Assessing changes in peatland plant community functions following seismic line disturbance of different ages

by

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Author's Declaration

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

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 2 and 3 of this thesis. As a result, repeated information may be included.

Tentative titles and authorship of future publications:

Manuscript 1: Impact of seismic line disturbance on environmental conditions and plant community structures. Authors: Bao, C., Strack, M., Goud, E.M., Dabros, A.

Manuscript 2: Impact of seismic line disturbance in peatlands on plant functional traits and plant community functions. Authors: Bao, C., Strack, M., Goud, E.M., Dabros, A.

Bao, C. conducted the field design and setup, data collection and analysis, and wrote the thesis chapters. Assistance with data collection was provided by Strack, M., Goud, E.M., and Dabros, A. in 2022. Strack, M. and Goud, E.M. assisted with study design, data processing, and manuscript review. Each manuscript, including figures and tables, was written in its entirety by Bao, C. and reviewed by Strack, M.

Abstract

Seismic lines are linear clearings created for petroleum exploration mostly across boreal peatlands and forests in northwestern Canada. Seismic line disturbance has resulted in significant environmental impacts, including changes in plant composition, predator-prey dynamics, and hydrological conditions. There are more than 1.8 million km of seismic lines in Alberta, Canada, and they often remain visible even after decades. Despite the extensive occurrence of seismic lines, their effects on peatland plant community functions remain poorly understood.

This study uses a trait-based approach to explore the impact of seismic line disturbance on peatland plant community functions. We measured key morphological plant traits, such as specific leaf area (SLA) and leaf dry matter content (LDMC), along with leaf chemical composition, such as nitrogen (N) and carbon (C). Vegetation cover was also assessed to understand species distribution across disturbed and undisturbed areas. Statistical analyses, including multivariate methods, were conducted to determine how seismic line disturbance influences plant traits and community composition.

The results indicate that seismic lines are on a positive recovery trajectory, as reflected by the similarities in both plant community composition and plant traits between undisturbed areas and the areas that have naturally regenerated for about 30 years. However, it does not imply that the peatlands have returned to their pre-disturbance state after three decades. The findings of this study have important implications for the restoration of boreal peatlands disturbed by seismic lines. While restoration strategies like mounding may accelerate ecosystem recovery, these interventions themselves can cause further disturbance. Therefore, it is crucial to balance the time required for natural recovery with the potential disturbances introduced by restoration efforts.

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List of Abbreviations

LDMC	Leaf dry matter content
SLA	Specific leaf area
LS	Leaf size
Lth	Leaf thickness
N	Nitrogen
C	Carbon
P	Phosphorus
K	Potassium
S	Sulfur
Ca	Calcium
TOC	Total organic carbon
EC	Electrical conductivity
DTW	Distance to water table

List of Species Abbreviations

P. mariana	*Picea mariana*
L. laricina	*Larix laricina*
B. glandulosa	*Betula glandulosa*
S. pedicellaris	*Salix pedicellaris*
A. polifolia	*Andromeda polifolia*
C. calyculata	*Chamaedaphne calyculata*
R. groenlandicum	*Rhododendron groenlandicum*
V. vitis-idaea	*Vaccinium vitis-idaea*
C. aquatilis	*Carex aquatilis*
E. fluviatile	*Equisetum fluviatile*
M. trifolium	*Maianthemum trifolium*
M. trifoliata	*Menyanthes trifoliata*
S. angustifolium	*Sphagnum angustifolium*
S. fuscum	*Sphagnum fuscum*
S. warnstorfii	*Sphagnum warnstorfii*
A. palustre	*Aulacomnium palustre*
T. nitens	*Tomentypnum nitens*
S. magellanicum	*Sphagnum magellanicum*
E. angustifolium	*Eriophorum angustifolium*
D. anglica	*Drosera anglica*
S. purpurea	*Sarracenia purpurea*
C. stellatum	*Campylium stellatum*

S. cossonii	*Scorpidium cossonii*
P. balcanica	*Pinguicula balcanica*
H. lanatus	*Holcus lanatus*
T. pratense	*Trifolium pratense*
P. australis	*Phragmites australis*
S. nigricans	*Stenaria nigricans*
S. grandis	*Stipa grandis*
C. chinensis	*Cleistogenes chinensis*
C. korshinskyi	*Carex korshinskyi*
L. chinensis	*Leymus chinensis*

Chapter 1 Introduction and literature review

1.1 Introduction

Seismic lines are linear clearings created for petroleum exploration across peatlands and forests in northwestern Canada. Extensive disturbance from natural resource extraction has notably impacted Alberta's boreal ecosystems (Lee & Boutin, 2006). As a byproduct, the industrial disturbances have created human footprints, such as roads, well pads, and trails, in boreal natural habitats. For example, roads and seismic lines account for the greatest area of linear disturbance in northern and central boreal Canada (Pasher et al. 2013). Initially established to transport geophysical survey equipment, these lines facilitate seismic exploration by clearing vegetation for geophone placement, recording energy reflections from underlying rock layers (Strack et al., 2017). This practice has been ongoing since 1929 (Alberta Culture and Tourism), and it leaves long-lasting linear disturbances often visible for decades (Dabros et al., 2018). This disturbance exerts negative effects on vegetation (Abib et al., 2019; MacFarlane, 2003), wildlife (Pattison et al., 2020), hydrology (Williams et al., 2013; Braverman & Quinton, 2015), and greenhouse gas (GHG) fluxes (Strack et al., 2019). Given these extensive impacts, this study aims to enhance our understanding of how seismic line disturbance influences plant community functions within boreal peatlands, thereby informing effective conservation and restoration strategies.

Peatlands are a type of wetlands of which the partially decayed organic matter forms peat at the surface (Zoltai & Vitt, 1995). The depth of peat must be greater than 40 cm to be classified as a peatland in Canada (National Wetlands Working Group, 1997). These ecosystems cover only 3% of Earth's land area but store up to 30% of the world’s soil carbon (Limpens et al., 2008). The carbon stored in peat layers (22.6 – 66.0 kg/m^2) is much greater than that in aboveground and

belowground tree biomass (2.8 – 5.7 kg/ m²) (Beaulne et al., 2021). Ongoing anthropogenic GHG emissions can be partially mitigated by the carbon sequestration of peatlands (Strack et al. 2022).

Seismic lines extensively fragment peatlands in Alberta, Canada, causing persistent disturbance across the landscape (Strack et al., 2019; Dabros et al., 2021). Seismic lines significantly impact peatland dynamics by affecting predator-prey interactions (DeMars and Boutin, 2018), GHG emissions (Strack et al., 2019), tree growth (Lee & Boutin, 2006), thermal regimes (Williams & Quinton, 2013), regional hydrology (Abib et al., 2019; Braverman and Quinton, 2016), and exacerbating permafrost degradation (Williams et al., 2013). Seismic lines can increase predator efficiency, which in turn decreases caribou calf survival rate (DeMars & Boutin, 2017). Furthermore, seismic activities can alter vegetation structure, often with changes in tree height and canopy density extending up to 55 m from seismic lines (Abib et al., 2019).

The plant community plays a crucial role in ecosystem functions. Understanding its role involves studying plant community composition and plant functional traits (Miedema Brown & Anand, 2022; Symstad et al., 1998). Plant community composition describes the variety and abundance of different plant species within a specific area. Disturbances often disrupt plant growth and community composition, influencing individual plant performance and overall ecosystem dynamics. For instance, in species-rich communities, plants are generally taller but have reduced biomass and a reduced likelihood of flowering (Schmidtke et al., 2010). However, the link between changes in plant community composition and community traits or functions is not always consistent. It has been proposed that significant functional impacts occur when functionally unique species are lost (Mokany et al., 2015).

The use of heavy machinery during seismic line creation causes significant tree removal, habitat fragmentation, and slow tree regeneration (Lee & Boutin, 2006). The disturbed areas are less hospitable for tree seedlings due to soil compaction and reduced water retention capability (Maynard & Senyk, 2004). The removal of the organic layer exposes mineral soil, which may lack the necessary nutrients and microbial environment supportive of young trees (Lee & Boutin, 2006). Additionally, the change in microtopography and the desiccation caused by increased light exposure can further inhibit the growth of trees that are adapted to the stable conditions of undisturbed forest interiors (Boehnke, 2021; Lee & Boutin, 2006). These combined effects of the physical alterations result in a prolonged delay in tree regeneration, especially in wetland ecosystems (van Rensen et al., 2015).

Active restoration programs have been used to treat peatlands disturbed by seismic lines. The main restoration techniques currently used are mounding and tree planting (Vodopija et al., 2021). Mounding involves the excavation and inversion of organic and mineral soil to form raised mounds (Shellian et al., 2024). This technique aims to mimic natural hummock and hollow microtopography, which is favourable for tree growth in boreal peatlands (Echiverri et al., 2023). By creating the artificial hummocks and hollows, the mounding process provides seedlings with an elevated growing site that has a warmer microclimate and better soil aeration (Pearson et al., 2011). The disturbed sites usually need to be prepared by mounding before tree planting can proceed (Filicetti et al., 2019). The tree species planted are primarily selected based on those found in the adjacent undisturbed areas, which are usually *L. laricina* and *P. mariana*. The effects of tree planting on vegetation community are significant. The treated seismic lines showed a considerable higher density of regenerating tree stems compared to untreated lines (Filicetti et al., 2019). The increase in tree stem density is an indicator of successful

establishment of seedlings, suggesting that the restoration technique is helpful in enhancing tree regeneration.

While some methods, such as tree planting, have shown benefits such as increased tree density (Pyper et al., 2014), uncertainties persist due to slow vegetation recovery and ongoing environmental disruptions (Dabros et al., 2018). Additionally, the complexities of peat conditions, hydrology, and permafrost stability complicate the standardization of effective restoration practices (Dabros et al., 2018).

1.2 Plant community composition in peatlands and its drivers

Vegetation gradients refer to the variation in plant species composition across an area, typically influenced by changes in environmental conditions or human impacts (Stohlgren et al., 2000). In peatlands, the composition of vegetation is strongly influenced by moisture levels, nutrient availability, and light exposure, resulting in a diverse array of plant species across these ecosystems (Jasieniuk & Johnson, 1982). Factors such as soil temperature, microtopography, water table depth, nutrient availability, electrical conductivity (EC), and pH play critical roles in shaping vegetation gradients in peatlands. For instance, fluctuations in the water table affect peatland plant communities by determining oxygen availability in the root zone, with plant species varying in their tolerance to waterlogged conditions (Lieffers & Rothwell, 1987).

Microtopography in peatlands describes the small variation in surface elevation (Gignac et al., 1991). The most common microtopographic units, also called microforms, described in peatlands are hummocks and hollows (Nungesser, 2003). The composition of plant species can vary significantly between the hummocks and hollows. Hummocks are often dominated by

shrubs such as *Chamaedaphne calyculata* and *Rhododendron groenlandicum*, with abundant *Sphagnum fuscum* and *Sphagnum magellanicum* (Graham et al., 2015). On the other hand, hollows have more sedges like *Carex aquatilis* and *Eriophorum angustifolium* and different species of *Sphagnum* that are adapted to wetter conditions (Moor et al., 2017). The microtopographic variation is linked to water table level that plays a pivotal role in determining the plant community composition, primarily by influencing the availability of water and oxygen (Bubier, 1995). When water table is close to the surface, the peat becomes saturated, creating anoxic (low oxygen) conditions that are unfavourable for most terrestrial plants but ideal for species adapted to wet conditions. This leads to the dominance of water-tolerant species, such as *Drosera anglica* and *Sarracenia purpurea*, and certain species of *Sphagnum* (Bradley et al., 2014). In contrast, lower water tables increase oxygen availability by exposing more of the peat profile to air. This condition supports species that require better-aerated peat, such as shrubs and trees. (Zhong et al., 2020).

The source of water is also a major driver of vegetation gradients, which is often referred to as the ombrotrophic – minerotrophic or bog – fen gradient. There are two major water sources: precipitation and surface/groundwater. Groundwater refers to the water that is stored in the peat soil and is part of the hydrological regime that influences biogeochemical processes (Sundari, 2020). Groundwater is typically characterized by a high mineral content, which increases as groundwater moves through deeper peat layers (Sundari, 2020). Rainwater, on the other hand, is the water that precipitates directly from the atmosphere and can influence the hydrology of peatlands by contributing to the water table and affecting the moisture content of the peat (Bourgault et al., 2019). Groundwater typically contains more minerals compared to rainwater (Zoltai & Vitt, 1995), resulting in higher mineral content, EC, and pH.

Depending on the water source, peatlands can be divided into two types based on their vegetation and water source: bogs and fens (Zoltai & Vitt, 1995). Bogs are *Sphagnum*-dominated, ombrotrophic, and acidic wetlands. Their water supply only comes from precipitation and snow (Weltzin et al., 2000). Most bogs have limited base cation content and nutrient availability, which restricts vascular plant production while allowing *Sphagnum spp.* to thrive (Zoltai & Vitt, 1995). Fens are minerotrophic peatlands, meaning they receive nutrients from groundwater, making them less acidic than bogs (Weltzin et al., 2000). Most fens are dominated by brown moss, such as *Tomentypnum nitens*, *Campylium stellatum*, and *Scorpidium cossonii* (Bérubé & Rochefort, 2018). They also support greater plant diversity than bogs, including species like sedges and reeds (Jabłońska et al., 2019). Fens can be further subdivided into rich fens and poor fens. Rich fens have higher pH levels and are influenced by calcium (Ca) and bicarbonate (HCO3), leading to a more diverse plant assemblage (Bailey, 2006). In contrast, poor fens are more acidic and less nutrient-rich, but they are more mineral-rich than bogs (Bailey, 2006). They are often dominated by acid-tolerant species, such as *Aulacomnium palustre* and *Drepanocladus aduncus* (Zoltai & Vitt, 1995).

Much of the variation in species along the bog-fen gradient is linked to the acidity or alkalinity of the peat, indicated by pH levels (Gorham & Janssens, 1992). Water pH influences plant species richness and composition (Hájková et al., 2006). The neutral to alkaline environments (pH 6.0-7.9) usually support species such as *Pinguicula balcanica, Larix laricina,* and *Salix pedicellaris* (Hájková et al., 2006; Jeglum, 1971). In contrast, the acidic conditions (pH 3.0-3.9) typically favour species such as *C. calyculata* (Jeglum, 1971). EC is a measure of the ionic concentration, which influences plant community composition by affecting nutrient availability (Beltman et al., 1996). Plants in environments with high EC (above 15 mS/cm) must

adapt to osmotic stress, as high ionic concentration can cause water to move out of plant cells and lead to dehydration (Batistel et al., 2022). Areas with higher EC typically support more vascular plants and fewer mosses, suggesting that vascular plants may tolerate or even thrive under conditions of high ionic concentration.

Beyond the effects of pH and EC on plant community composition, nutrient gradients also play a crucial role in shaping plant biodiversity in peatland ecosystems. Nutrient gradients are influenced by surrounding land-use activities, geology, and hydrology (Sjögersten et al., 2010). These gradients are crucial in dictating plant biodiversity, especially tree diversity (Sjögersten et al., 2010). Nitrogen (N) and phosphorus (P) are important nutrients for plant growth, and the imbalance of these nutrients can significantly affect plant community composition (Zhao et al., 2019). Excessive N inputs can alter plant community structures by promoting the growth of certain species, such as *Carex spp.*, which reduces overall diversity and richness in the ecosystem (Neher, 1999). This shift often occurs because the additional N alleviates N limitation for plant growth but exacerbates P limitation, changing the competitive balance among plant species (Gao et al., 2022). Certain species, such as *E. angustifolium* and *C. aquatilis,* show robust growth and can outcompete other species under increased N availability, leading to shifts in plant community dynamics (Normand et al., 2017; Larmola et al., 2013). The shifts in plant community dynamics usually result in decreased species diversity over time.

Other nutrients, such as calcium (Ca), potassium (K), iron (Fe), and sulfur (S), also play an important role in plant growth as they promote cell wall stability and regulate enzymatic processes (Long & Peng, 2023). High Ca levels are often associated with the growth of species such as *Phragmites australis* and *Stenaria nigricans* in fens (Srivastava et al., 2014). Some herb species, such as *Holcus lanatus* and *Trifolium pratense*, benefit greatly from high K levels,

especially when combined with N (Kirkham et al., 1996). However, a high nutrient level is not always beneficial for plant growth. Iron-rich conditions can lead to the formation of iron plaques on the roots of plants, which can affect nutrient uptake and tolerance to soil contaminants (Batty, 2003). Only few plant species can tolerate high Fe levels, such as *G. spiculose*. They can exclude dissolved Fe and precipitate Fe oxides on their roots, which can help manage Fe level in their immediate environment (Jia et al., 2018).

Environmental factors, such as soil temperature, also significantly influence the plant community composition in peatlands. *Sphagnum* mosses create and maintain an acidic, waterlogged environment that favours peat accumulation (Chiapusio et al., 2022). The acidic conditions created by *Sphagnum* inhibit the decomposition of organic material, including the *Sphagnum* itself. The slow decomposition is crucial for peat accumulation. The acidic, anoxic conditions are ideal for further growth of *Sphagnum*, as many competing plant species cannot thrive under such conditions. As more *Sphagnum* grows, it enhances these conditions, reinforcing the cycle. This stability is beneficial for peat accumulation. However, the abundance of *Sphagnum* significantly declines when the annual average temperature is raised (Dieleman et al., 2014). An increase in *Carex* happens at the same time as the decline of *Sphagnum* (Szajdak et al., 2019). *Carex* does not maintain the acidic, anaerobic conditions that are created by *Sphagnum*. Instead, they are associated with conditions that favour faster decomposition rates and less peat accumulation (Szajdak et al., 2019). As *Carex* becomes more dominant, the conditions that *Sphagnum* created begin to deteriorate. The growth of *Carex* in place of *Sphagnum* suggests a weakening of this feedback mechanism, which can lead to a less effective peat accumulation (Dieleman et al., 2014; Szajdak et al., 2019). The transition to vascular plant

dominance can alter the peatland's structure and functions as they have different nutrient and water needs compared to mosses.

Species have different responses to climate change, such as increase in annual average temperature. For instance, *L. laricina* usually shows increased water stress and altered hydraulic properties under warming conditions, making it less competitive (Warren et al., 2021) In contrast, *P. mariana* can maintain a more stable water relation and demonstrate resilience to hydraulic stress (Warren et al., 2021). Such varied responses suggest that altered temperature may shift species dominance within the ecosystem, thus alter the structure and functions of the plant community. Additionally, temperature change, especially the increase in temperature, can decrease species diversity (Greiser et al., 2024; McPartland et al., 2020). In northern and temperate climates, warming conditions typically foster a greater abundance of shrubs, which in turn results in a reduction in overall species diversity due to the shading effect these taller plants have on the ground layer (Greiser et al., 2024). This shading disrupts the growth of *Sphagnum* and graminoids (McPartland et al., 2020). Prolonged droughts usually have similar effects on plant communities, with a decrease in *Sphagnum* species and an increase in shrubs and lichens (Munir et al., 2014).

These interacting factors work together to form the unique plant communities in peatlands. The intricacies of how environmental drivers, such as water level fluctuations, temperature changes, and variation in peat chemistry, shape these communities are crucial for understanding peatland dynamics. Each of these factors can drastically influence the survival, growth, and reproduction of plants, contributing to a dynamic balance within the plant community. Recognizing the drivers of plant community structure in peatlands not only highlights the complexity of these ecosystems but underscores the need for conservation

strategies. By focusing on the interplay between environmental factors and plant responses, we can better predict and manage the impacts of human activities on these critical habitats, ensuring the preservation of the plant communities and the ecological benefits they provide.

1.3 Effects of seismic lines on peatland plant community composition

Seismic lines exert many effects on plant community composition, including lowering species diversity, promoting invasive species colonization, and increasing area of edge habitats (Dabros et al., 2018; Dabros & Higgins, 2023). The fragmentation caused by seismic lines disrupts habitat continuity, leading to slow vegetation recovery and negatively affect biodiversity. The fragmentation of landscape hinders the movement and distribution of species across the ecosystem, which often leads to decreased species richness (Dabros et al., 2018). Seismic lines can indirectly affect plant community composition by depressing the elevation and simplifying the microtopography (Stevenson et al., 2019; Franklin et al., 2021). These effects disrupt the variety of microsites that are necessary for seedling establishment, which is crucial for maintaining diverse plant community (Stevenson et al., 2019).

Beyond their direct impact on plant communities, seismic lines can affect species composition by altering environmental conditions. Seismic lines increase light penetration to forest floor by creating gaps in canopy cover, which shifts the thermal profile and alter microclimates (Draper et al., 2018; Franklin et al., 2021). The increase in soil temperature typically accelerate the thawing of ground and increase the depth of the active layer in permafrost areas (Woo et al., 2007; Williams & Quinton, 2013). The disturbed areas often have a shallower water table due to soil compression (Strack et al., 2017). This disruption can alter the

natural flow of water, potentially leading to localized flooding or drying in areas adjacent to the seismic lines (Strack et al., 2017). The wetter conditions and higher bulk density of the soil on the seismic lines tend to increase its thermal conductivity. This can further contribute to changes in soil temperature profiles and affect the overall energy balance of the peatland (Strack et al., 2017; Franklin et al., 2021).

