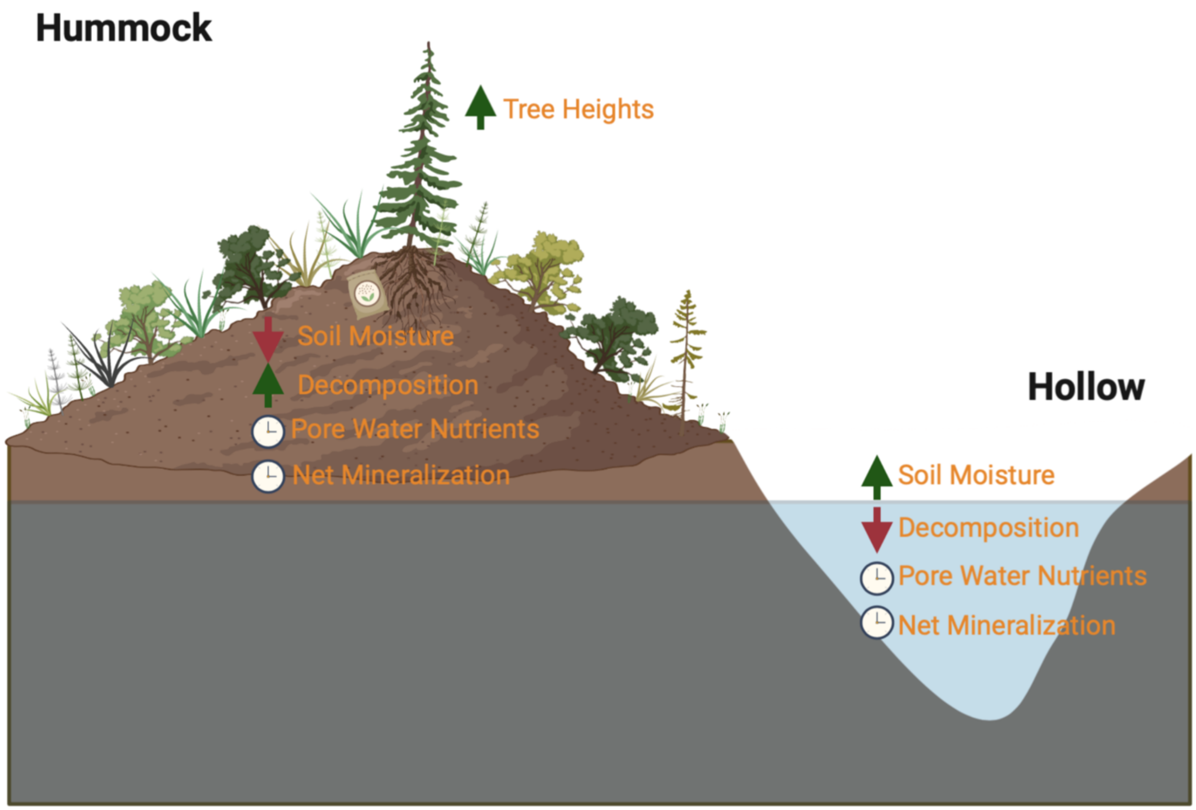

Figure 5.1. Conceptual model demonstrating that although the introduction of hummocks were successful in creating differences in soil moisture and decomposition similar to the natural, more time is needed to see the impacts of the re-introduced microtopography and fertilizer on the nutrient pools and mineralization rates.

Based on the major findings of this study, it is recommended that future seismic line restoration projects for peatland ecological functions should consider the following: (1) implement restoration techniques, such as Hummock Transfer, Line Mounding, and Rip and Lift, that introduce hummock and hollow microtopography that will increase microbial activity and allow oxidation of N, (2) Using additional restoration techniques, such as fertilization to enhance tree growth and peatland seismic line restoration. (3) NPK fertilizer should be applied in moderation, as the addition of fertilizer also resulted in increased graminoid cover. These results are preliminary covering only the first two growing seasons post-restoration and first growing-season after tree planting and fertilization, so it is essential to continue to monitor the biogeochemical processes of the restored seismic line to 1) better understand the trajectory of the restoration, 2) evaluate the longevity and impact of the fertilizer on the reestablishment of trees, and 3) understand the feasibility of the tested treatments for reducing the footprint of seismic activity.

Future research can build on the insights from this study to advance our knowledge and understanding of the restoration techniques, mounding and fertilization, influence on the nutrient availability. Future research could determine the best type of fertilizer to apply on newly restored seismic lines. NPK fertilizer proved to be effective at enhancing the height of trees, but it resulted in increased gramionoid cover. This sugguests that the use of an alternate fertilizer, such as a phosphate fertilizer, may be more approapriate for the targeted vegetation, of trees, on the seismic lines. The type of fen in which the fertilizer is applied can also impact the fate of the fertilizer. A rich fen would have more cations that can bind to available P making it unavailable to plants and microbes. Additional research is needed to evaluate the most effective moisture conditions for the fertilizer, as the water activates the release of the fertilizer. However, too moist of conditions are not optimal for tree growth and can resure in leaching of fertilizer from the site. Therefore, futher research needs to be conducted on the fate of the fertilizer to elevuate if there would be any leaching of fertilizer from the site. This could potentially cause eutrophication downstream, which is a concern that would limit the use of fertilization in seismic line restoration.

6.0 References

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