The soil moisture level is another important environmental variable. The increased soil moisture level creates conditions that favour different plant species than those present in undisturbed areas, leading to shifts in plant community composition (Dabros et al., 2022; Goud et al., 2024). The altered environmental conditions on seismic lines usually favour the dominance of low ericaceous shrubs and *Sphagnum* in peatlands, compared to the undisturbed areas which support a dense treed overstory (Dabros et al., 2022; Goud et al., 2024). The abundance of some herbaceous plants, such as horsetails and graminoids, may be much higher on the lines (Goud et al., 2024).

The linear disturbance can alter environmental conditions, such as light, moisture, and soil structure, making the ecosystem more hospitable to invasive species that can thrive under altered conditions (Stern et al., 2018). Seismic lines can facilitate the dispersal of seeds and plant materials due to increased wind speeds along the lines (Roberts et al., 2018). This enhanced dispersal can lead to the introduction and spread of invasive species, which can outcompete native vegetation and alter biodiversity.

The creation of the linear disturbance can also significantly alter the landscape structure itself, fragmenting forest cover and creating edge habitats. These edge environments, formed where the cleared seismic lines meet the undisturbed areas, exhibit different ecological conditions that further influence plant community dynamics and interactions. These edges alter

the microclimates, including increased light availability, decreased soil moisture level, and fluctuated soil temperature (Franklin et al., 2021). Such changes can lead to lower humidity and greater wind exposure, which significantly affect plant growth and species composition (Franklin et al., 2021). For plants, edge effects have been reported to extend up to 15 m from seismic lines into the undisturbed areas, resulting in greater invasion by opportunistic plant species (Buss et al., 2024). Opportunistic species are typically early successional species that would be well adapted to edge habitats. They often thrive in these conditions because they are more tolerant of light, drought, and disturbed soils (Finnegan et al., 2018). Edge effects may vary with the width and orientation of the seismic lines (Dabros et al., 2022; Finnegan et al., 2018). Wider seismic lines might have more pronounced edge effects due to greater exposure to environmental changes like sunlight and wind, which can penetrate deeper into the adjacent forest (Dabros et al., 2022; Finnegan et al., 2018).

The orientation of seismic lines affects how sunlight and wind interact with the forest edges by determining the direction and intensity of these elements (Franklin et al., 2021). East-west lines experience different sun exposure throughout the day compared to the north-south lines. On the east-west lines, the light intensity is the highest at the centres, followed by the northern edges, and then the southern edges (Franklin et al., 2021). On the north-south lines, the light intensity is the highest at the centres, followed by the east edges, and then the west edges (Franklin et al., 2021). The alignment with prevailing wind directions can influence how much wind penetrates the forest edge, impacting evaporation rates and microclimate stability (Franklin et al., 2021). All of these shifts in conditions can potentially affect plant community composition.

Seismic lines undoubtably disturb environmental conditions and vegetation communities. It is necessary to monitor the natural recovery process and implement recovery strategies when

needed. Seismic lines typically stall natural woody vegetation regrowth, especially in moist conditions (van Rensen et al., 2015), due to the compacted peat and altered microtopography (Stevenson et al. 2019). The recovery process can vary by environmental conditions, disturbance levels, and the presence of invasive species (Filicetti et al., 2019; Finnegan et al., 2019). Generally, regions with dry seismic lines show more promising recovery trends (Filicetti & Nielsen, 2018; Filicetti et al., 2019). In drier conditions, young plants face fewer barriers that lead to rotten roots or reduced oxygen availability in peat (Filicetti et al., 2019). Recovery is slower in areas with heavier machinery use or deeper peat disturbance.

Despite extensive research into the effects of seismic lines on plant community composition, many uncertainties persist regarding their ecological impact. Firstly, there is uncertainty about the long-term ecological impacts of seismic lines, particularly how permanent the changes to plant community might be (Dabros et al., 2018). The ability of vegetation to naturally regenerate on seismic lines is uncertain, especially when the original peat structure is heavily altered (Chasmer et al., 2021). While slow recovery suggests a need for restoration, there remain questions about the most appropriate restoration strategies. The effectiveness of recovery efforts is unclear due to the lack of long-term monitoring (van Dongen et al., 2022). It is uncertain whether current restoration methods can successfully restore the original biodiversity and ecosystem functions (Dabros et al., 2018). It is unclear how plant communities might change over time post-restoration, and different trajectories of succession can lead to varied ecological outcomes. Variability in factors such as climate, peat fertility, and competition from existing vegetation also creates uncertainty (Vodopija, 2021). Collectively, the long-term impact of seismic line restoration is not well understood.

Secondly, the responses of different plant functional types to seismic line disturbance are not well studied. Different plant types exhibit varied recovery patterns (Echiverri et al., 2022). Bryophytes, specifically species within the *Hylocomiaceae* family, might show significant regeneration on narrower seismic lines, whereas vascular plants might show little sign of regeneration (Dabros and Higgins, 2023). Trees generally show low regeneration success due to altered soil and light conditions. Shrubs may exhibit faster recovery as they are often more resilient to changes in light and soil conditions (Teixeira et al., 2022). Graminoids might be more abundant on seismic lines as they thrive under increased light availability (Finnegan et al., 2018). However, their recovery can be impeded by shading from shrubs or invasive species competition (Stevenson et al., 2019; Echiverri et al., 2020; Echiverri et al., 2022).

Thirdly, the cumulative impact of multiple seismic lines in close proximity and their interaction with other landscape features and disturbances are not well understood (Stern et al., 2018). The high density of seismic lines can amplify the overall environmental impact as the synergistic effects might not be apparent when considering individual lines. The synergistic effects can vary significantly depending on local environmental conditions and the characteristics of the seismic lines, such as width and orientation (Stern et al., 2018; Franklin et al., 2021).

Lastly, there is ongoing debate about the best practices for mitigating the negative impacts of human footprint disturbance (Roberts et al., 2018). Many restoration techniques, such as planting native species or altering the physical environment (e.g., mounding), aim to enhance recovery, but the long-term success and ecological integration of these efforts are not well understood. Factors contributing to this uncertainty include the differences in environmental conditions, vegetation, topography, and restoration prioritizations (Rivas et al., 2010; Finnegan et al., 2018). In the areas with sparse vegetation and dry conditions, it is crucial to prioritize the

establishment of groundcover plants, such as *C. aquatilis*, and enhance water retention capabilities (Finnegan et al., 2018; Souza-Alonso et al., 2022). Effective restoration techniques for these areas include applying soil amendments, creating small depressions to retain moisture, and planting drought-tolerant species (Souza-Alonso et al., 2022). In contrast, areas with dense vegetation and wet conditions should focus on managing excess moisture and elevating the soil profile (Sutton & Price, 2020). Effective methods for these areas involve mounding and the installation of water control structures (Finnegan et al., 2018). However, these restoration techniques are costly and may cause additional disturbance. Thus, understanding if and when they are needed is critical.

In conclusion, seismic line disturbance often leads to increased light penetration, increased moisture, and greater fluctuations in peat temperature, which promotes the invasion of non-native species. The altered conditions typically favour early successional and more resilient species, thereby shifting the ecological balance and potentially altering long-term ecosystem functions. Despite considerable research efforts, significant uncertainties remain about the full ecological impacts of seismic lines, such as long-term recovery processes and impacts to ecological function. Filling these knowledge gaps can help inform restoration planning.

1.4 Plant functional traits, their use in inferring plant community functions, and their responses to disturbances

Plant functional traits are defined as the morpho-physio-phenological traits that impact fitness through their effects on growth, reproduction, and survival (Violle et al., 2007). A functional trait is characterized not just by its presence but by its measurable impact on the

plant's performance (Pan et al., 2019). Functional traits are crucial for understanding how plants adapt to environmental changes and how these responses influence ecological processes (Duckworth et al., 2000). Functional traits are also helpful in assessing biodiversity and ecosystem productivity by linking individual plant physiology with broader ecological dynamics (Díaz et al., 1999).

Some plant functional traits are measured more often than others, such as plant height, specific leaf area (SLA), leaf size (LS), leaf dry matter content (LDMC), leaf thickness (Lth), and leaf nitrogen (N) level (Körner & Renhardt, 1987; Reich et al., 1998). Plant height measures the height between the soil surface to the top of the plant, and it reflects changes to specific environmental pressures and resource allocation (Miedema Brown & Anand, 2022). Plant height is an indicator of competitive ability, particularly in dense communities where taller individuals can outcompete others for sunlight (Lavorel & Garnier, 2002). Additionally, it can influence the microclimate, including temperature, humidity, and soil moisture levels. Taller plants can provide shade and reduce ground temperature, which impacts the species composition and ecosystem processes at the ground level (Lavorel & Garnier, 2002).

Specific leaf area (SLA) indicates the leaf area relative to its dry mass, which is a crucial indicator of the photosynthetic rate and water use efficiency (Hassan et al., 2007). High SLA values are often associated with fast-growing species that can quickly exploit resources, especially in high-light environments (Miedema Brown & Anand, 2022). Leaf dry matter content (LDMC) is a measure of the dry mass per unit of fresh leaf area. Plants with higher LDMC are generally more resistant to physical and environmental stress, such as drought (Guo et al., 2022). Higher LDMC allows leaves to lose water more slowly, which makes plants more tolerant to drought (Wilson et al., 1999). Also, LDMC is inversely related to decomposition rate as leaves

with higher LDMC tend to decompose slower and are more resistant to breakdown (Wilson et al., 1999). Leaf size (LS) measures the area of one side of a leaf. Bigger leaves have a greater surface area for capturing sunlight, which can increase photosynthetic rate (Rezai et al., 2018). LS also affects the thermal dynamics of a plant's microenvironment. Larger leaves can cool down more effectively, which is important for maintaining leaf temperature within optimal ranges for photosynthesis in warmer climates (Li et al., 2020). Leaf thickness (Lth) can be measured by a digital micrometer or calculated using leaf fresh mass divided by leaf area (Witkowski & Lamont, 1991). Plants exposed to high light intensity typically develop thicker leaves because it enhances their ability to absorb light and improve photosynthesis efficiency (Smith et al., 1997). Leaf thickness is also closely associated with a plant's ability to store water, especially in challenging environments (Kutlu et al., 2018). This relationship is more pronounced in succulent plants, which have evolved to thrive in conditions where water is scarce or sporadically available (Mauseth, 2000). In these environments, water storage is essential for maintaining cellular function and metabolic activity during extended periods of drought or salt stress.

Leaf N level can reflect the nutritional status of a plant and is often directly related to photosynthetic capacities (Evans, 1989). Higher leaf N content usually correlates with higher rates of photosynthesis per unit leaf area, impacting plant growth rates and ecosystem productivity (Makino, 2010; Poorter & Evans, 1998). Content of other nutrients, such as phosphorus (P) and potassium (K), can also be reflective of plant nutritional status. P and K are important growth parameters for plants. The optimal level of P and K can maximize plant growth by influencing plant height, chlorophyll content, and biomass (Mohidin et al., 2019). Plants with higher P and K levels typically have a greater nutrient uptake capability and indicate a more nutrient-rich environment (Yanbuaban et al., 2007).

Many studies have investigated how plant functional traits can be used to predict ecosystem services in various case studies. The relationship between plant functional traits and ecosystem functions was assessed in an urban woodland study in Montreal, Canada (Cardou et al., 2022). A total of 13 functional traits, such as rooting depth, SLA, and LDMC, were used to predict three key ecosystem properties: colonization, water infiltration, and decomposition (Cardou et al., 2022). For example, increased SLA was associated with faster decomposition rates, as leaves with higher SLA have thinner, more decomposable tissue, contributing to quicker nutrient cycling. Greater rooting depth was linked to improved water infiltration, as deeper roots help break up soil compaction, allowing water to penetrate more efficiently. In contrast, higher LDMC was associated with slower decomposition rates, as leaves with higher LDMC are tougher and more resistant to breakdown, leading to slower carbon cycling.

In a boreal forest study in northeastern Canada, researchers investigated the role of understory functional traits in predicting black spruce tree growth following two types of harvesting methods: clearcutting and careful logging (Wei et al., 2021). The study examined 11 functional traits, such as SLA and rooting depth. It was found that traits like deeper roots and higher SLA were positively correlated with tree growth, especially in clear-cut forests. This finding highlights the importance of functional diversity and specific traits in predicting forest productivity under different disturbance regimes.

Aside from vascular species, bryophytes also play a vital role in inferring ecosystem functions. Bryophytes, such as *Sphagnum spp.*, have an exceptional ability to retain water, up to 20 times their dry weight for some species (Walker et al., 2015). The high water-retention capacity of *Sphagnum* helps maintain high moisture levels in peatlands, which affects the growth and survival of many plant species and hydrological cycling. Furthermore, *Sphagnum spp*. are

the primary contributors to peat formation due to their ability to build up substantial layers of dead organic matter that does not fully decompose (Tveit et al., 2020). Many bryophyte traits are directly linked to peat accumulation rate, such as growth rate, decomposition rate, photosynthetic rate, and germination potential (Janssens, 1983; Longton & Greene, 1979; Rzepczynska et al., 2022). Different species of *Sphagnum* have varying growth and decomposition rates, which influence the amount of organic matter they contribute to the peat layer. Fast-growing and slow-decomposing species contribute more to peat accumulation. The ability of a *Sphagnum* species to perform photosynthesis efficiently under varying light conditions affects their growth and survival, which indirectly influence their contribution to peat accumulation (Bengtsson et al., 2016). Healthy spore germination of bryophytes, which is characterized by successful germination, robust growth, and sufficient nutrient (Longton & Greene, 1979), is also important in peat accumulation. Healthy spore germination is necessary for successful establishment and growth of moss populations, which in turn contributes to peat formation over time.

Intraspecific trait variation (ITV) describes the differences in characteristics that occur within a species (Silva et al., 2019). This variation is influenced by genetic diversity, environmental factors, developmental stages, and the intensity of disturbance (Cope et al., 2022; Silva et al., 2019). It plays a crucial role in how species interact with each other and their environment. ITV can result from the comparative trait trade-offs during peatland succession. When peatlands transition toward more stable and mature ecosystems, such as the transition from fens to bogs, the plants experience notable changes in their traits (Palozzi & Lindo, 2017). The height, SLA, photosynthetic rate, and nutrient content tend to decrease for some shrubs and *Sphagnum* to adapt to the nutrient-poor environments (Laine et al., 2021). LDMC tends to increase to enhance the survival and reproduction of plants (Fantinato et al., 2023). Similarly,

disturbances such as seismic lines can cause shifts in species composition, which lead to decreased height and SLA but increased root length and LDMC (Dabros et al., 2022). These changes are mostly driven by shifts in species composition, and the influence of ITV on plant functional responses to seismic line disturbance are less studied.

Overall, plant functional traits, such as LS and LDMC, are helpful in inferring ecosystem functions. Plant functional traits provide essential insights into the strategies of plants in response to environmental challenges. Functional trait analysis facilitates a deeper understanding of biodiversity patterns and ecosystem productivity, linking individual physiological responses to collective ecological outcomes.

1.5 Objectives and hypotheses:

Given the continued uncertainty of the effects of seismic line disturbance on peatland plant community functions, this study employs a trait-based approach to help fill the knowledge gap. The objectives of this study are to: 1) examine how peatland plant community functions differ on seismic lines compared to natural areas, and 2) assess variation between newly disturbed and recovering seismic lines. Specifically, the research investigates how changes in plant community composition impact plant community functions by measuring functional traits. It also explores ITV within plant species on seismic lines and undisturbed areas. To address this, my research focuses on the following questions: 1) Do peatland plant community composition and functions vary between seismic lines and the adjacent natural areas? 2) Do plant community composition and function differ between newly disturbed and recovering seismic lines? 3) How does ITV influence the community responses of peatland plants to seismic line disturbance? 4)

Does seismic line disturbance cause ITV? The following hypotheses are formulated to investigate these effects, focusing on variation in plant community functions across different conditions:

Hypothesis 1: Peatland plant community on seismic lines would exhibit altered composition and functions compared to natural areas, such as fewer woody species or increased nutrient cycling rate.

Hypothesis 2: Plant community composition and functions on newly disturbed seismic lines would differ from those on the older seismic lines, with newly disturbed areas more likely to shift towards fast-growing and resource-acquisitive species.

Hypothesis 3: ITV would play a critical role in the response of peatland plant communities to seismic line disturbance, potentially driving observed differences in plant community functions between disturbed and undisturbed areas.

Chapter 2 Impact of seismic line disturbance on environmental conditions and plant community composition

2.1 Introduction

Peatlands contain deep organic layers rich in carbon that have accumulated over millennia (Loisel & Gallego-Sala, 2022). These ecosystems act as long-term carbon sinks and influence the global carbon cycle (Alexandrov et al., 2020). Peatlands cover approximately 3% of the Earth's land area and store one-third of the global soil carbon stock, which is twice as much carbon as the entire world's forests (Harenda et al., 2017). Their ability to store carbon helps mitigate the atmospheric concentrations of CO_2, thereby contributing to a net cooling effect on the climate (Yu et al., 2011). However, disturbances, such as fires, resource development, and climatic shifts, can affect the carbon sequestration capabilities of peatlands (Turetsky, 2002).

Human activities in the boreal region have resulted in extensive disturbance to peatland ecosystems. One such disturbance is seismic lines, which are linear clearings in forests and peatlands, and they are primarily created for petroleum exploration. The construction of seismic lines involves the removal of vegetation and the use of heavy machinery, which can compress and compact the soil (Davidson et al., 2020). Seismic line disturbance has been shown to alter environmental conditions and plant community structures (Abib et al., 2019; Dabros et al., 2021; MacFarlane, 2003). It is difficult for vegetation communities to return to the pre-disturbance state once disturbed by seismic lines. Seismic lines have been shown to significantly affect the environmental conditions in peatlands, causing increased bulk density, higher water content, and altered soil nutrient levels (Filicetti, 2021). Many of these changes arise from soil compaction, as compressed soil has a reduced capacity for water infiltration (Nawaz et al., 2012). The organic matter content is often reduced on seismic lines as well due to the shifts in substrate type

(Davidson et al., 2020). Alterations to soil nutrient levels primarily include decreased organic matter content, increased C/N ratio, and changes in isotopic composition ($\delta^{13}C$ and $\delta^{15}N$) (Davidson et al., 2020; Kleinke, 2021). These changes reflect a shift in the balance between total carbon and total nitrogen, potentially driven by microbial dynamics in response to altered oxygen availability (Kleinke, 2021).

The concept of "re-disturbance" in seismic line disturbance refers to the two-stage disruption process. Initially, seismic lines are created by clearing vegetation and flattening soil for petroleum exploration. This first disturbance creates linear clearings in the peatland (Stevenson et al., 2019). The disturbed area is left to naturally regenerate without any active restoration efforts. Then, the re-evaluation of the petroleum deposit or detailed mapping at the time of extraction may result in a second clearing of existing lines. The second clearing, which is the re-disturbance, occurs to minimize the need for creating new lines (van Rensen et al., 2015). This repeated disturbance interrupts the natural regeneration process and resets the ecological succession that had begun after the first disturbance (Bormann et al., 2015). The practice of re-disturbance can lead to compounded ecological impacts, which may include decreased biodiversity or altered nutrient cycling (Kurulok, 2004; He et al., 2022). While it is known that some seismic lines experience re-disturbance, the difference between re-disturbed seismic lines and those that have only been disturbed once remain unclear.

The altered environmental conditions often lead to variation in plant community composition. There are significant differences in plant and lichen species composition between the disturbed and the adjacent undisturbed areas (Dabros et al., 2021; Goud et al., 2024). Specifically, in bogs, disturbed areas tend to have a higher cover of *Sphagnum*, whereas the undisturbed peatlands are richer in lichens, trees, and other bryophytes (Dabros et al., 2021). In

fens, seismic lines often show significantly higher graminoid cover and lower shrub cover compared to the undisturbed areas (Strack et al., 2017). The findings reported in studies vary because plant community composition is also influenced by other factors, such as the continuous use of the line for transportation. Echiverri et al. (2022) reported that seismic lines and natural areas may have comparable bryophyte cover, contrasting with Strack et al. (2017), who observed that bryophyte cover on seismic lines was typically less than half of that in adjacent undisturbed regions. Aside from disturbance, species composition is also influenced by microtopography. The hummocks on seismic lines tend to have a higher shrub and total understory cover compared to the hollows (Echiverri et al., 2020). The alterations in microtopography, along with other effects of disturbance, result in the slow recovery of the vegetation community on seismic lines. As a result, ecological functions do not return to their pre-disturbance state even after 50 years (van Rensen et al., 2015). The slow recovery is particularly evident in boreal peatlands, where seismic lines have been shown to remain in early successional stages for many decades (Dabros et al., 2018).

Plant community composition on seismic lines is likely the result of direct disturbance in combination with the shift in environmental conditions caused by seismic line creation. In peatlands, many factors play critical roles in shaping vegetation gradients, such as microtopography, water table depth, nutrient availability, light availability, EC, and pH (Andersen et al., 2011; Jasieniuk & Johnson, 1982). Water table level plays a pivotal role in determining the plant community composition by influencing the availability of water and oxygen (Dickopp et al., 2018). When water table is close to the surface, peat becomes saturated, creating anoxic (low oxygen) conditions that are ideal for species adapted to wet conditions (Potvin et al., 2014). A lower water table exposes more peat to air, increasing oxygen availability

and supporting species such as *S. fuscum, Betula glandulosa*, and *Picea mariana* (Zhong et al., 2020). Microtopography is another driver of the shift in plant species composition as it affects water distribution and soil characteristics (Pinzon et al., 2022). Hummocks are typically drier compared to their surroundings and support species that can tolerate less water-saturated conditions, such as *S. fuscum*, *T. nitens*, and *P. crista-castrensis* (Pinzon et al., 2022; Echiverri et al., 2020). Hollows are more water-saturated and support plant species that can endure wetter and more anoxic conditions, such as aquatic mosses and sedges (Dabros et al., 2022; Pinzon et al., 2022; Vodopija, 2021).

The pH level determines the types of plants that can survive in the area (Hájková et al., 2006). Acidic conditions favour species such as *C. calyculata* and *Sphagnum spp.* In contrast, neutral and alkaline conditions (pH 6.0-7.9) support a different set of species, such as *L. laricina* and *Salix spp.* (Jeglum, 1971). EC is a measure of conductive ions in concentration, which influences plant community composition by affecting nutrient availability (Weltzin et al., 2003). *Sphagnum spp.,* which are species that contribute the most to peat accumulation, are not adapted to high EC levels (Saberi Riseh et al., 2021). *Sphagnum* is intolerant of saline conditions as it is adapted to low-nutrient and acidic environments. High EC levels, which indicate increased mineral and salt concentrations, can inhibit the growth of *Sphagnum* by creating osmotic stress (Negrão et al., 2016). Thus, any changes in local soil and water chemistry arising from seismic line disturbance potentially will affect plant community composition.

Nutrient gradients, which are influenced by the surrounding geology, land-use, and hydrology, can dictate plant biodiversity in peatlands (Sjögersten et al., 2010). Nitrogen (N) and phosphorus (P) are two of the most important nutrients for plant growth, and the imbalance of these nutrients can significantly affect plant community. Excessive N and P can significantly

change the plant community composition in peatlands, such as reducing diversity and causing a shift from sedge-dominated to grass-dominated ecosystems (van der Hoek et al., 2004; Gao et al., 2022). Other nutrients, such as Ca, K, Fe, S, also play an important role in plant growth as they promote cell wall stability and regulate enzymatic processes (Long & Peng, 2023; Toor et al., 2021). High Ca levels favour species like *Drepanocladus* spp., *Carex* spp., and *Juncus* spp. (Wind-Mulder et al., 1996). K, Fe, and S are important nutrients that affect soil fertility, which indirectly determines which species can establish and thrive in the area (Wind-Mulder et al., 1996).

Light availability plays a crucial role in the growth and distribution of plant species. Seismic lines create openings in forest canopies that increase light penetration (Franklin et al., 2021). The increased light availability generally favours the growth of pioneer species, such as shrubs and sedges (Houlihan et al., 2013). In contrast, species that are adapted to the shade conditions often struggle under increased light conditions (Houlihan et al., 2013). Most of the bryophytes are adapted to lower light conditions and experience reductions in biomass due to the decreased competitive ability under increased light conditions (Bubier et al., 2007). The greater light intensity often enhances the growth of tree seedlings by increasing their growth rate (Franklin et al., 2021; Sevillano et al., 2016). However, the presence of understory vegetation, such as shrubs, complicates the scenario. As shrubs mature and establish a dense understory, they compete more effectively for light and other resources and impend tree seedling growth (Kara et al., 2023).

Seismic lines are known to cause a loss of canopy cover, reduce microtopographic variability (Stevenson et al., 2019), create wetter conditions (Lovitt et al., 2018; Davidson et al., 2020), and alter peat nutrient content (Davidson et al., 2020; Kleinke et al., 2022). As a result,

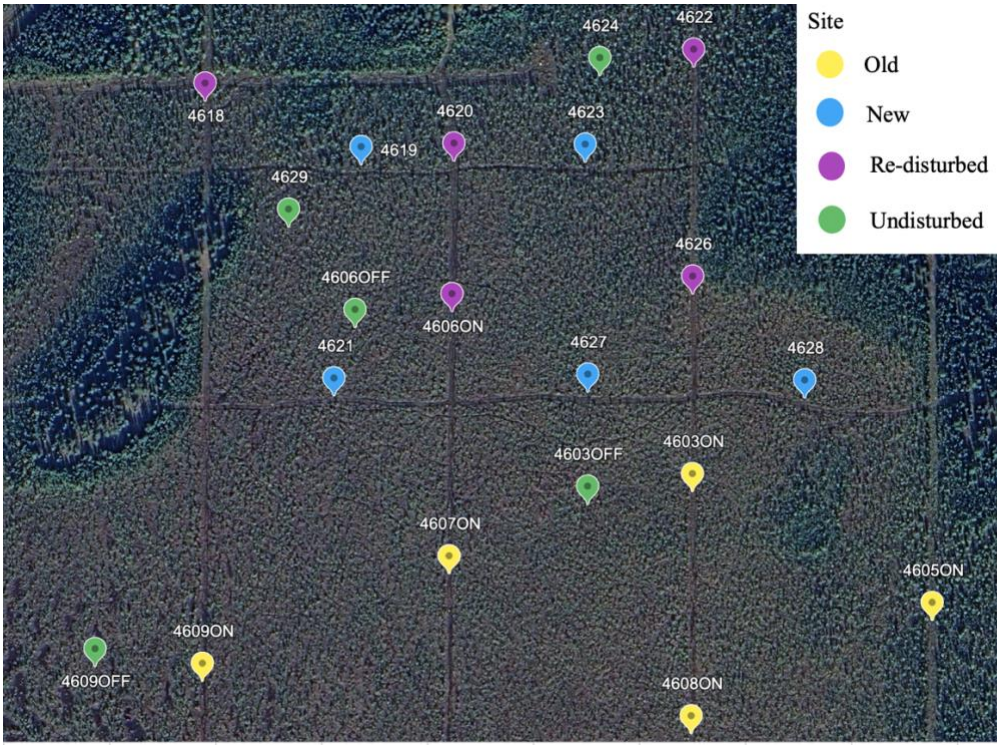
plant community composition likely shifts toward species that thrive in open and wet conditions. However, it remains unclear how environmental conditions on seismic lines change with the disturbance regime (i.e., time since disturbance, re-disturbance impact). Therefore, we conducted a study in a rich fen located in Alberta, Canada, where we examined seismic lines that were initially created as part of exploration activities and have since experienced varying levels of disturbance. These seismic lines were compared to the adjacent undisturbed areas. The different disturbance levels examined were: 1) old sites: disturbed about 30 years ago, 2) new sites: disturbed in winter 2022, which was a few months before the study, 3) re-disturbed sites: disturbed once about 30 years ago and once in winter 2022. The objectives of this study were to: 1) examine the changes in plant community composition following different disturbance histories; 2) examine the differences in species diversity at different disturbance levels; and 3) investigate the environmental variables that drive these changes. We hypothesized that the species composition, species diversity, and environmental conditions of the old sites would be the most similar to the undisturbed sites as they had the longest time to recover. In contrast, the newly disturbed sites would have intermediate recovery levels, and the re-disturbed sites would have the least recovery towards the pre-disturbance state. We also expected that significant differences in species composition, diversity, and environmental conditions would exist among the four disturbance levels, particularly between the undisturbed and more recently disturbed sites. Lastly, we hypothesized that some environmental conditions, such as moisture content, soil P level, and EC, would be more important in driving these changes compared to others, such as soil K level.

2.2 Materials and Methods

2.2.1 Site description

The study took place at the Canadian Natural Resources Limited (CNRL) Kirby South site (55° 21' N, 111° 10' W), located in northeastern Alberta about 40 km south of the hamlet of Conklin. The study site spans approximately 0.13 km² within a rich fen, characterized by sparse tree cover and an average elevation of 690 m (Elevation Finder, 2019). The predominant vegetation includes mosses such as *Sphagnum angustifolium* and *S. fuscum*, shrubs such as *B. glandulosa* and *S. pedicellaris*, and forbs such as *Menyanthes trifoliata*. The plant growing season extends from May to September, with an average temperature of 13.4 °C and average precipitation of 456 mm (Climate and Weather Averages; Climate Data Canada). The fen is intersected by seismic lines averaging 1.5–5 m in width, oriented in north-south, east-west, and diagonal directions. Due to its remoteness and inaccessibility, the area is unlikely disturbed by recreational activities. Four types of study sites were designated (Figure 2.1): 1) undisturbed sites, 2) new sites: disturbed in winter 2022, 3) old sites: disturbed about 30 years ago, and 4) re-disturbed sites: disturbed twice – once about 30 years ago and once in winter 2022. Each site type had five replicates, totaling 20 study sites.

(a)



(b)



Figure 2.1 (a) Site distributions and (b) a site photo with a rich fen in Alberta, Canada. There are 20 study sites in total, and each site type has five replicates. The old sites had seismic lines created about 30 years ago. The new sites had seismic lines established in winter 2022, which is the winter immediately before the study took place. The re-disturbed sites had seismic lines initially established about 30 years ago and then re-disturbed in winter 2022. The undisturbed sites serve as the reference.

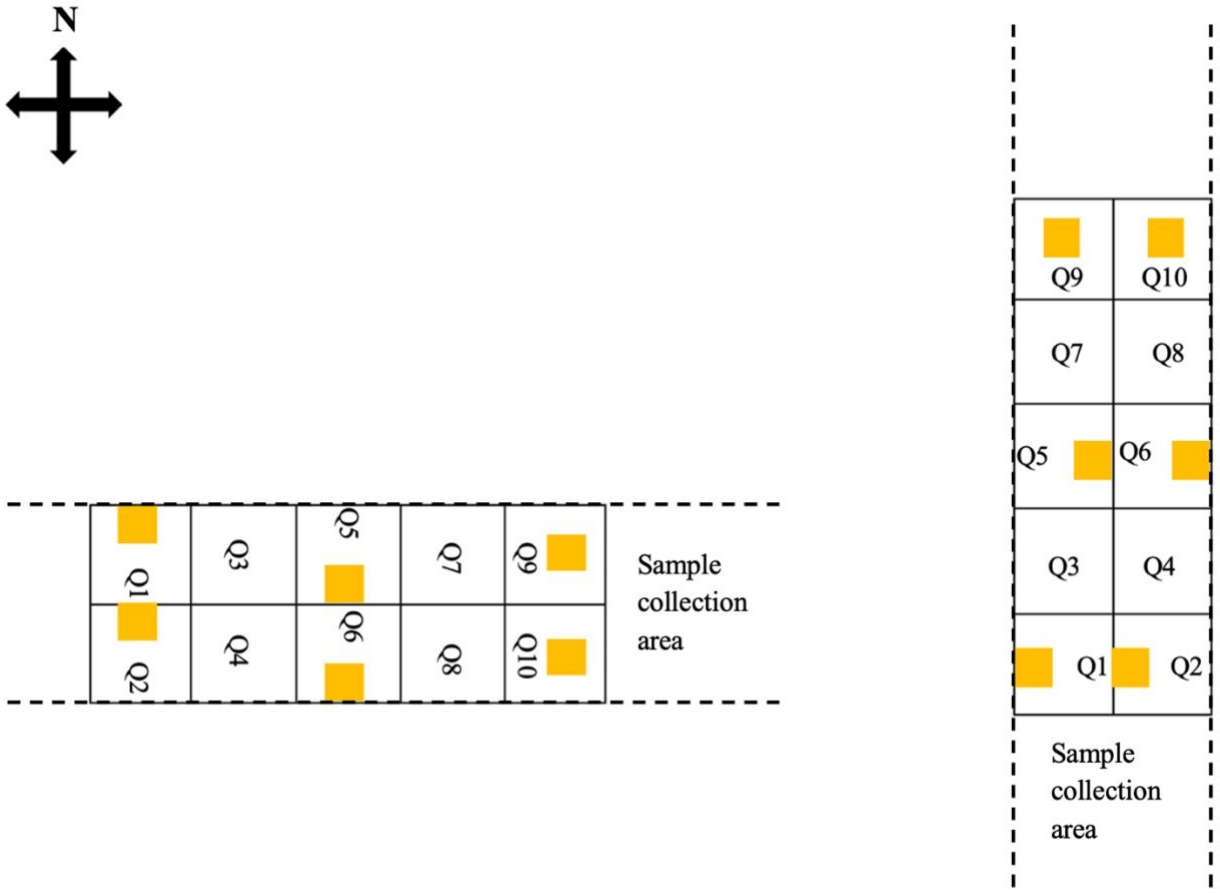


Figure 2.2 The distribution of quadrats (Q) within a study site. The distribution of quadrats is based on the orientation of the seismic line. The orange squares are the sub-quadrats (1 m x 1 m) in which vegetation cover was estimated by species and functional groups. The plant samples were collected outside of the plots, but nearby. The entire plot of 10 quadrats is 100 m^2 in area, spanning the width of the seismic line and varying in length to achieve the required area.

2.2.2 Field data collection

In July and August 2022, we collected data along the seismic lines and in adjacent undisturbed areas, which were 50 m away from the line edge. We established a 100 m^2 plot at each study site, subdivided into 10 quadrats in alignment with the orientation of the seismic lines (Figure 2.2). For north-south (N-S) oriented lines, quadrats were numbered from south to north; for west-east (W-E) lines, from west to east. Quadrats 1, 2, 5, 6, 9, and 10 each included a 1 m x

1 m sub-quadrat positioned at varying locations (left, middle, right) to capture spatial variability within plots.

The study examined 17 frequently encountered species (Table 2.1), which encompass a diverse array including mosses, shrubs, forbs, trees, a horsetail, and a sedge. Preliminary vegetation surveys in 2021 determined that these species are predominant within the study area, representing the full spectrum of the local plant communities. The vegetation surveys were conducted from mid-July to early August 2022, focusing specifically on 1 m x 1 m sub-quadrats to accurately assess vegetation cover within the study area. Visual estimations of vegetation cover were quantified with a precision of 1%. In cases where species cover was less than 1%, a finer resolution of 0.5% was employed to better capture the presence of these species. Consistency in data collection was maintained by having the same observers conduct all the surveys.

The Shannon index was used to calculate the species diversity in each disturbance class.

$$H = -\sum_{i=1}^{S} p_i \log (p_i)$$

p_i represents the proportion of the total count made up of species i, and S is the total number of species (Omayio & Mzungu, 2019). This index considers both the abundance and evenness of the species present in a community. The log base used was e (natural logarithm).

Environmental variables, including pH, EC, bulk density, and depth to water table (DTW), were measured concurrently with the vegetation cover at the sub-quadrat level. We utilized a portable pH/EC/TDS tester (model HI98129, Hanna Instruments, Woonsocket, RI, USA) to determine pH, EC, and temperature at the peat surface of each sub-quadrat. We

extracted water from the near-surface soil by squeezing a small sample of peat when there was no standing water present and used the water to measure those variables. Results from the six measurements per plot were averaged to enhance accuracy. Additionally, we obtained DTW estimates using drones in May and August 2022. In a brief summary, LiDAR and true-colour imagery data were collected using a DJI Matrice 300 RTK drone equipped with DJI Zenmuse L1 and P1 sensors. The LiDAR data were processed to generate a high-resolution digital terrain model (DTM) and canopy height model (CHM) using the *lidR* package (Roussel et al., 2020). Concurrently, the optical imagery was processed into a true colour orthomosaic with Pix4Dmapper, facilitating detailed surface analysis. The DTW was estimated by adapting the water table estimation methods outlined by Rahman et al. (2020), tailored to peatland ecosystems where surface water closely reflects groundwater levels. Additional methodological details can be found in Appendix A.

For bulk density measurements, we collected two soil samples from the top 10 cm of soil, one from a hummock and one from a hollow in each plot, using a standardized 595.8 cm^3 soup can. We considered the top of the moss surface to be the top of the soil. Samples were subsequently dried at 60 °C for 48 hours and weighed to calculate the bulk density. The chemical composition of soil samples was analyzed in the dry peat samples at the Analytical Services Laboratory in Canadian Forest Service. Total carbon and nitrogen content were determined using the Leco 828 Combustion System, with carbon measured via an Infrared Detector and nitrogen quantified through a Thermal Conductivity Detector. Metals were analyzed using an acid digestion protocol combining HNO3 and HCl, facilitated by a Microwave Accelerated Reaction System (MARS), and quantified using an Inductively Coupled Plasma Optical Emission Spectrometer (ICP OES). Additionally, Total Organic Carbon (TOC) was assessed using the

same Leco 828 Combustion system, supplemented by a muffle Furnace for Loss on Ignition (LOI) analysis. Extractable S was determined by extracting with monocalcium phosphate ($CaH_4P_2O_8$) in a 1:10 ratio, with subsequent ICP OES analysis. Easily extractable P was analyzed using the Bray 1 dilute acid fluoride procedure, also followed by ICP OES detection. Available nitrogen in the soil was extracted using a 2 M KCl solution and quantified via Phenate Blue colorimetric detection employing Segmented Flow Analysis.

2.2.3 Statistical analysis

We conducted all analyses using the statistical software R 4.4.0 (R Core Team, 2023), and we used a significance level of $\alpha = 0.05$. We assessed the effects of disturbance levels on the percent cover of each of the 17 target species, as well as on soil properties, such as pH, EC and DTW. The values of environmental variables were log-transformed to ensure they meet the assumptions of ANOVA test. We used the *aov()* function to conduct a one-way Analysis of Variance (ANOVA) to determine the impact of disturbance levels on these variables. Where significant effects were identified, we performed the Tukey's Honest Significant Difference (HSD) test to evaluate differences among disturbance levels. This analysis was completed by using the *agricolae* package (de Mendiburu, 2023), which allowed us to ascertain statistically similar groups while adjusting for multiple comparisons.

We conducted ANOVA analysis to assess the impact of disturbance levels on environmental variables: pH, EC, bulk density, DTW, soil Ca, soil S, soil NO_3, soil NH_4, and soil P. For pH, EC, DTW, and soil properties, we included disturbance level as the main effect to investigate its influence. Then, we conducted the Tukey's HSD tests to pinpoint specific pairs of

groups that differed significantly. We examined the influence of disturbance levels and microtopographic variation on bulk density using a two-way ANOVA, considering both factors and their interaction. Next, we performed Tukey's HSD tests to explore significant differences between combinations of disturbance level and microtopography, without using replicate sites as a random variable.

Similarly, we assessed the effects of disturbance levels on the percent cover of each of the 17 target species using two-way ANOVA tests. Then, we conducted the Tukey's HSD tests to pinpoint specific pairs of groups that differed significantly. We also calculated the species richness and Shannon diversity for each disturbance level. We used the *vegan* package (Oksanen et al., 2024) to calculate the species richness at each disturbance level. We also used the *vegan* package (Oksanen et al., 2024) and the Shannon diversity index to calculate the species diversity at each disturbance level.

To assess the relationship between environmental variables and vegetation cover, we used the *vegan* package (Oksanen et al., 2024) to perform the Canonical Correspondence Analysis (CCA), which did not include the collinearity assessment. In our CCA analysis, we included a comprehensive set of environmental variables, including pH, EC, bulk density, DTW, and soil concentrations of Ca, S, NO3, NH4, and P. Prior to analysis, all environmental variables were logarithmically transformed to address non-linear relationships and reduce the influence of outliers and enhance the suitability of the ecological data for CCA (Zhou et al., 2023). This transformation strategy not only stabilizes variance but allows a more accurate interpretation of the ecological gradients, as suggested by the Hellinger transformation method applied to the vegetation cover data (Ter Braak, 1987).

Table 2.1. The complete list of the species examined in the study. Each species has a unique code that is used in the figures. The scientific names were retrieved from the International Plant Name Index (IPNI, 2024).

Common name	Scientific name	Code	Functional group
Black spruce	*Picea mariana*	Picmar	Conifer tree
Tamarack	*Larix laricina*	Larlar	Conifer tree
Bog birch	*Betula glandulosa*	Betgla	Shrub
Bog willow	*Salix pedicellaris*	Salped	Shrub
Bog rosemary	*Andromeda polifolia*	Andpol	Shrub
Leatherleaf	*Chamaedaphne calyculata*	Chacal	Shrub
Labrador tea	*Rhododendron groenlandicum*	Rhogro	Shrub
Lingonberry	*Vaccinium vitis-idaea*	Vacvit	Shrub
Water sedge	*Carex aquatilis*	Caraqu	Sedge
Swamp horsetail	*Equisetum fluviatile*	Equflu	Horsetail
Three-leaf false Solomon's-seal	*Maianthemum trifolium*	Maitri	Forb
Buckbean	*Menyanthes trifoliata*	Mentri	Forb
Peat moss	*Sphagnum angustifolium*	Sphang	Moss
Rusty peat moss	*Sphagnum fuscum*	Sphfus	Moss
Fen moss	*Sphagnum warnstorfii*	Sphwar	Moss
Ribbed bog moss	*Aulacomnium palustre*	Aulpal	Moss
Golden moss	*Tomentypnum nitens*	Tomnit	Moss

2.3 Results

2.3.1 Environmental variables

Bulk density showed significant variation across disturbance levels ($F_{3, 32} = 3.32$, $p < 0.05$; Table 2.6). The new sites had the highest bulk density (0.04 g/cm³; Table 2.7), which was significantly different from old sites (0.03 g/cm³). The old, re-disturbed and undisturbed sites had the same bulk density value (0.03 g/cm³). The pH values also varied significantly among disturbance levels ($F_{3, 113} = 3.54$, $p < 0.05$; Table 2.6), with old sites having the lowest pH value (6.83, Table 2.7), and new and re-disturbed sites having significantly higher pH values (7.02 and 7.03, respectively). The undisturbed sites had a moderate pH value (6.91; Table 2.7). Similarly, EC showed significant differences across disturbance levels ($F_{3, 113} = 16.12$, $p < 0.001$; Table

2.6). Old sites (66.33 µS/cm; Table 2.7) had the lowest EC value than all other sites. The differences among the new, re-disturbed, and undisturbed sites were minor, with respective EC values of 101.07 µS/cm, 103.11 µS/cm, 88.00 µS/cm (Table 2.7).

DTW in both May and August showed significant variation across disturbance levels (May: $F_{3, 113} = 32.37$, $p < 0.001$; August: $F_{3, 113} = 40.22$, $p < 0.001$; Table 2.6). In both May and August, the DTW levels of all sites were significantly different from each other (Table 2.7). In May, the undisturbed sites had the highest DTW (i.e., driest condition; 0.17 m), followed by old, new, and re-disturbed sites (0.12 m, 0.09 m, 0.06 m, respectively; Table 2.7). Similarly, in August, the undisturbed sites again showed the highest DTW (0.18 m), while new sites had the lowest (0.08 m). The old and re-disturbed sites had intermediate values (0.13 m and 0.08 m, respectively).

2.3.2 Species richness, diversity, and percent cover

Old sites had the greatest species richness, followed by re-disturbed, undisturbed, and new sites (Figure 2.3). The re-disturbed and undisturbed sites had similar species richness levels, but an outlier at the lower end in undisturbed sites resulted in a slight lower richness. In contrast, new sites had the highest species diversity, followed by undisturbed, re-disturbed, and old sites (Figure 2.3). The old and re-disturbed sites had similar species diversity levels, with re-disturbed sites being slightly higher.

The percent cover of all species combined was significantly different across disturbance levels ($F_{3, 3116} = 3.14$, $p < 0.05$; Table 2.2). The undisturbed sites had the highest total cover (116.0%; Table 2.3), followed by old and re-disturbed sites (92.6%, 85.8%, respectively). The

total cover in new sites (81.4%) was the lowest. These vegetation covers represent the sum of species cover of all quadrats and then averaged by disturbance levels.

For individual species, *P. mariana* had the highest cover in undisturbed sites (3.53%), which was significantly higher than all other sites. The old sites had a higher percent cover than new sites, followed by re-disturbed sites (0.85%, 0.23%, and 0.00%, respectively; Table 2.3). Similarly, *L. laricina* had the highest cover in undisturbed sites (2.73%), with lower covers in re-disturbed (0.92%), old (0.53%), and new sites (0.30%). Similar to the trees, *B. glandulosa* had the highest cover in undisturbed sites (12.27%), which was significantly higher than all other sites that had similar cover (Table 2.3).

R. groenlandicum, Andromeda polifolia, and *T. nitens* had the same pattern in vegetation cover across disturbance levels. Each of them had the highest cover in undisturbed sites, which was significantly higher than re-disturbed sites (Table 2.3). In new and old sites, the covers of these species were intermediate and there were no significant differences between each other. Likewise, *Equisetum fluviatile* and *S. angustifolium* showed similar patterns in vegetation cover. Both species had the highest cover in undisturbed sites, which was slightly higher than new sites and significantly higher than old sites (Table 2.3).

M. trifoliata and *Sphagnum warnstorfii* also demonstrated similar patterns. Both species had highest vegetation cover in old sites, followed by re-disturbed, undisturbed, and new sites (Table 2.3). *M. trifoliata* showed similar vegetation cover in re-disturbed and undisturbed sites. Conversely, *S. warnstorfii* had higher cover in re-disturbed sites than undisturbed sites. *A. palustre* had the highest cover in new sites, followed by undisturbed, old, and re-disturbed sites. New sites had significantly higher cover than old and re-disturbed sites, with undisturbed sites having intermediate cover (Table 2.3).

2.3.3 Soil chemical composition

The soil chemical composition was strongly influenced by disturbance levels and microtopography classes. Concentrations of several key chemicals varied significantly between hollows and hummocks (Table 2.8). Specifically, total N and Ca had higher concentrations in hollows compared to hummocks (Table 2.10). Conversely, total C, P, and K showed higher levels in hummocks than hollows. Although total organic carbon (TOC), S, NO3, NH4 did not show statistically significant differences between the microtopography classes (Table 2.8), they were generally more concentrated in hummocks than in hollows (Table 2.10).

Total C and NH4 showed similar patterns, with both having the highest concentration in the more recently disturbed (new and re-disturbed) sites (Table 2.9). They also had the lowest concentrations in undisturbed sites, which were significantly lower than all other sites. K had the highest level in old sites (2054.8 mg/kg) and the lowest in new sites (1410.2 mg/kg). In contrast, total N, TOC, P, Ca, S, NO3, did not show significant differences across disturbance levels. The effects of disturbance levels and microtopography classes generally did not interact significantly, except for total N, which showed a significant interaction ($F_{3, 32} = 3.99$, $p < 0.05$; Table 2.8). The total N level at hollows was significantly higher than hummocks in old, re-disturbed, and undisturbed sites ($F_{32, 32} = 3.99$, $p < 0.05$; Table 2.11), but not significantly lower in new sites.

2.3.4 The relationship between plant community composition and environmental variables across disturbance levels

The CCA results (Figure 2.5) illustrated the interactions between environmental variables and soil chemistry composition in relation to vegetation patterns across disturbance levels. The CCA1 axis, accounting for 44.04% of the variance, predominantly reflected the gradients in bulk

density and soil chemistry. Bulk density, pH, EC, soil NO3, and soil NH4 showed a significant influence on the distribution and composition of the plant community, as evidenced by their long vectors on the right side of the plot (Figure 2.5). Conversely, soil S, soil P, and soil Ca demonstrated less pronounced effects, indicated by their shorter vectors. The spatial distribution of study sites shows that the new, re-disturbed, and undisturbed sites are predominantly located on the right side of the plot, whereas most of the old sites are positioned on the left side (Figure 2.5). This suggests that the new, re-disturbed, and undisturbed sites have a positive relationship with the influential variables, while the old sites have a negative relationship.

The CCA2 axis explains 28.44% of the variance (Figure 2.5) and reveals a significant influence from DTW May and DTW August. The DTW consistently affected plant community, despite seasonal variation. On the other hand, soil K had a minimal influence on plant community composition due to its short vector on the plot. Notably, no distinct clusters of study sites are formed, suggesting that the plant community composition is more influenced by the local environment rather than the disturbance levels.

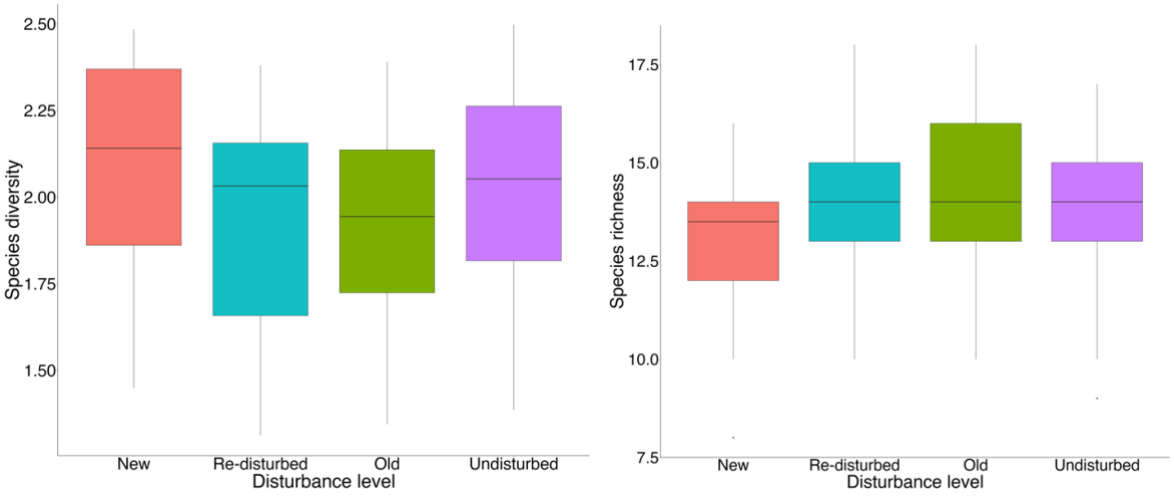


Figure 2.3 Boxplot showing the species diversity and richness across disturbance levels in a rich fen in Alberta, Canada.

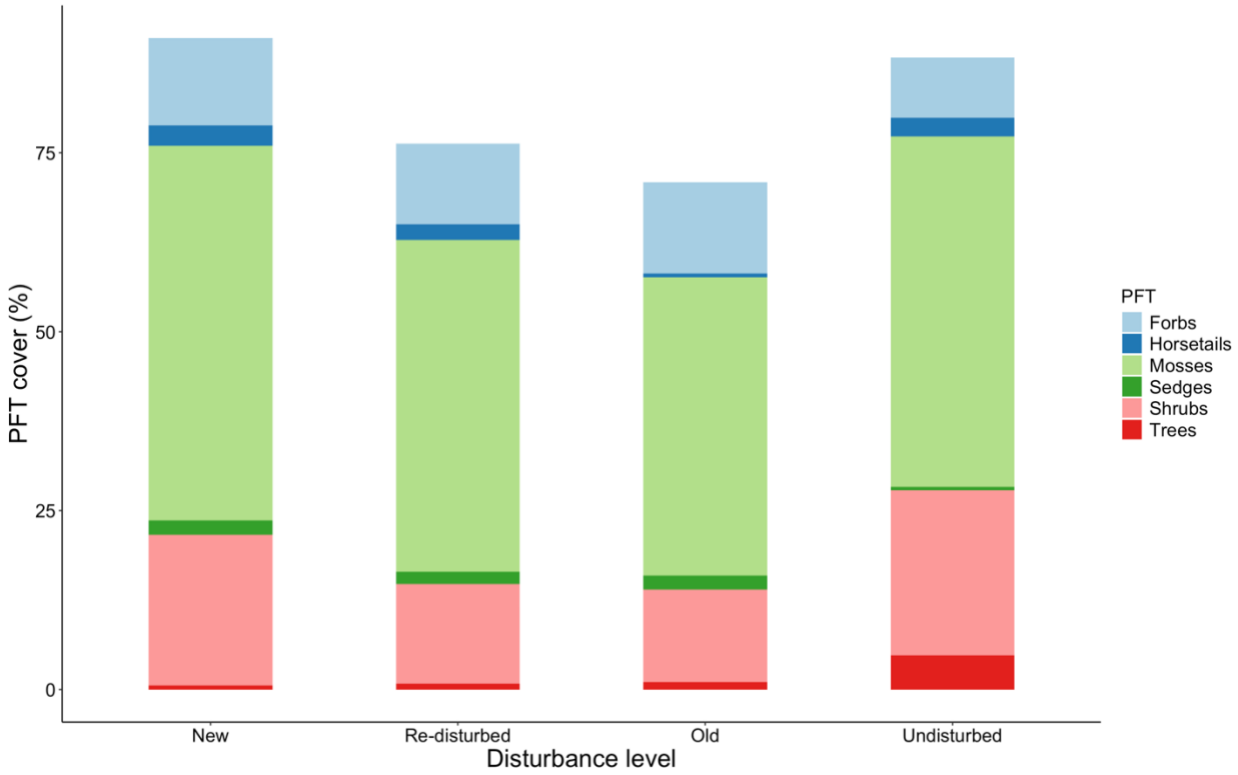


Figure 2.4 Stacked bar graph showing the species composition of each plant functional type (PFT) across disturbance levels in a rich fen in Alberta, Canada.

Table 2.2 ANOVA results of the vegetation cover (%) of 17 dominant species across disturbance levels in a rich fen in Alberta, Canada.

Species	df	SS	F	P
All species	3	47678	3.14	**0.029** *
Picmar	3	238.00	5.07	**0.002** **
Larlar	3	109.80	3.43	**0.020** *
Salped	3	112.80	2.49	0.064
Betgla	3	943.00	5.66	**0.001** **
Vacvit	3	3.69	1.49	0.220
Rhogro	3	32.20	3.22	**0.026** *
Chacal	3	27.50	0.63	0.596
Andpol	3	262.30	3.59	**0.016** *
Caraqu	3	65.70	2.67	0.051
Equflu	3	120.70	3.02	**0.033** *
Mentri	3	505.00	2.89	**0.039** *
Maitri	3	31.00	0.68	0.568
Aulpal	3	665.00	4.24	**0.007** **
Tomnit	3	541.00	3.76	**0.013** *
Sphang	3	6516.00	4.82	**0.003** **
Sphfus	3	318.00	1.11	0.350
Sphwar	3	12955.00	5.24	**0.002** **

Table 2.3 The vegetation cover (%) of 17 dominant species across disturbance levels in a rich fen in Alberta, Canada. Listed values represent the mean, with standard errors in brackets. Group letters denote Tukey's HSD test results where disturbance levels have significantly different covers if they do not share a letter.

Species	New	Re-disturbed	Old	Undisturbed
All species	**81.4 (5.17) b**	**85.8 (6.34) a**	**92.6 (6.99) ab**	**116.0 (5.63) ab**
Picmar	**0.23 (0.15) b**	**0 (0) b**	**0.85 (0.83) b**	**3.53 (1.17) a**
Larlar	**0.3 (0.17) b**	**0.92 (0.32) ab**	**0.53 (0.36) b**	**2.73 (1.08) a**
Salped	5.33 (0.71) a	4.33 a	3.47 a	6.02 a
Betgla	**6.2 (0.83) b**	**5.33 (0.85) b**	**5.97 (1.92) b**	**12.27 (1.52) a**
Vacvit	0.33 (0.18) a	0 (0) a	0 (0) a	0.37 (0.28) a
Rhogro	**0.45 (0.18) ab**	**0.17 (0.11) b**	**0.27 (0.19) ab**	**1.47 (0.6) a**
Chacal	0.7 (0.53) a	1.5 (0.57) a	0.73 (0.3) a	1.8 (1.11) a
Andpol	**5.78 (0.94) ab**	**4.32 (0.6) b**	**6.4 (0.71) ab**	**8.43 (1.23) a**
Caraqu	**1.78 (0.37) ab**	**1.95 (0.62) ab**	**2.62 (0.73) a**	**0.57 (0.18) b**
Equflu	**2.57 (0.6) ab**	**2.52 (0.4) ab**	**0.72 (0.22) b**	**3.48 (1.1) a**
Mentri	**8.15 (1.23) b**	**10.77 (1.27) ab**	**13.47 (1.78) a**	**8.9 (1.21) ab**
Maitri	2.75 (0.9) a	1.88 (0.46) a	3.17 (0.86) a	2.12 (0.51) a
Aulpal	**9.32 (1.98) a**	**3.17 (0.74) b**	**4.2 (1.35) b**	**4.77 (0.81) ab**
Tomnit	**3.58 (1.27) ab**	**0.92 (0.38) b**	**2.03 (0.45) b**	**6.57 (2.11) a**
Sphang	**16.53 (3.29) ab**	**11.83 (3.56) b**	**8.53 (2.54) b**	**28 (5.49) a**
Sphfus	4.67 (3) a	0.37 (0.27) a	1.6 (0.62) a	3.23 (1.81) a
Sphwar	**12.7 (3.56) b**	**35.87 (6.79) a**	**38.03 (5.11) a**	**21.8 (4.99) ab**

Table 2.4 ANOVA results of the vegetation cover (%) of major PFTs across disturbance levels in a rich fen in Alberta, Canada.

PFT	df	SS	F	P
Trees	3	324.10	8.28	**< 0.0001 *****
Shrubs	3	619.00	9.03	**< 0.0001 *****
Horsetails	3	60.60	2.47	0.062
Forbs	3	194.00	1.58	0.193
Sedges	3	65.7	2.67	0.051
Mosses	3	777.00	0.73	0.534

Table 2.5 The vegetation cover (%) of major PFTs across disturbance levels in a rich fen in Alberta, Canada. Listed values represent the mean, with standard errors in brackets. Group letters denote Tukey's HSD test results where the covers of PFTs are significantly different if they do not share a letter.

PFT	New	Re-disturbed	Old	Undisturbed
Trees	**0.60 (0.04) b**	**0.81 (0.09) b**	**1.06 (0.12) b**	**4.77 (0.33) a**
Shrubs	**21.03 (0.14) b**	**13.91 (0.39) b**	**12.89 (0.42) b**	**23.09 (0.74) a**
Horsetails	**2.87 (0.30) ab**	**2.24 (0.13) ab**	**0.55 (0.05) b**	**2.65 (0.40) a**
Forbs	12.19 (0.41) a	11.24 (0.31) a	12.73 (0.45) a	8.38 (0.28) a
Sedges	2.99 (0.12) a	1.73 (0.10) a	2.00 (0.12) a	0.43 (0.02) a
Mosses	52.36 (2.58) a	46.34 (2.36) a	41.65 (0.75) a	48.98 (1.31) a

Table 2.6 ANOVA results of environmental variables across disturbance levels in a rich fen in Alberta, Canada.

Environmental variable	Model	df	SS	F	P
Bulk density (g/cm^3)	Microtopography	1	0.05	0.71	0.405
	Disturbance level	3	0.64	3.32	**0.035 ***
	Interaction	3	0.06	0.32	0.810
pH	**Disturbance level**	3	0.02	3.54	**0.019 ***
EC (µS/cm)	**Disturbance level**	3	3.65	16.12	**< 0.001 *****
DTW in May (m)	**Disturbance level**	3	24.36	32.37	**< 0.001 *****
DTW in August (m)	**Disturbance level**	3	18.32	40.22	**< 0.001 *****

Table 2.7 Environmental variables across disturbance levels in a rich fen in Alberta, Canada. Listed values represent the mean, with standard errors in brackets. Group letters denote Tukey's HSD test results where environmental variables are significantly different if they do not share a letter.

Environmental variable	New	Re-disturbed	Old	Undisturbed
Bulk density (g/cm^3)	**0.04 (0) a**	**0.03 (0) ab**	**0.03 (0) b**	**0.03 (0) ab**
pH	**7.02 (0.04) a**	**7.03 (0.06) ab**	**6.81 (0.04) a**	**6.91 (0.08) b**
EC (µS/cm)	**101.07 (2.55) a**	**103.11 (6.87) b**	**66.33 (2.84) ab**	**88 (5.1) c**
DTW in May (m)	**0.09 (0) a**	**0.06 (0.01) b**	**0.12 (0.01) b**	**0.17 (0.01) c**
DTW in August (m)	**0.08 (0) a**	**0.08 (0.01) c**	**0.13 (0.01) b**	**0.18 (0.01) c**

Table 2.8 ANOVA results of Soil chemical composition across disturbance levels in a rich fen in Alberta, Canada.

Soil chemical	Model	df	SS	F	P
Total N (%)	**Microtopography**	1	0.47	18.82	**< 0.001** ***
	Disturbance level	3	0.10	1.38	0.265
	Interaction	3	0.30	3.99	**0.016** *
Total C (%)	**Microtopography**	1	0.01	11.13	**0.002** **
	Disturbance level	3	0.01	6.05	**0.002** **
	Interaction	3	0.00	0.04	0.989
TOC (%)	Microtopography	1	0.08	1.51	0.228
	Disturbance level	3	0.30	1.81	0.166
	Interaction	3	0.06	0.37	0.776
P (mg/kg)	**Microtopography**	1	1.33	14.96	**< 0.001** ***
	Disturbance level	3	0.10	0.37	0.774
	Interaction	3	0.15	0.58	0.634
K (mg/kg)	**Microtopography**	1	1.65	14.72	**< 0.001** ***
	Disturbance level	3	1.15	3.42	**0.029** *
	Interaction	3	0.50	1.48	0.238
Ca (mg/kg)	**Microtopography**	1	1.82	24.02	**< 0.001** ***
	Disturbance level	3	0.52	2.31	0.095
	Interaction	3	0.23	1.04	0.390
S (mg/kg)	Microtopography	1	0.05	0.51	0.478
	Disturbance level	3	0.38	1.32	0.285
	Interaction	3	0.27	0.96	0.423
NO3 (mg/kg)	Microtopography	1	0.09	0.09	0.767
	Disturbance level	3	0.23	0.08	0.971
	Interaction	3	0.66	0.23	0.877
NH4 (mg/kg)	Microtopography	1	0.19	3.01	0.092
	Disturbance level	3	2.09	10.79	**< 0.001** ***
	Interaction	3	0.54	2.77	0.057

Table 2.9 Soil chemical composition across disturbance levels in a rich fen in Alberta, Canada. Chemical levels were analyzed using log transformation to meet ANOVA assumptions. Listed values represent the mean of the actual data, with standard errors of transformed data in brackets. Group letters denote Tukey's HSD test results where chemical levels are significantly different if they do not share a letter.

Soil chemical	New	Re-disturbed	Old	Undisturbed
Total N (%)	1.02 (0.05) a	0.98 (0.09) a	0.97 (0.05) a	0.89 (0.05) a
Total C (%)	**43.45 (0.33) a**	**41.52 (0.38) a**	**42.94 (0.36) a**	**42.9 (0.41) b**
TOC (%)	**30.54 (2.03) a**	**26.35 (2.31) a**	**28.62 (1.86) a**	**32.41 (1.45) b**
P (mg/kg)	263.3 (30.81) a	251 (31.89) a	230.1 (20.35) a	226.3 (20.97) a
K (mg/kg)	**1410.2 (234.32) b**	**1890.3 (278.7) ab**	**2054.8 (193.58) a**	**1878.5 (165.21) ab**
Ca (mg/kg)	12351.2 (821.48) a	12468.4 (841.42) a	10802.6 (1202.59) a	10128.5 (1096.39) a
S (mg/kg)	81.2 (5.61) a	104.99 (11.44) a	94.72 (10) a	80.45 (5.44) a
NO3 (mg/kg)	30.65 (10.86) a	30.21 (7.84) a	21.64 (6.05) a	27.35 (8.5) a
NH4 (mg/kg)	**666.18 (26.08) a**	**765.07 (58.05) a**	**424.66 (43.55) a**	**590.61 (62.54) b**

Table 2.10 Soil chemical composition between microtopography classes in a rich fen in Alberta, Canada. Chemical levels were analyzed using log transformation to meet ANOVA assumptions. Listed values represent the mean of actual data, with standard errors of transformed data in brackets. Group letters denote Tukey's HSD test results where chemical levels are significantly different if they do not share a letter.

Soil chemical	Hummock	Hollow
Total N (%)	**0.87 (0.04) b**	**1.06 (0.03) a**
Total C (%)	**43.26 (0.25) a**	**42.14 (0.3) b**
TOC (%)	30.64 (1.29) a	28.32 (1.51) a
P (mg/kg)	**286 (17.89) a**	**199.35 (13.21) b**
K (mg/kg)	**2136.35 (145.35) a**	**1480.55 (142.73) b**
Ca (mg/kg)	**9348.5 (690.35) b**	**13526.85 (352.63) a**
S (mg/kg)	91.92 (5.15) a	88.76 (7.3) a
NO3 (mg/kg)	27.85 (6.31) a	27.38 (5.66) a
NH4 (mg/kg)	642.58 (38.15) a	580.68 (49.07) a

Table 2.11 The interactions of total N level between disturbance levels and microtopography classes in a rich fen in Alberta, Canada.

Treatment	Microtopography	Mean (%)	df	SS	F value	p value
New	Hollow	0.997	32	0.3	3.99	0.762
	Hummock	1.0458				
Old	Hollow	1.078	32	0.3	3.99	**0.035 ***
	Hummock	0.8604				
Re-disturbed	Hollow	1.2016	32	0.3	3.99	**< 0.001 *****
	Hummock	0.7538				
Undisturbed	Hollow	0.9808	32	0.3	3.99	**0.036 ***
	Hummock	0.8078				

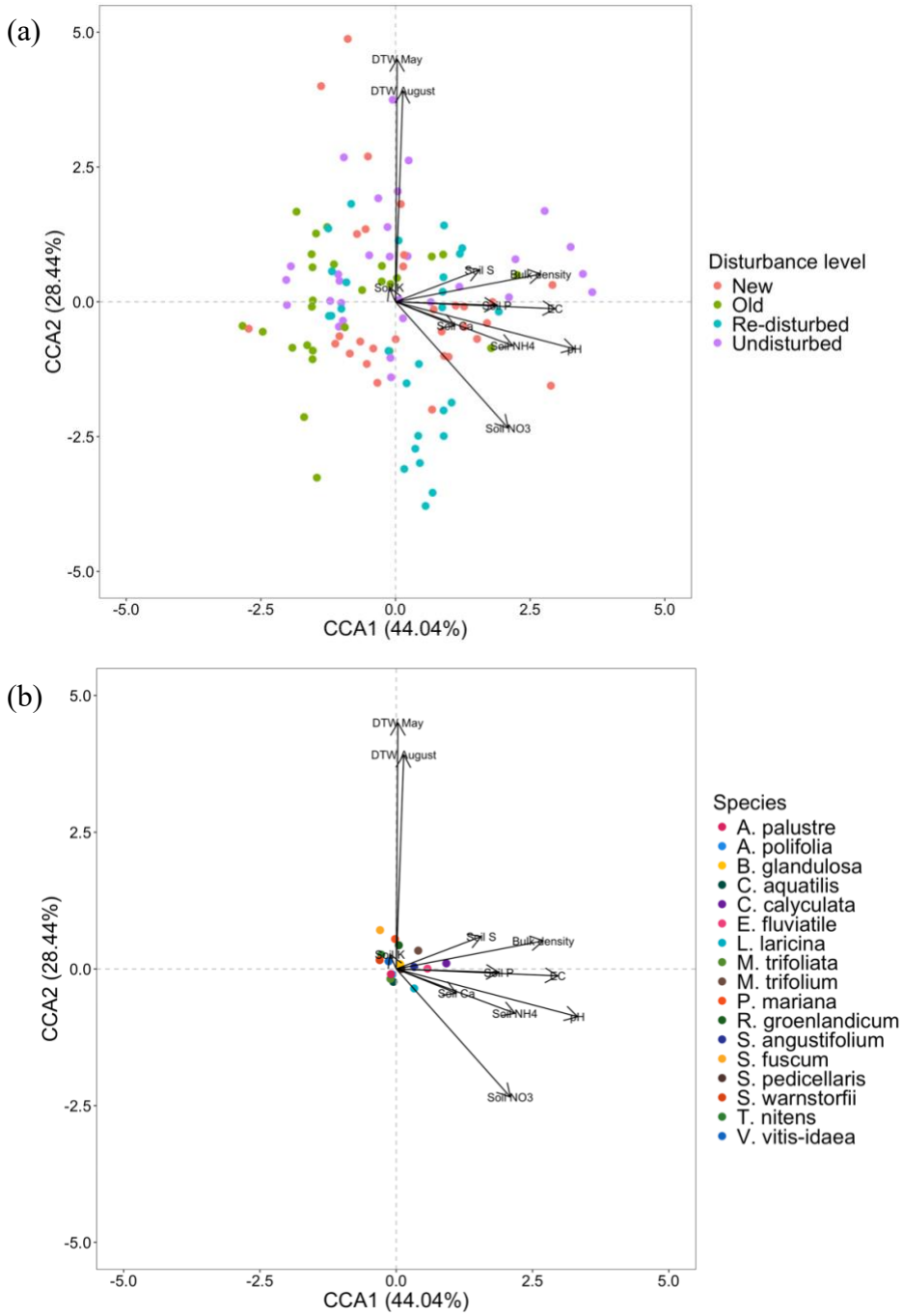


Figure 2.5 CCA results showing the relationships between environmental variables and plant composition across (a) disturbance levels and (b) species. The disturbance levels are categorized as follows: 1) new: areas disturbed in winter 2022, 2) old: areas disturbed about 30 years ago, 3) re-disturbed: areas initially disturbed about 30 years ago with additional disturbance in winter 2022, and 4) undisturbed: areas never disturbed. The species in (b) are the 17 target species in this study, and their full names can be found in List of Species Abbreviations. Key environmental variables shown include bulk density, pH, EC, DTW, soil NO3, soil NH4, soil S, soil P, and soil Ca, with their influence on plant distributions indicated by vector lengths. DTW was measured twice, in May and August 2022.

2.4. Discussion

2.4.1 Plant community composition changes

Species diversity and richness were significantly influenced by seismic line disturbance. The results in this study showed that older seismic lines had the highest species richness, and more recent sites had the highest species diversity (Figure 2.3). This suggests that seismic line disturbance can potentially increase ecosystem diversity. However, in other studies, seismic lines often show a decrease in diversity and richness when comped to the adjacent undisturbed areas (Dabros et al., 2021; Dabros et al., 2018). The increase in species diversity in this study may be explained by the intermediate disturbance hypothesis (IDH), which suggests that biodiversity in boreal regions peaks at intermediate levels of human disturbance (Mayor et al., 2012). Such disturbance can create a habitat mosaic, which supports a wider variety of species and thus increases the overall diversity (Mayor et al., 2012).

We observed that certain species, such as *C. aquatilis*, *M. trifoliata*, and *S. warnstorfii,* increased cover on seismic lines. *C. aquatilis* was more abundant in all three types of seismic lines, indicating a post-disturbance shift towards graminoids and other herbaceous plants. This shift is likely due to the seismic line disturbance creating environments where species with plastic traits, such as tolerance to moisture and high light availability, become dominant (Dabros et al., 2021; Dabros et al., 2018). Forbs like *M. trifoliata* was more abundant in disturbed sites due to the favourable light availability (Finnegan et al., 2018). However, some studies showed the opposite observations. A study conducted in arctic regions of western Canada observed a decrease in forbs cover on seismic lines (Kemper & Macdonald, 2009). It suggested that the mechanical damage from seismic line construction, such as compressed soil, disrupted organic

layer, and potential changes to permafrost layer, can adversely affect forbs survival and growth (Kemper & Macdonald, 2009).

Moss species had contrasting responses to seismic line disturbance. *A. palustre* and *S. warnstorfii* had the highest cover in new and old sites, respectively, whereas *T. nitens* and *S. angustifolium* had the highest cover in undisturbed sites (Table 2.3). Similar to *M. trifoliata*, some mosses, such as *A. palustre* and *S. warnstorfii***,** benefited from the altered conditions on seismic lines. *A. palustre* is a pioneer species in peatlands and known for its high tolerance to moist conditions (Felix & Raynolds, 1989). The construction of seismic lines usually results in a wetter condition, which is favourable for *A. palustre* but stressful for other moss species (Echiverri, 2021). In addition, *A. palustre* can quickly colonize and grow in disturbed areas, which allows it to take advantage of reduced competition from other plants (Li & Vitt, 1995). Some studies suggested that some moss species, such as *Sphagnum spp. and T. nitens*, are sensitive to disturbances, and their cover is typically lower in disturbed sites (Echiverri et al., 2022; Felix & Raynolds, 1989). Seismic line disturbance often alters the microtopography and hydrology of the ecosystem (Stevenson et al., 2019), which typically results in less optimal conditions for moss growth (Echiverri et al., 2022). However, contrasting responses were reported in different studies. Dabros et al. (2021) suggested that seismic lines in bogs have shallower water table and higher soil moisture during the growing season, which is favourable for *Sphagnum spp.*, but not for other bryophytes. In contrast, some studies reported that the depressed microtopography on seismic lines negatively influences the development of hummock-forming *Sphagnum* mosses (Caners & Lieffers, 2014; van Rensen et al., 2015). Overall, it is commonly accepted that *Sphagnum* mosses have different responses than other bryophytes, but their responses can vary based on numerous factors.

In contrast to forbs and graminoids, trees and shrubs generally had lower covers on seismic lines. *P. mariana* and *L. laricina* both had significantly lower covers on seismic lines due to the increased shading and competitive exclusion by fast-growing herbaceous plants (Davidson et al., 2020). Similarly, shrubs such as *B. glandulosa, R. groenlandicum*, and *A. polifolia* showed lower covers in all three disturbed sites. Woody species, including shrubs, were less abundant in areas with increased soil compaction (Echiverri et al., 2020; Jackson et al., 2023). Compared to herbaceous species, they grow more slowly due to the energy required to build woody tissues, so it takes longer to achieve a high cover after disturbances. Likewise, *E. fluviatile*, a horsetail, had a lower cover in all three disturbed sites. The removal of vegetation during seismic line construction can change the thermal dynamics of the soil surface (Dabros et al., 2018). In winter, the absence of insulating snow and vegetation can lead to deeper soil freezing. In summer, the darker exposed soil may heat up more than usual, affecting the root systems of horsetails (Kemper, 2005). Additionally, vegetation removal leaves the remaining plants more exposed to natural forces like wind, rain, and temperature extremes. This can lead to increased erosion, which can strip away the nutrient-rich topsoil essential for horsetails (Kemper, 2005). However, some studies suggest that horsetails are resilient and can adapt to disturbed environments on seismic lines (Filicetti & Nielsen, 2022). Horsetails generally thrive in wet conditions, and the changes to soil moisture dynamics induced by seismic lines can create favourable conditions for them. In areas where seismic lines disrupt the canopy cover, horsetails can also benefit from the increased light availability (Filicetti & Nielsen, 2022).

2.4.2 The relationship between environmental variables and changes in plant community composition

The CCA analysis was used to examine how environmental variables influenced plant community composition. The first axis accounted for approximately 44% of the variance and was strongly associated with bulk density, pH, EC, and soil NH4, suggesting that these factors are key drivers of plant community composition in both undisturbed and disturbed sites. Bulk density was the highest in new sites (Table 2.7), indicating an increased soil compaction following the disturbance. Compacted soils tend to have reduced oxygen levels, which slows the decomposition of organic matter and the release of nutrients from organic forms (Vodopija, 2021). This decrease in nutrient availability favours resilient species, leading to changes in plant community composition.

The pH levels in disturbed sites varied, with new and re-disturbed sites being more basic and old sites more acidic (Table 2.7). pH significantly influences plant community composition by affecting the solubility of micronutrients, such as Fe and Mn (Hussain, 2021; Seth et al., 2018). Although EC varied among disturbance types, the mean EC varied from only 66 to 103 µS/cm (Table 2.7). This EC range is typically associated with rich fens (Heidel et al., 2017). The narrow range of EC values suggests that EC itself may not be a strong differentiating factor for plant community compositions across disturbance categories. Instead, it may be driving major compositional gradients in combination with other factors such as pH and nutrient availability.

Unlike other environmental variables, soil NH4 levels were significantly higher in all disturbed sites compared to undisturbed sites (Table 2.9). NH4 is essential for plant growth and serves as a direct nutrient source in nutrient-poor peatlands. NH4 can promote the growth of certain plant species that can efficiently utilize it under anaerobic conditions (Lemmer, 2022).

However, a sudden increase in NH4 can be detrimental to certain species, such as *P. mariana, L. laricina*, and *C. calyculata*. NH4 in soil can lead to acidification when absorbed by plants, releasing hydrogen (H) ions into the soil (Ramnarine, 2018). This change in pH affects nutrient solubility and availability, potentially harming sensitive species and altering microbial communities (Ramnarine, 2018).

The second axis of the CCA, accounting for about 28% of the variance in plant community composition, was strongly associated with the DTW in May and August. The DTW was significantly lower in re-disturbed sites in both months, indicating wetter conditions, which influence the plant community composition (Table 2.7). High water levels, indicated by low DTW, create waterlogged conditions that are favourable for species like *Sphagnum* mosses and low ericaceous shrubs (Dabros et al., 2022). This is partially supported by the vegetation cover results, where *S. warnstorfii* had the highest cover in old sites (Table 2.3). In the CCA plot, the newly disturbed sites were primarily associated with lower DTW, suggesting that these sites tend to be wetter (Figure 2.5). Species such as *S. warnstorfii*, *C. aquatilis*, and *S. angustifolium* are found near the wetter areas, which aligns with their ecological preferences for wetter conditions (Hartsock et al., 2021). Conversely, higher DTW indicates drier soil conditions, which support species such as *P. mariana* and *L. laricina* (van Rensen et al., 2015). This trend is supported by the vegetation cover results showing that *P. mariana* and *L. laricina* had the highest cover in undisturbed sites, which are generally drier (Table 2.5). The distribution of these species in the CCA plot is consistent with these observations, with *P. mariana* positioned away from the wetter areas (Figure 2.5).

The importance of DTW in structuring plant community composition is further emphasized in recent studies. Echiverri & Macdonald (2019) reported that DTW is a significant

predictor of understory vegetation patterns in boreal forests, influencing species diversity, abundance, and composition. Similarly, Goulsbra (2011) showed that DTW is a critical factor in distinguishing between different peatland types and understanding vegetation dynamics, with wet conditions favouring hydrophilic species and drier conditions supporting different plant communities. These findings reinforce the observed relationships in this study, highlighting DTW as a key environmental variable driving plant community composition in peatland ecosystems.

Although over 70% of the variation in plant community composition was described by the variables included in the CCA, there was no clear clustering of plots in relation to disturbance level (Figure 2.5). This suggests that local environmental conditions play a more significant role in shaping the observed understory plant community than the seismic line disturbance. Some studies had similar findings. Elo et al., (2016) explored the effects of anthropogenic disturbance and productivity on community composition and dispersion in boreal peatlands. The findings indicate that while disturbances, such as drainage, cause changes in community composition, these changes are primarily driven by local environmental conditions, such as altered hydrology, pH, and nutrient gradients (Elo et al., 2016). Similarly, Mitchell et al., (2017) assessed the relative importance of abiotic, biotic, and disturbance events on plant community structure in the sagebrush steppe. They found that the local environmental conditions, such as moisture availability, were more influential in determining plant community composition than disturbances like grazing or fire (Mitchell et al., 2017). Notably, we did not include assessment of the overstory cover here, which varies greatly between disturbed and undisturbed plots. The inclusion of which could potentially lead to clearer clustering of undisturbed plots.

2.4.3 Implications for the post-disturbance management

Overall, all disturbed sites showed significant differences from undisturbed sites in understory plant community composition and environmental variables. Species diversity and richness were higher in new and old sites, which might initially seem positive. However, this increase indicates a shift away from the pre-disturbance state, which is not beneficial for the recovery towards the pre-disturbance conditions.

The variation observed in undisturbed areas and the overlap with disturbance levels suggest that the seismic line disturbance altered the ecosystem by increasing the proportion of wet habitats. This shift has made the plant community in these areas more similar to the hollows in undisturbed sites. To achieve a balance of conditions that mirrors the natural ecosystems, it is necessary to explore restoration techniques that encourage the development of drier microsites, such as mounding (Pinzon et al., 2022). Implementing such treatment could help guide the recovery process toward more typical pre-disturbance state.

2.5 Conclusion

The results of this study highlight that seismic line disturbances have caused notable shifts in both environmental conditions and plant community structures in peatlands. Although these disturbances have caused lasting changes, our findings indicate that plant communities can adapt to varying disturbance histories. Old sites show a tendency toward recovery in both environmental conditions and species composition, indicating that, given sufficient time, peatland ecosystems can gradually return to a state that is similar to the pre-disturbance state.

The results also suggest that natural regeneration processes are at play, where certain species and functional groups can adapt to altered environmental conditions over time. The high species diversity in new sites, alongside the decrease in tree percentage, suggests that early successional species, such as *C. aquatilis* and *E. fluviatile*, grow better in these areas immediately after disturbance. While overall diversity increased, tree species, which are crucial for long-term ecosystem stability and structure, are slower to recover and may need more time or favorable conditions to re-establish. Our results imply that environmental conditions, such as pH, bulk density, and moisture content, continue to play a significant role in structuring plant communities on seismic lines. However, rather than viewing these changes as purely negative, they can be interpreted as part of responses that allows certain species to establish and thrive in these disturbed areas. Thus, while seismic lines cause persistent environmental changes, the plant responses suggest that over time, these ecosystems may approach a new equilibrium, which balances the demands of altered conditions with the inherent resilience of peatland species.

Future restoration efforts could benefit from leveraging the natural responses observed in old sites, supporting species and functional traits that enhance recovery, and promoting a long-term succession pathway toward ecosystem resilience. Although active restoration may be required in more severely affected areas, the evidence from this study suggests that natural recovery processes, if given time, can contribute a lot to the restoration of peatland ecosystems.

Chapter 3 Impact of seismic line disturbance in peatlands on plant functional traits

3.1 Introduction

Peatlands, a form of wetland, contain organic carbon-rich layers that have accumulated over millennia (Loisel & Gallego-Sala, 2022). They play a vital role in combating climate change (Leng et al., 2019), safeguarding biodiversity (Maltby & Acreman, 2011), reducing flood risks (Dadson et al., 2017), and securing clean drinking water (Laudon & Hasselquist, 2023). Peatland ecosystems are the largest natural terrestrial organic carbon reservoirs, storing more carbon than all forests combined (Beaulne et al., 2021). Peatlands have historically helped cool the Earth over thousands of years (Frolking & Roulet, 2007). It is expected that if left undisturbed, they will keep absorbing carbon despite yearly fluctuations in their individual performance (Müller & Joos, 2021; Qiu et al., 2020). However, the carbon sequestration in peatlands is significantly influenced by disturbances like fires, resource extraction, and changes in climate (Turetsky, 2002).

Human activities have greatly disrupted peatland ecosystems in boreal regions, with seismic lines being a notable example (Strack et al., 2019). Primarily created for oil and gas exploration, seismic line construction involves the removal of vegetation and the use of heavy machinery to clear narrow corridors for geological testing (Dabros et al., 2018). This process not only changes the environmental conditions but significantly alters the vegetation community within these sensitive ecosystems (Abib et al., 2019; Dabros et al., 2021; MacFarlane, 2003). The construction and maintenance of seismic lines slow down the natural regrowth of woody plants, particularly in bogs and fens (van Rensen et al., 2015). Moreover, the physical disturbance results in soil compaction and altered soil moisture (Davidson et al., 2020), prompting variation in plant traits as the native flora adjusts to the new environmental pressures. Beyond the

immediate physical impacts, the seismic lines disrupt the peatland habitat continuity, exacerbating hydrological alterations, increasing erosion, and facilitating the invasion of non-native species (Dabros et al., 2021; Povoroznyuk et al., 2022). The altered hydrology and increased soil exposure are particularly detrimental in peatlands, as they are crucial for carbon storage. As critical carbon sinks, the disruption of peatlands by seismic lines poses significant risks to their carbon sequestration capabilities, potentially releasing stored carbon back into the atmosphere and contributing to greenhouse gas (GHG) emissions (Strack et al., 2019). Understanding these extensive impacts is crucial for developing effective mitigation and restoration strategies that aim to preserve the ecological integrity and carbon storage functions of peatlands. To effectively address these challenges, it is crucial to explore not only the shifts in species composition on seismic lines but whether environmental changes lead to trait variation within species. Thus, my study aims to determine if these altered environmental conditions influence trait variation within individual species, providing deeper insights into the resilience mechanisms of peatlands.

Plant functional traits are the morpho-physio-phenological characteristics that determine how plants respond to environmental variables and affect ecosystem processes (Violle et al., 2007). These traits provide a comprehensive framework for understanding plant responses and ecosystem functions, highlighting how traits like leaf morphology, root architecture, and reproductive timing are essential for plants to manage environmental stresses and influence ecological processes (Lavorel & Garnier, 2002; Liu et al., 2024). Trait-based approaches are widely used to assess ecosystem responses to environmental changes, including resilience to disturbances such as seismic line impacts (Dabros et al., 2022). Intraspecific trait variability (ITV) plays a critical role in promoting ecological stability and enhancing biodiversity in

response to disturbance. It enables species to adapt to a wider range of environmental conditions, thereby maintaining ecosystem functions (Liu et al., 2024). Key plant functional traits include plant height, leaf dry matter content (LDMC), specific leaf area (SLA), leaf size (LS), leaf thickness (Lth), and leaf chemical composition such as carbon (C), nitrogen (N), and phosphorus (P). These traits are important in understanding plant interactions with their environment and their role in ecosystem functions.

In undisturbed areas, plant height is expected to reflect the typical growth in a peatland, where natural vegetation thrives without any human disturbances. In contrast, the areas that have recently undergone some disturbance events, such as flooding or drought, are likely to show a reduced plant height. On newly disturbed seismic lines, plants might be in early regrowth stages, leading to increased heights as they re-establish themselves in the altered environment (Locky & Bayley, 2007). On older seismic lines, plants have had a longer period for regeneration, potentially allowing plant height to rebound. However, the plants might still be shorter compared to the undisturbed areas due to the lingering effects of the disturbance. It is important to note that on seismic lines, variation in plant height is more caused by mechanical cutting rather than biological responses to changes in environmental factors. Taller plants, especially trees and shrubs, were physically cut by machinery, while ground layer vegetation, such as mosses, may be less affected. As a result, the variation in plant height on seismic lines is affected by two factors: the initial machinery cutting during seismic line creation and the regrowth of plants afterward.

Leaf dry matter content (LDMC) can indicate the density and longevity of leaves, with higher values suggesting a greater investment in structural tissues (Yang et al., 2020). Similar to plant height, LDMC level in undisturbed areas typically reflect the baseline, usually with optimal balance between leaf structure and function. Disturbed areas that have been cleared often provide

ample space for species colonization. As a result, plants on seismic lines may have lower LDMC due to the rapid colonization process (Wei et al., 2023). In contrast, once sites have decades to naturally regenerate, the LDMC level may shift toward undisturbed areas, reflecting a return to a more balanced state.

Specific leaf area (SLA), defined as the leaf area per unit dry mass, is closely linked to photosynthetic rate (Shipley et al., 2006). Plant species show different responses in SLA, even under the same changes in environmental conditions. For example, species of *Stipa*, such as *Stipa grandis*, showed a decrease in SLA as mean annual precipitation (MAP) increased (Liu et al., 2017). This response suggests that *Stipa* adapted to higher water availability by growing thicker and smaller leaves. In contrast, *Cleistogenes spp.*, such as *Cleistogenes chinensis*, and *Carex spp.*, such as *Carex korshinskyi*, showed a positive relationship between SLA and MAP (Liu et al., 2017). As MAP increased, *Cleistogenes* developed thinner and larger leaves, as indicated by a higher SLA level. This strategy can increase light capture and photosynthesis in more favourable water conditions (Sterck et al., 2006; Xu et al., 2009).

Unlike the other genera mentioned, *Leymus*, such as *Leymus chinensis*, did not show a significant correlation between SLA and precipitation. In *Leymus*, SLA remained relatively stable with changes in precipitation, suggesting that its leaf growth strategy may be more influenced by other environmental variables other than water availability.

Leaf size (LS) can influence the microclimate around leaves and transpiration rate (Givnish, 2008). Plants in undisturbed treed peatlands tend to have bigger leaves due to the limited light availability (Konings et al., 2019). These plants are adapted to efficiently use the diffuse light available under the canopy. On the contrary, disturbed areas are likely to have

canopy gaps and increased light availability, which favour the growth of early successional plants that have bigger leaves (Jurik et al., 1982).

Leaf thickness (Lth) often correlates with water retention capability and photosynthetic activity (Poorter et al., 2009). Undisturbed environments tend to have a well-developed canopy, resulting in lower light availability. Plants in such low-light environment often have thinner leaves, which is a response to maximize light capture per unit of leaf tissue (Niinemets, 1999). The thinner leaf structure is advantageous in shaded conditions as it allows for a greater surface area relative to volume, improving the efficiency of photosynthesis under limited light (Rozendaal et al., 2006; Niinemets, 1999). In contrast, disturbed areas likely experience increased light availability due to the removal of vegetation. Plants often develop thicker leaves, which are beneficial in high-light environments (Chung et al., 2023).

In undisturbed peatlands, plants typically show high leaf C levels, reflecting their efficient carbon storage in mature settings. When disturbance events happen, such as fires and harvesting, leaf C levels typically decline as plants redirect energy towards recovery and rapid growth, moving away from long-term storage strategies prevalent in stable, undisturbed conditions (Pellegrini et al., 2015). Conversely, leaf N levels in leaves often increase in response to these disturbances, driven by the release of N from decomposing organic matter (Carreño-Rocabado et al., 2012). This nutrient release enhances the availability of N, supporting the plant's accelerated growth in the disturbed setting.

P and S levels are typically lower in undisturbed areas due to effective recycling but may increase in disturbed areas due to mineralization processes (Vitousek & Farrington, 1997; Redel et al., 2013). K and Ca are elements essential for structural stability. They tend to show moderate

levels in undisturbed conditions with possible increases post-disturbance due to organic matter breakdown (Stinner et al., 1984; Chen et al., 1983; Esmaeilzadeh & Ahangar, 2014).

Intraspecific trait variation (ITV) refers to the differences in functional traits within a single species across different environmental conditions (Silva et al., 2019). This variation is critical for understanding the capability of species to tolerate environmental changes and disturbances. Such variability allows for a finer resolution in predicting how ecosystems respond to disturbances by providing insights into the range of possible plant responses under varying environmental stresses. In the context of seismic line disturbance, ITV can play a decisive role in how plant community restructure and recover. For instance, within a single species, individuals with traits that favour rapid resource utilization might thrive in newly disturbed areas, where resources are temporarily abundant (Lavorel & Garnier, 2002). In contrast, those with traits favouring resource conservation might be better suited for survival in areas with prolonged disturbances (Lavorel & Garnier, 2002). In peatlands, where seismic lines disrupt soil and hydrological conditions, understanding these variations becomes essential. Examining how specific traits vary within species across a disturbance gradient provides valuable insights into the mechanisms of plant responses, informing broader ecological and conservation strategies. This detailed exploration into trait variability sets the stage for a trait-based approach, aiming to further understand how such variation can directly influence the resilience and functionality of ecosystems subjected to seismic line disturbance.

The adoption of a trait-based approach in this study is fundamentally aligned with understanding how seismic line disturbance influences plant functional traits and, consequently, ecosystem resilience and functionality in peatlands. This framework posits that some plant traits are not just passive responses to environmental stresses but active determinants of a plant's

ability to adapt to and influence ecosystem processes (Lavorel & Garnier, 2002; Violle et al., 2007). In the context of seismic line disturbance, which often leads to altered soil composition, water regimes, and light availability (Dabros et al., 2022), these traits can indicate how plants respond to the disruption. For example, changes in SLA might be responses to the modified hydrological conditions and compacted soils. Such trait modifications can signal shifts in competitive dynamics and ecological succession pathways, thereby impacting the overall stability and carbon sequestering functions of peatlands. Further, shifts in plant trait expression at the community level may result from changes in community composition, species traits arising from ITV, or a combination of both. By systematically examining these traits, the study aims to explain the mechanisms by which seismic line disturbance reshapes plant community and to assess the potential for recovery in these ecosystems. This trait-based perspective not only enhances our understanding of ecological responses at the species and community level but informs broader conservation strategies aimed at mitigating the impacts of such disturbances. However, we do not know exactly how these theoretical insights hold up under the complex conditions of real-world peatland ecosystems.

To explore these dynamics, we conducted a study in a rich fen located in Alberta, Canada, where we examined seismic lines with varied disturbance histories. There are four types of sites with different disturbance histories: 1) old sites: disturbed about 30 years ago, 2) new sites: disturbed in winter 2022, which was a few months before the study, and 3) re-disturbed sites: disturbed once about 30 years ago and once in winter 2022. We also compared these disturbed sites with the adjacent undisturbed areas. Measuring across these disturbance levels, the objectives of this study are to: 1) examine the changes in key plant functional traits at species

and community levels following different disturbance histories, and 2) assess the ITV in response to different disturbance histories.

We hypothesized that plant height in old sites, which have had the longest time to regenerate, would most closely resemble that of undisturbed sites. Conversely, we expected new sites to show significantly shorter plants due to less time to regenerate, with re-disturbed sites showing the least progress in regaining original plant height. Regarding LDMC, we predicted that it would be the highest in old sites, approaching levels found in undisturbed sites, while newly disturbed and re-disturbed sites would show lower LDMC. We also anticipated that SLA would be the highest in new sites to maximize rapid growth and photosynthesis in newly available light-rich spaces, whereas SLA in old and undisturbed sites would be lower as these areas host more mature, competitive plant dynamics. Additionally, LS is expected to be the largest in new sites as plants capitalize on the increased light availability to facilitate rapid colonization. In contrast, old sites should show smaller LS, close to undisturbed conditions. Lth is hypothesized to be greater in old sites compared to new and re-disturbed sites, reflecting responses that optimize water retention and structural integrity that are less developed in sites with recent disturbances.

3.2 Materials and Methods

3.2.1 Site description

The research was conducted at the Canadian Natural Resources Limited (CNRL) Kirby South location (55° 21' N, 111° 10' W), approximately 40 km south of Conklin in northeastern Alberta. The area covers roughly 0.13 km^2 in a rich fen with sparse tree coverage at an elevation

of about 690 m (Elevation Finder, 2019). The dominant plant species include mosses such as *S. angustifolium* and *S. fuscum*, shrubs like *B. glandulosa* and *S. pedicellaris*, and forbs like *M. trifoliata*. The growing season lasts from May to September, during which the average temperature is 13.4 °C and the average precipitation is 456 mm (Climate and Weather Averages; Climate Data Canada). The fen is crossed by seismic lines that are between 1.5 and 5 m wide and run in north-south, east-west, northeast-southwest, and northwest-southeast directions. The site is untouched by recreational activities due to its remote and inaccessible location. There are four types of study sites (Figure 2.1): 1) undisturbed sites, 2) old sites: disturbed about 30 years ago, 3) new sites: disturbed in winter 2022, and 4) re-disturbed sites: disturbed twice – once about 30 years ago and once in winter 2022. Each type of site has five replicates, making a total of 20 study sites.

3.2.2 Field data collection

In July and August 2022, we collected data along the seismic lines and adjacent undisturbed areas. At each study site, a 100 m^2 plot was set up and divided into 10 quadrats aligned with the seismic lines (Figure 2.2). For lines running north-south, the quadrats were arranged sequentially from south to north. For those running east-west, the sequence ran from west to east. To assess spatial variation, quadrats 1, 2, 5, 6, 9, and 10 each included a 1 m x 1 m sub-quadrat, positioned at various locations (left, middle, right) within the bigger quadrat. The vegetation surveys were conducted from mid-July to early August 2022, focusing specifically on the 1 m x 1 m sub-quadrats to visually assess the vegetation cover within the study area (see section 2.2.2 for detail).

This study examined 17 species (Table 2.1), which comprise a diverse array including mosses, shrubs, forbs, trees, a horsetail, and a sedge. These species are prominent in the study area and are representative of the full range of local plant community. Plant samples for trait measurements were collected outside the designated 100 m² plots to not additionally disrupt the sampling plots (Figure 2.2). Leaf samples were collected from three healthy plants of varying sizes for each species at each study site, totaling approximately 1020 samples. This approach aimed at capturing the variability of each species within a site. At the sites lacking certain species, additional samples of these species were collected from other sites with the same disturbance level to maintain sample size uniformity across disturbance levels. Plant heights were measured using measuring tapes or rulers from the ground to the topmost point of the plant before leaf removal. Leaves were sampled from all around each plant, from the topmost branches to the lowest, to ensure a comprehensive representation of the entire plant. No other parts were collected from plants. Ten leaves of varying sizes were selected from each leaf sample for analysis to ensure representativeness. For *E. fluviatile*, it was the photosynthetic brunches that were measured instead of the true leaves, which are not photosynthetic. Then, the leaves were weighed on a high-precision digital scale (Smart Weigh, SW-GEM50) for their fresh mass. Subsequently, each set of ten leaves was photographed on a white background with a ruler for scale using an iPhone 13. The photographs were analyzed with ImageJ software (Rueden, 2021) to determine the leaf area. Leaf samples were dried at 60 °C for 48 hours, and their dry mass was measured immediately. If there was a delay between drying and weighing, the leaf samples were dried again for 12 hours at 60°C to prevent moisture absorption. Both fresh mass and dry mass were measured using the same digital scale (Smart Weigh, SW-GEM50).

The chemical composition of dried leaf samples was analyzed at the Analytical Services Laboratory in the Canadian Forest Service Department (Table S1 and S2). Total carbon (C) and nitrogen (N) content were determined using the Leco 828 Combustion System, with carbon measured via an Infrared Detector and nitrogen quantified through a Thermal Conductivity Detector. Metals were analyzed using an acid digestion protocol combining HNO_3 and HCl, facilitated by a Microwave Accelerated Reaction System (MARS), and quantified using an Inductively Coupled Plasma Optical Emission Spectrometer (ICP OES).

3.2.3 Calculation of derived variables

Certain plant traits, such as SLA and Lth, are not easily measured and were instead derived from the measured traits (Table 3.1). SLA (cm^2/g) was derived by dividing the total leaf area by the dry mass of the leaf sample. Lth (mm) was estimated by dividing the total leaf area by the fresh mass of the leaf sample. LDMC was calculated as the ratio of dry mass to fresh mass. LS (cm^2), which represents the average of leaf area, was determined by dividing the total area of all leaves in a sample by the number of leaves. For mosses, only LDMC was measured, as it is impractical to measure their height or leaf area.

3.2.4 Statistical analysis

We conducted all analyses using the statistical software R 4.4.0 (R Core Team, 2023) and we used a significance level of $\alpha = 0.05$. In cases of missing data, we handled these instances as NA values, which were appropriately accounted for in the ANOVA and subsequent community weighted mean (CWM) analysis. We evaluated the impact of species and disturbance levels on

the morphological plant traits and leaf chemical composition by using a two-way Analysis of Variance (ANOVA) with the *aov()* function in *stats* package (R Core Team, 2023). Significant results were subsequently examined with Tukey's Honest Significant Difference (HSD) test to identify differences among the disturbance levels. The Tukey's HSD tests were performed using the *agricolae* package (de Mendiburu, 2023), which facilitates the identification of statistically similar groups and adjusts for multiple comparisons.

In addition, we calculated the CWM of plant traits and leaf chemical composition for each study site. The CWM of LDMC included the LDMC values of both moss and vascular species. For the CWM calculations, trait values for each species were averaged across all sites within the same disturbance level. The advantage of using CWM over the traditional mathematical mean is that it accounts for the influence of the abundance of each plant species. In this method, more abundant species have greater impact on CWM, which allows for the evaluation of shifts in plant traits at the community level. The CWM analysis was conducted using *weighted.mean()* function in *dplyr* package (Wickham et al., 2023).

Table 3.1 Methods of measurement or calculation for plant traits.

Plant trait	Measurement/calculation
Height (cm)	Measured in the field with a measuring tape or a ruler
Leaf size (cm^2)	$\frac{Total\ leaf\ area\ (cm^2)}{number\ of\ leaves}$
Specific leaf area (cm^2/g)	$\frac{Total\ leaf\ area\ (cm^2)}{leaf\ dry\ mass\ (g)}$
Leaf thickness (mm)	$\frac{Total\ leaf\ area\ (cm^2)}{leaf\ fresh\ mass\ (g)}$
Leaf dry matter content	$\frac{Leaf\ dry\ mass\ (g)}{leaf\ fresh\ mass\ (g)}$

3.3 Results

3.3.1 Morphological plant traits

Most morphological plant traits showed significant variation across species and disturbance levels of seismic lines. The only exception was Lth, which did not vary significantly across disturbance levels ($F_{3, 597} = 0.46$, $p = 0.707$; Table 3.2). In contrast, plant height, LS, and LDMC not only had significant differences across species and disturbance levels ($p < 0.001$ for both) but showed significant interactions between these factors. This suggests that the effect of disturbance was species-specific for these traits. SLA differed significantly across disturbance levels ($F_{3, 597} = 4.90$; $p < 0.01$) and species ($F_{11, 597} = 138.95$; $p < 0.001$), although there were no significant interactions between these two factors ($F_{33, 597} = 0.70$; $p = 0.897$). Similarly, Lth showed no significant interactions between these factors either ($F_{33, 597} = 0.88$; $p = 0.662$), but it was significantly different across species ($F_{11, 597} = 119.36$; $p < 0.001$).

The plant height of the 12 vascular species showed a wide range of variation from very short to very tall. The tallest species, *B. glandulosa* and *C. aquatilis*, exceed 65 cm (Table 3.4). *L. laricina* closely followed *B. glandulosa* and *C. aquatilis*, which reached a considerable height (61.53 cm) but was slightly shorter than those two species. Some species were moderately tall, such as *E. fluviatile, P. mariana,* and *C. calyculata*. Their heights spanned from approximately 38 cm to just under 50 cm (Table 3.4). *R. groenlandicum, M. trifoliata* and *A. polifolia* are much shorter, hovering around 20 to 45 cm (Table 3.4). The very short species, *Maianthemum trifolium* and *Vaccinium vitis-idaea*, were significantly shorter than all other species, with heights below 12 cm (Table 3.4). The plants in old and undisturbed sites had similar heights and were generally taller, with average heights of 40.96 cm and 40.28 cm, respectively (Table 3.3). In contrast, plant heights decreased in new and re-disturbed sites (34.09 cm and 35.63 cm, respectively; Table 3.3). Plant heights of re-disturbed sites aligned more closely with new sites instead of old or undisturbed sites.

There were many species that showed variation in plant height across disturbance levels (Table 3.2). Species such as *B. glandulosa*, *P. mariana*, and *S. pedicellaris* demonstrated a consistent increase in height from new to undisturbed (Figure 3.5). In contrast, *V. vitis-idaea* exhibited minimal height variation across disturbance levels (Figure 3.5). Lastly, *M. trifoliata* and *R. groenlandicum* had mixed responses, with heights fluctuating non-linearly (Figure 3.5). The CWM figure (Figure 3.2) showed that plant community was the tallest in old sites, followed closely by undisturbed sites, which had a higher median but less variation. The re-disturbed sites had the lowest median height, which was slightly lower than new sites (Figure 3.2).

The LS of the 12 vascular species varied notably across species. The species with the largest leaves were *M. trifoliata* and *E. fluviatile* (40.49 cm^2 and 10.06 cm^2, respectively). *C.*

aquatilis also showed a relatively big LS, which was slightly over 10 cm² (Table 3.4). In contrast, *C. calyculata*, and *R. groenlandicum* had much smaller leaves, roughly around 1 cm² or slightly above (Table 3.4). The species with the smallest leaves were *V. vitis-idaea*, *L. laricina*, and *P. mariana*, all below 0.4 cm² (Table 3.4). Additionally, LS showed significant variation across disturbance levels. In newly disturbed areas, the average LS was 8.13 cm², marking the highest among the disturbance levels (Table 3.3). The LS reduced to 6.4 cm² in old sites and 7.76 cm² in re-disturbed sites (Table 3.3). The undisturbed sites showed an average LS of 8.20 cm², closely aligned with the new sites (Table 3.3). The biggest leaves were observed in new and undisturbed sites.

The LS responded to disturbance levels differently across various species. *A. polifolia*, *B. glandulosa*, and *V. vitis-idaea* maintained consistent LS across all disturbance categories (Figure 3.4). *L. laricina* and *P. mariana* demonstrated decreasing LS from new to undisturbed sites (Figure 3.4). In contrast, *E. fluviatile* and *M. trifoliata* showed notable decreases from new to old sites (Figure 3.4). The CWM of LS showed less variation across disturbance levels compared to plant height (Figure 3.2). The new and old sites had similar LS with old sites having a higher median (Figure 3.2). In contrast, the undisturbed sites had a median LS similar to re-disturbed sites (Figure 3.2).

The LDMC levels were relatively consistent across the 17 species (Table 3.4). *A. polifolia* and *S. pedicellaris* had the highest LDMC levels among all species although only slightly higher than *R. groenlandicum* and *C. aquatilis* (Table 3.4). *B. glandulosa* and *L. laricina* shared comparable LDMC levels, which were significantly higher than *E. fluviatile, M. trifolium*, and *M. trifoliata* (Table 3.4). The LDMC also showed significant variation across disturbance levels, with the lowest value in new and highest value in old sites (0.39 and 0.43, respectively; Table

3.3). The LDMC levels in re-disturbed and undisturbed sites (0.41 for both) were similar to new sites.

Similar to plant height and LS, the responses of LDMC to disturbance levels were species-specific. *A. polifolia* and *V. vitis-idaea* had a generally consistent LDMC across all disturbance categories, with only slight fluctuations (Figure 3.5). In contrast, *S. pedicellaris* and *S. fuscum* had significant variation (Figure 3.5). The CWM of LDMC did not show as much variation as plant height (Figure 3.2). The new and old sites had similar variation and median LDMC, which were lower than undisturbed and higher than re-disturbed sites (Figure 3.2).

The SLA levels showed significant variation among species. *M. trifoliata* and *M. trifolium* had the highest SLA levels, which were significantly higher than all other species (Table 3.4). Similarly, *C. calyculata* and *L. laricina* had relatively high SLA levels, which were significantly higher than the rest of the species. *P. mariana* had the lowest SLA level. In contrast to species, SLA did not differ significantly across disturbance levels. The new and re-disturbed sites had similar SLA levels (115.63 cm^2/g and 114.21 cm^2/g, respectively; Table 3.3), which were higher than old sites (105.74 cm^2/g). The SLA reached its highest value at 118.46 cm^2/g in undisturbed areas. The CWM of SLA had similar variation in new and old sites, with new sites having a higher median (Figure 3.2). In contrast, re-disturbed sites had very little variation, but its median was higher than new and old sites (Figure 3.2). The undisturbed areas had the lowest median with an intermediate variation.

The Lth varied significantly across species. *E. fluviatile* and *P. mariana* had the highest Lth levels, which were significantly higher than all other species (Table 3.4). Species like *A. polifolia* and *R. groenlandicum* had intermediate Lth levels. *C. calyculata* and *L. laricina* had the lowest Lth levels. Unlike other plant traits, Lth did not differ significantly across disturbance

levels, with all of them having an average Lth of 0.03 mm (Table 3.3). The little variation among disturbance levels was also reflected in the CWM figure (Figure 3.2). The median Lth was consistent across all disturbance levels, with new sites having a slightly greater variation.

3.3.2 Leaf chemical composition

Leaf chemical composition showed significant variabilities across species and disturbance levels. All leaf chemistries were significantly different across species ($p < 0.001$ for all; Table 3.5). Similarly, most leaf chemistries varied significantly across disturbance levels, with the exceptions of total N ($F_{3, 263} = 0.88$; $p = 0.45$) and P ($F_{3, 263} = 2.58$; $p = 0.054$). Additionally, there were no significant interactions between species and disturbance levels for total N, P, and S ($p = 0.054$, $p = 0.231$, $p = 0.806$, respectively).

Total N showed significant variation among species. *M. trifoliata* had the highest total N level, which was significantly higher than all other species (Table 3.7). The total N levels of *M. trifolium* and *E. fluviatile* closely followed *M. trifoliata.* Some species had intermediate total N levels, such as *A. polifolia, B. glandulosa,* and *V. vitis-idaea. P. mariana* had the lowest total N level. The CWM of total N showed some variability across disturbance levels (Figure 3.2). The new and re-disturbed sites had similar levels, which were slightly higher than undisturbed and lower than old sites (Figure 3.2).

Similar to total N, total C showed significant variation across species ($F_{16, 263} = 156.93$; $p < 0.001$). *R. groenlandicum* had the highest total C level, but it was only slightly higher than *A. polifolia* and *C. calyculata* (Table 3.7). Many species had similar intermediate total C levels, such as *M. trifoliata, C. aquatilis,* and *S. warnstorfii. E. fluviatile* had the lowest total C level,

which was significantly lower than all other species. The total C levels were consistent across new, old, and undisturbed sites, all significantly higher than re-disturbed sites (Table 3.6). The total C responses to disturbance categories were species-specific, with *A. polifolia* and *V. vitis-idaea* having minimal variation and *E. fluviatile* and *L. laricina* having the most variation (Figure 3.6). The CWM of total C in new, old, and undisturbed sites had similar medians and variation, which were higher than re-disturbed sites (Figure 3.2).

P also showed significant variation among species ($F_{16, 331} = 100.04$; $p < 0.001$). *M. trifoliata, E. fluviatile,* and *M. trifolium* had similar P levels, which were significantly higher than all other species (Table 3.7). In contrast, *S. angustifolium* and *S. fuscum* had the lowest P levels, which were significantly lower than species like *C. calyculata* and *P. mariana*. Unlike total C, P did not show significant differences across disturbance levels or had significant interaction between species and disturbance ($p = 0.054$; $p = 0.231$, respectively). The new and re-disturbed sites had similar CWM of P (Figure 3.2). They had comparable variation with re-disturbed sites but a slightly higher median value. Conversely, old sites had the minimal variation but the highest median P value.

Similar to total C, K also had significant differences across species, disturbance levels, and significant interactions between these two factors. *E. fluviatile, M. trifolium,* and *M. trifoliata* had the highest K levels, which were significantly higher than all species (Table 3.7). Mosses, such as *S. angustifolium, A. palustre,* and *T. nitens,* had the lowest K levels. The old and undisturbed sites had similar K levels, which were higher than new and re-disturbed sites (Table 3.6). The K levels of *L. laricina* and *E. fluviatile* varied a lot across disturbance levels (Figure 3.7). However, many species, such as *B. glandulosa, S. angustifolium,* and *T. nitens*, did not have considerable variation across disturbance levels. The CWM of K had similar patterns as the

CWM of P (Figure 3.2). The new, re-disturbed, and undisturbed sites had similar median values, which were lower than old sites.

Similar to total C and K, Ca showed significant differences across species and disturbance levels and strong interactions. *E. fluviatile* and *S. pedicellaris* had the highest Ca levels (Table 3.7). Shrubs, such as *S. pedicellaris* and *C. calyculata,* had intermediate Ca levels, which were significantly higher than the sedge *C. aquatilis.* The Ca levels were similar in new and re-disturbed sites, which were significantly higher than old and undisturbed sites (Table 3.6). The species-specific responses of Ca level had the most complex variation compared to other plant traits (Figure 3.8). Some species had minimal variation, such as *P. mariana* and *M. trifoliata,* while some species had large fluctuations, such as *S. angustifolium,* and *S. fuscum.* Other species had consistently increased or decreased, such as *E. fluviatile*, and *L. laricina*. The new and re-disturbed sites had similar CWM of Ca, with re-disturbed sites having more variation (Figure 3.2).

There were significant differences in S levels across species ($F_{16, 263} = 56.55$; $p < 0.001$) and disturbance levels ($F_{3, 263} = 2.89$; $p < 0.05$; Table 3.5). *M. trifoliata* had the highest S level, closely followed by *E. fluviatile* and *M. trifolium* (Table 3.7). Shrubs, such as *A. polifolia, R. groenlandicum,* and *V. vitis-idaea,* had intermediate S levels, which were significantly higher than mosses. The old sites had the highest S level, which was marginally higher than new and re-disturbed sites (Table 3.6). The undisturbed sites had the lowest S level. Similar to total N and P, S did not show species-specific responses to disturbance levels ($F_{48, 263} = 0.81$; $p = 0.806$). S and P had similar CWM patterns (Figure 3.2). They both had the most variation in re-disturbed and the minimal variation in old sites. The re-disturbed sites had the highest median of S, and the undisturbed had the lowest.

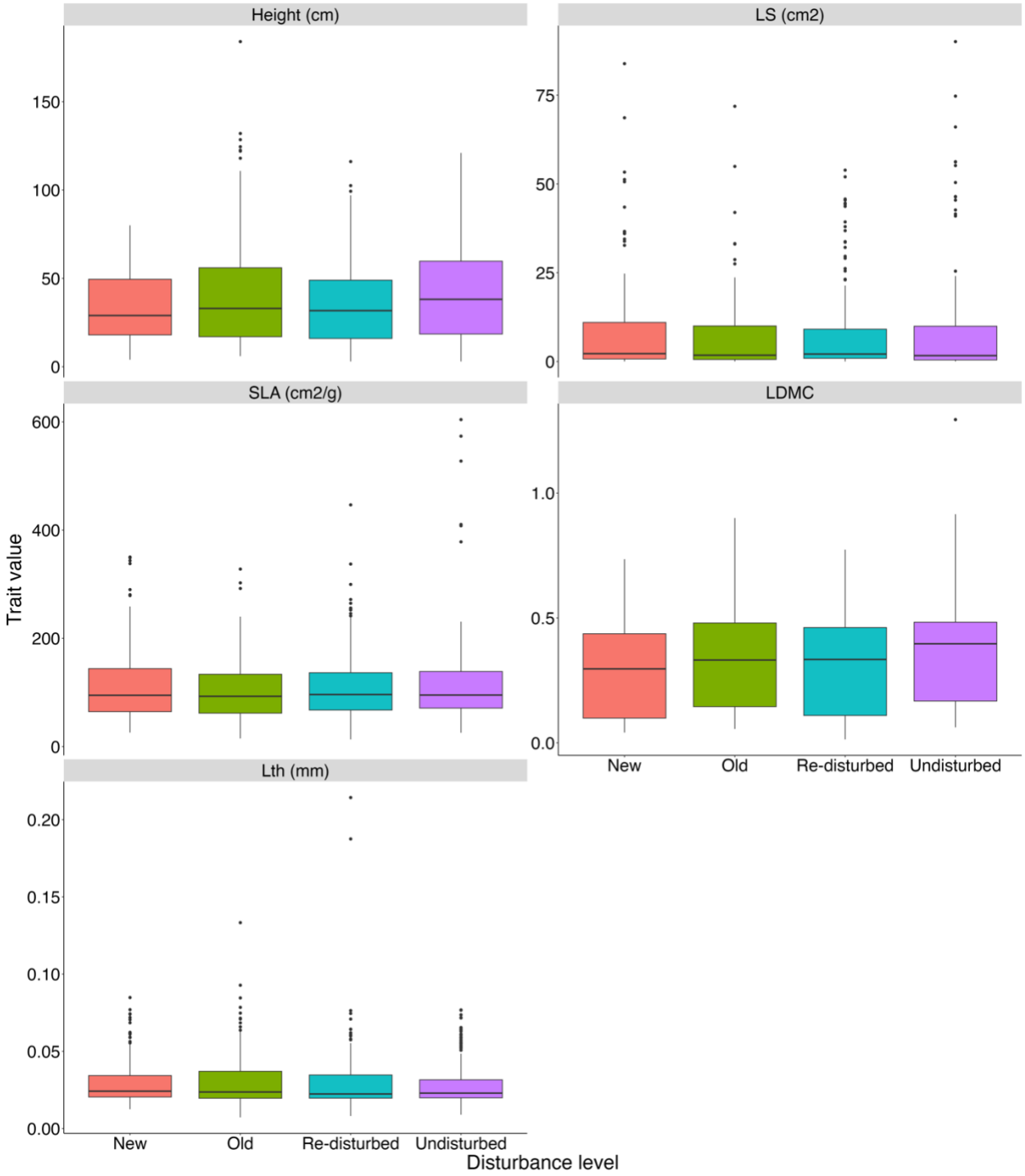


Figure 3.1 Variation in morphological traits across disturbance levels in a rich fen in Alberta, Canada. Each panel represents the distribution of a morphological trait across disturbance levels, and each boxplot represents the distribution within a disturbance level.

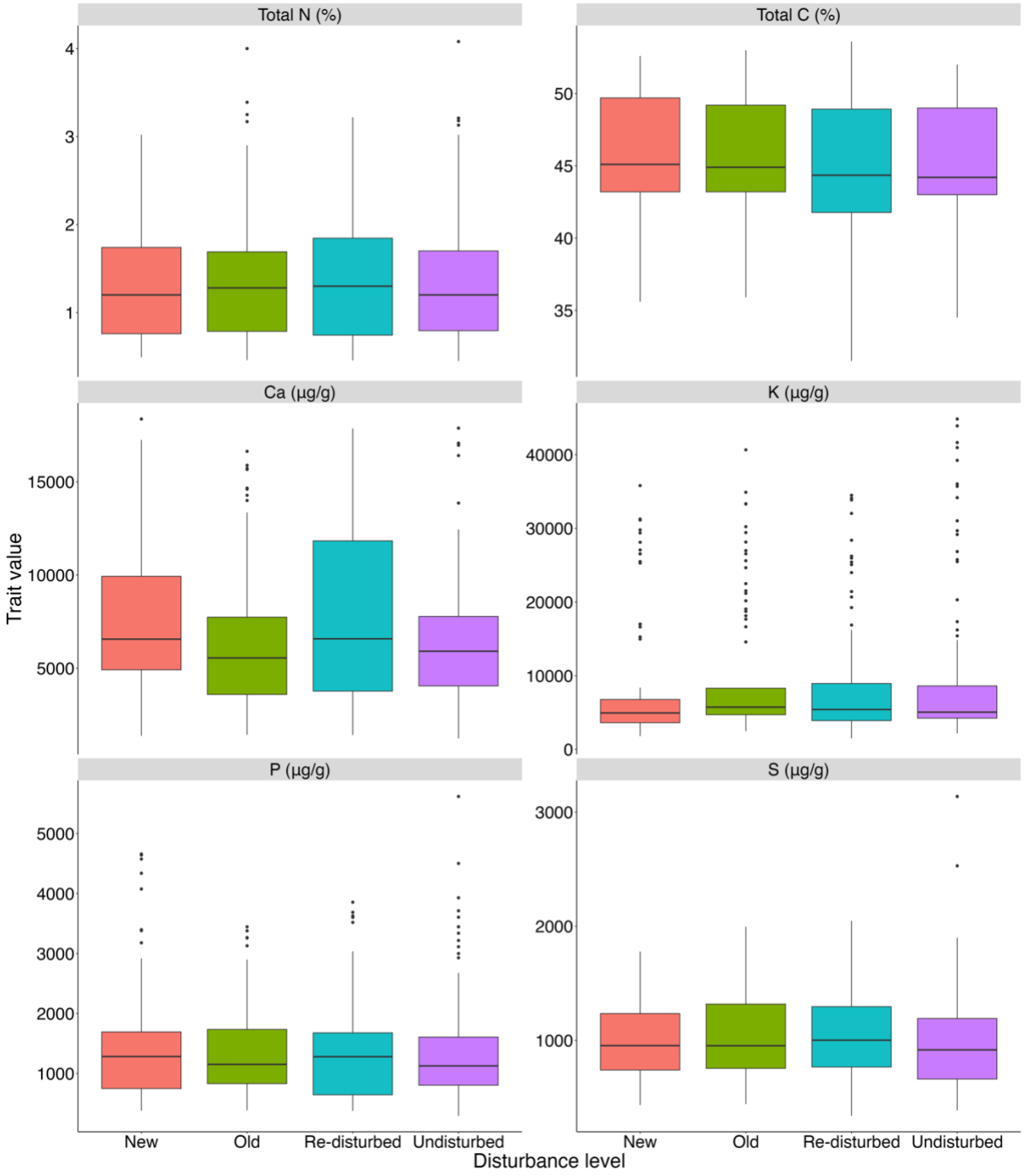


Figure 3.2 Variation in leaf chemical composition across disturbance levels in a rich fen in Alberta, Canada. Each panel represents the distribution of a leaf chemical across disturbance levels, and each boxplot represents the distribution within a disturbance level.

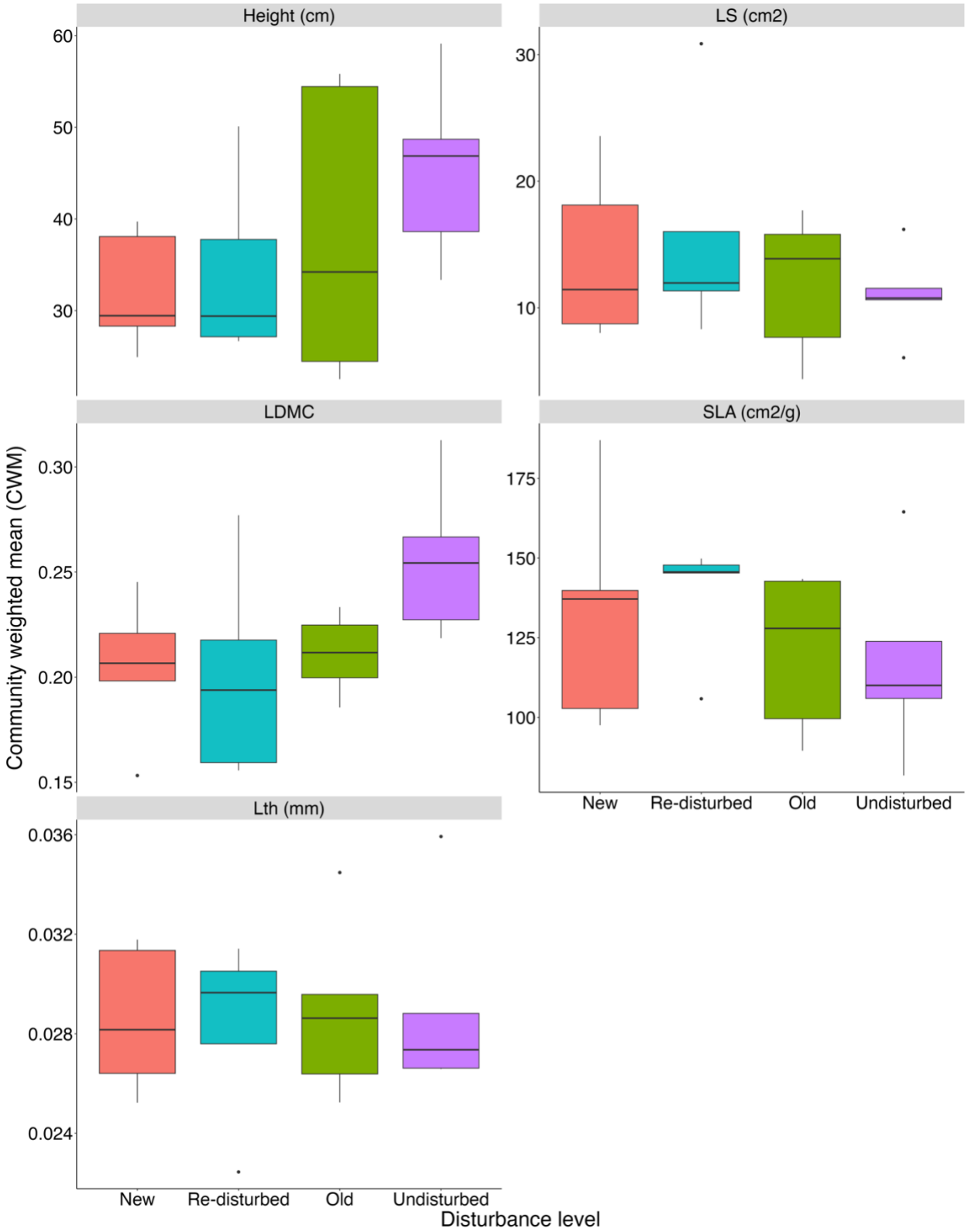


Figure 3.5 Disturbance-specific community weighted mean (CWM) of morphological traits across disturbance levels in a rich fen in Alberta, Canada. The CWM was calculated using trait values that were specific to each disturbance level for each species.

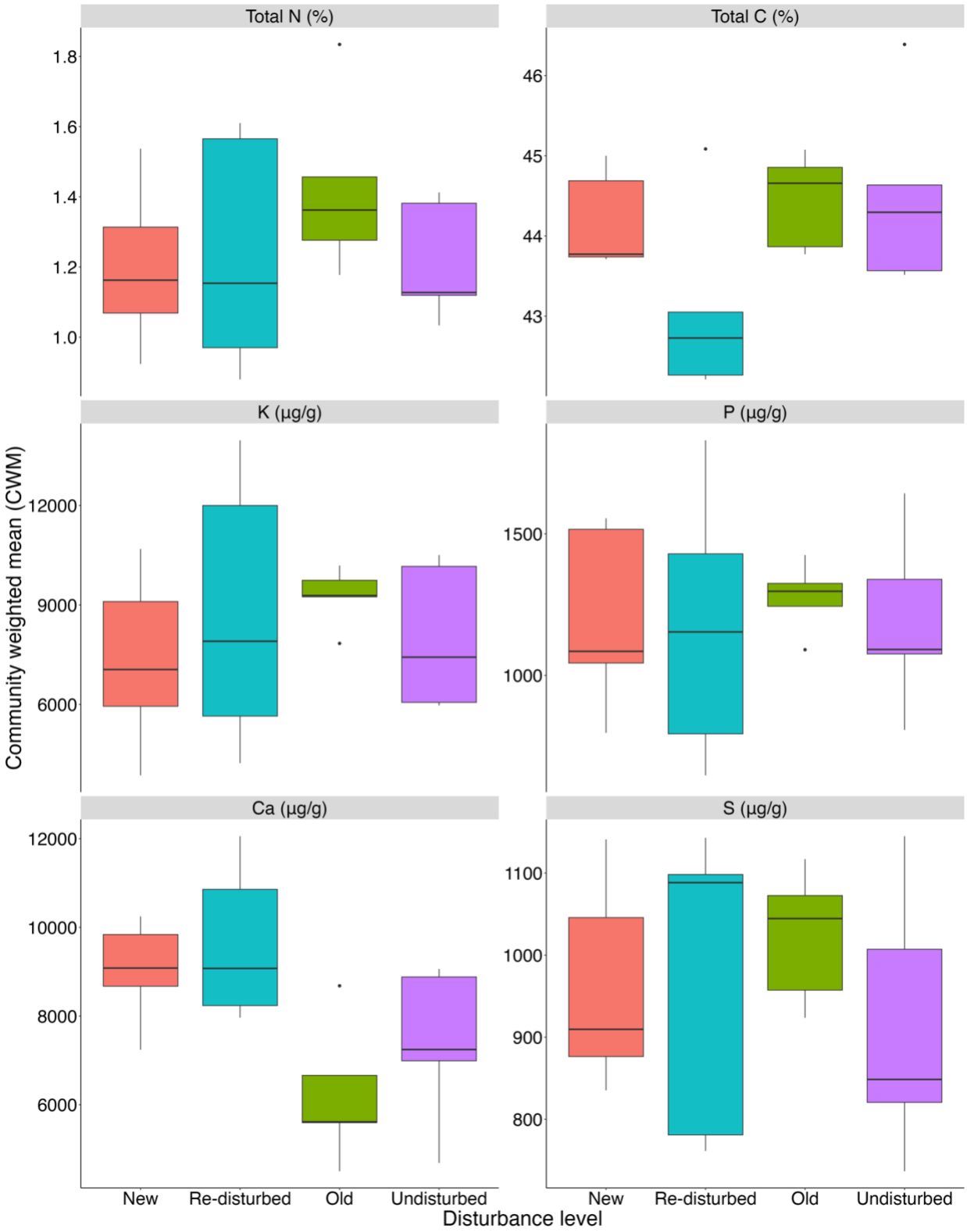


Figure 3.4 Disturbance-specific community weighted mean (CWM) of leaf chemical composition across disturbance levels in a rich fen in Alberta, Canada. The CWM was calculated using trait values that were specific to each disturbance level for each species.

Table 3.2 ANOVA results of plant traits of 17 species across disturbance levels and species in a rich fen in Alberta, Canada. Plant traits were analyzed using log transformation to meet ANOVA assumptions.

Plant trait	Model	df	SS	F value	P value
Height (cm)	**Species**	11	270.75	184.60	**< 0.001** ***
	Disturbance level	3	3.71	9.28	**< 0.001** ***
	Interaction	33	11.55	2.62	**< 0.001** ***
LS (cm^2)	**Species**	11	2259.66	1525.36	**< 0.001** ***
	Disturbance level	3	3.88	9.59	**< 0.001** ***
	Interaction	33	10.01	2.25	**< 0.001** ***
LDMC	**Species**	16	461.22	452.14	**< 0.001** ***
	Disturbance level	3	3.59	18.75	**< 0.001** ***
	Interaction	48	20.52	6.71	**< 0.001** ***
SLA (cm^2/g)	**Species**	11	147.55	138.95	**< 0.001** ***
	Disturbance level	3	1.42	4.90	**0.002** **
	Interaction	33	2.23	0.70	0.897
Lth (mm)	**Species**	11	92.79	119.36	**< 0.001** ***
	Disturbance level	3	0.09	0.46	0.707
	Interaction	33	2.05	0.88	0.662

Table 3.3 Plant traits of 17 species across disturbance levels in a rich fen in Alberta, Canada. Plant traits were analyzed using log transformation to meet ANOVA assumptions. Listed values represent the mean of actual data, with standard errors of transformed data in brackets. Group letters denote Tukey's HSD test results where disturbance levels are significantly different if they do not share a letter.

Plant trait	New	Re-disturbed	Old	Undisturbed
Height (cm)	**34.09 (0.03) ab**	**35.63 b**	**40.96 a**	**40.28 ab**
LS (cm^2)	**8.13 (0.03) a**	**7.76 a**	**6.40 b**	**8.20 b**
LDMC	**0.29 (0.01) b**	**0.31 b**	**0.34 a**	**0.34 a**
SLA (cm^2/g)	115.63 (0.03) a	114.21 a	105.74 a	118.46 a
Lth (mm)	0.03 (0.02) a	0.03 a	0.03 a	0.03 a

Table 3.4 Plant traits of 17 species across species in a rich fen in Alberta, Canada. Plant traits were analyzed using log transformation to meet ANOVA assumptions. Listed values represent the mean of actual data, with standard errors of transformed data in brackets. Group letters denote Tukey's HSD test results where disturbance levels are significantly different if they do not share a letter.

Species	Height (cm)	LS (cm^2)	LDMC	SLA (cm^2/g)	Lth (mm)
Andpol	20.41 (0.72) e	0.62 (0.05) g	0.47 (0.01) a	62.28 (4.56) g	0.04 (0) b
Betgla	67.13 (3.54) a	2.46 (0.11) d	0.44 (0.01) a	112.31 (3.26) c	0.02 (0) de
Caraqu	65.31 (2.06) a	10.06 (0.56) c	0.48 (0.01) a	83.64 (3.25) ef	0.03 (0) e
Chacal	38.23 (1.65) d	1.52 (0.05) e	0.47 (0.01) a	138.75 (4.46) b	0.02 (0) f
Equflu	49.04 (1.96) bc	13.88 (0.79) b	0.28 (0.01) b	73.31 (6.47) fg	0.06 (0) a
Larlar	61 .53 (4.65) ab	0.06 (0) i	0.47 (0.03) a	120.72 (5.07) bc	0.02 (0) e
Maitri	11.95 (0.44) f	10.28 (0.45) c	0.25 (0.01) bc	222.69 (9.63) a	0.02 (0) e
Mentri	20.43 (1.04) e	40.49 (2.19) a	0.22 (0.01) c	213.23 (11.56) a	0.02 (0) cd
Picmar	41.08 (2.9) cd	0.06 (0) i	0.52 (0.01) a	36.22 (1.88) h	0.06 (0) a
Rhogro	25.02 (1.65) e	1.12 (0.05) f	0.47 (0.01) a	85.19 (2.82) de	0.03 (0) c
Salped	45.61 (2.2) bcd	2.2 (0.16) d	0.49 (0.01) a	100.65 (2.62) cd	0.02 (0) de
Vacvit	6.82 (0.43) g	0.39 (0.02) h	0.49 (0.01) a	77.28 (3.19) ef	0.03 (0) c
Aulpal	NaN (NA)	NaN (NA)	0.15 (0.01) a	NaN (NA)	NaN (NA)
Sphang	NaN (NA)	NaN (NA)	0.1 (0.01) a	NaN (NA)	NaN (NA)

Sphfus	NaN (NA)	NaN (NA)	0.08 (0) e	NaN (NA)	NaN (NA)
Sphwar	NaN (NA)	NaN (NA)	0.07 (0) f	NaN (NA)	NaN (NA)
Tomnit	NaN (NA)	NaN (NA)	0.2 (0.02) fg	NaN (NA)	NaN (NA)

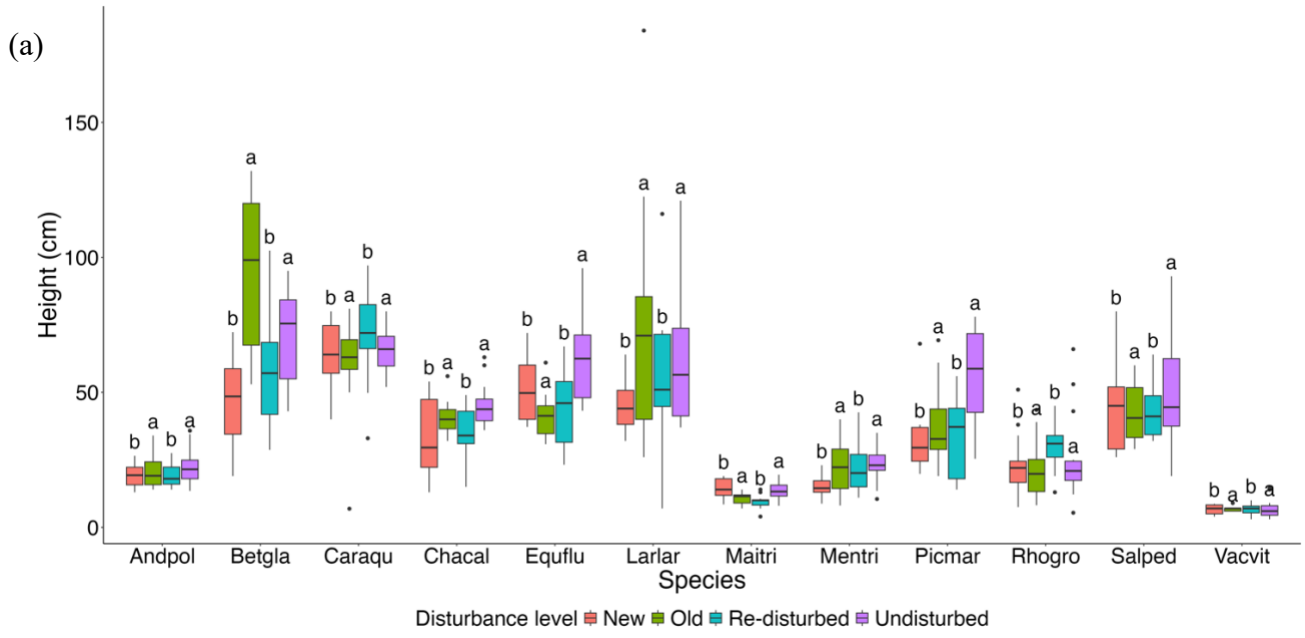


Figure 3.5 Variation in (a) plant height across species and disturbance levels in a rich fen in Alberta, Canada. Species full names can be found in List of Species Abbreviations.

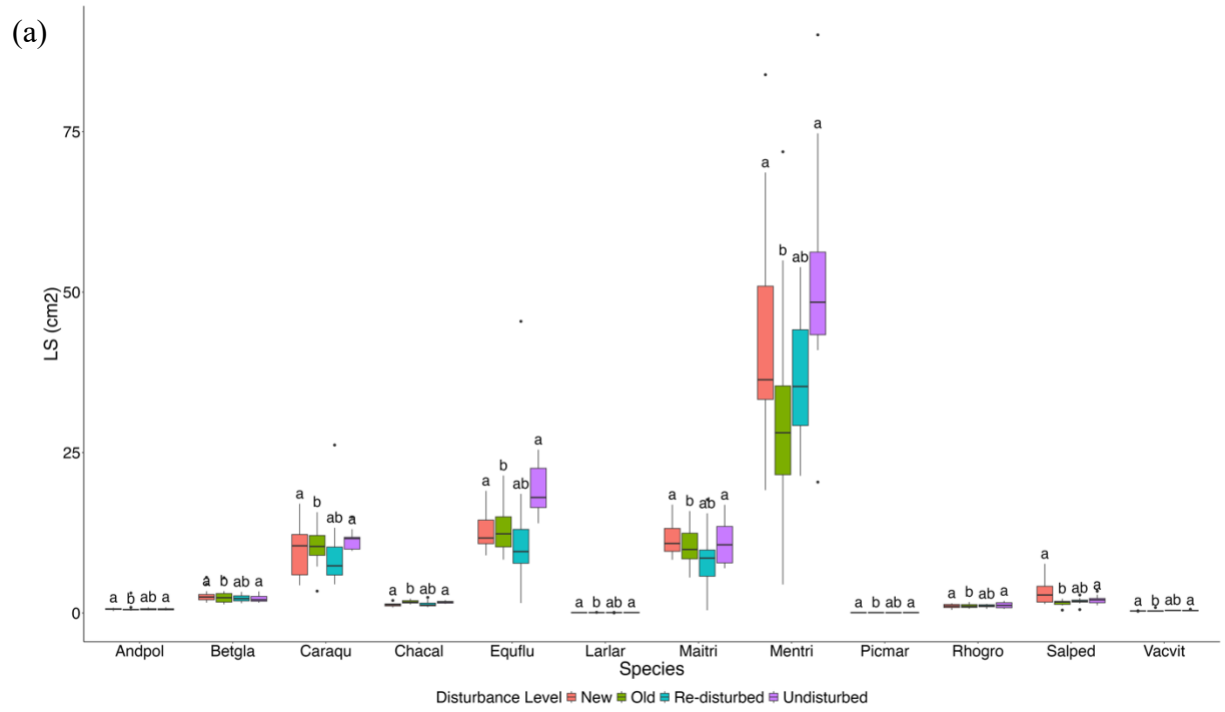


Figure 3.5 Variation in (b) LS across species and disturbance levels in a rich fen in Alberta, Canada. Species full names can be found in List of Species Abbreviations.

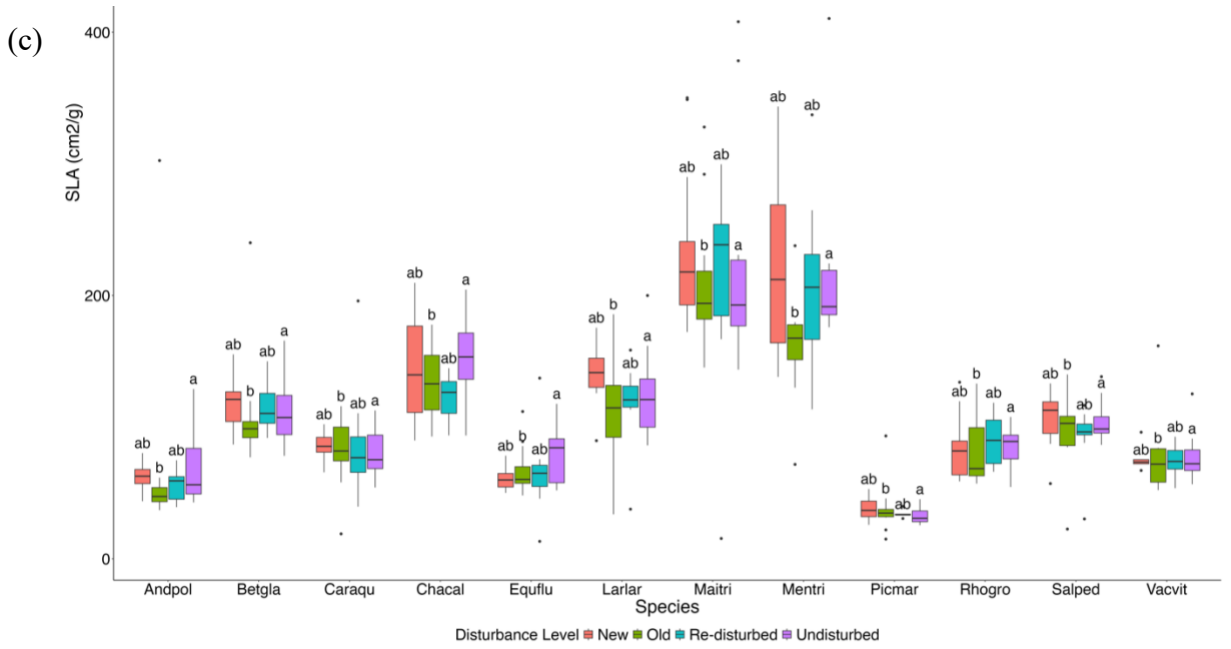


Figure 3.5 Variation in (c) SLA across species and disturbance levels in a rich fen in Alberta, Canada. Species full names can be found in List of Species Abbreviations.

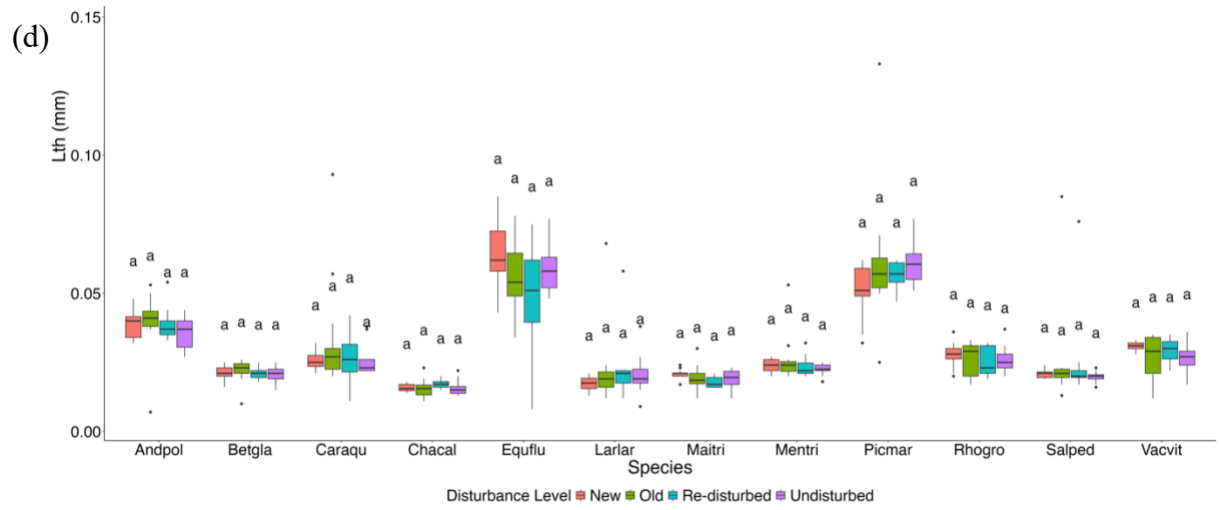


Figure 3.5 Variation in (d) Lth across species and disturbance levels in a rich fen in Alberta, Canada. Species full names can be found in List of Species Abbreviations.

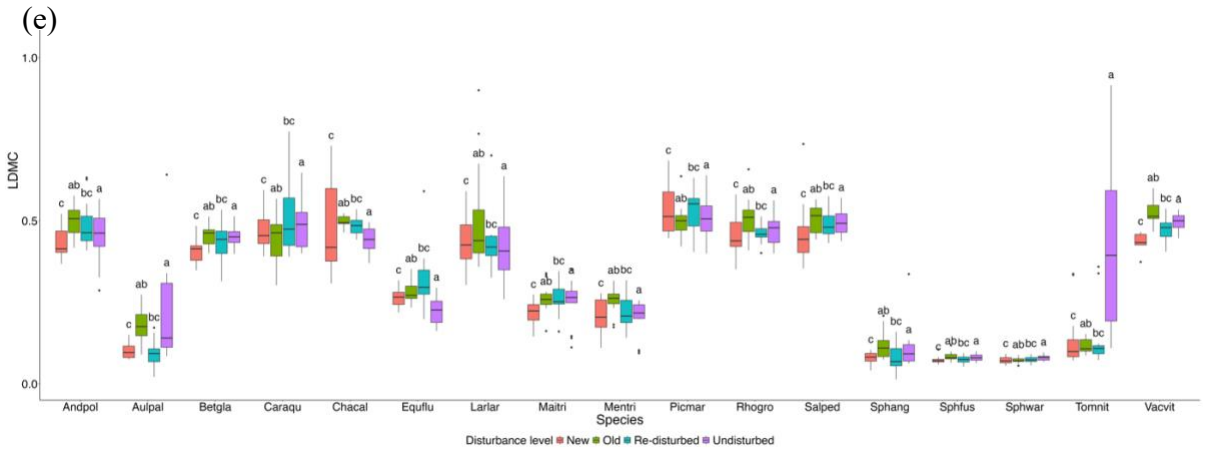


Figure 3.5 Variation in (e) LDMC across species and disturbance levels in a rich fen in Alberta, Canada. Species full names can be found in List of Species Abbreviations.

Table 3.5 ANOVA results of leaf chemical compositions of 17 species in a rich fen in Alberta, Canada. Leaf chemical compositions were analyzed using log transformation to meet ANOVA assumptions.

Leaf chemical	Model	df	SS	F value	P value
Total N (%)	**Species**	16	75.09	162.06	**< 0.001** ***
	Disturbance level	3	0.08	0.88	0.45
	Interaction	48	1.94	1.4	0.054
Total C (%)	**Species**	16	2.69	156.93	**< 0.001** ***
	Disturbance level	3	0.03	9.04	**< 0.001** ***
	Interaction	48	0.11	2.22	**< 0.001** ***
P (µg/g)	**Species**	16	97.8	100.04	**< 0.001** ***
	Disturbance level	3	0.47	2.58	0.054
	Interaction	48	3.41	1.16	0.231
K (µg/g)	**Species**	16	171.64	151.78	**< 0.001** ***
	Disturbance level	3	1.38	6.52	**< 0.001** ***
	Interaction	48	5.99	1.77	**0.003** **
Ca (µg/g)	**Species**	16	71.04	35	**< 0.001** ***
	Disturbance level	3	2.82	7.42	**< 0.001** ***
	Interaction	48	15.52	2.55	**< 0.001** ***
S (µg/g)	**Species**	16	34.81	56.55	**< 0.001** ***
	Disturbance level	3	0.33	2.89	**0.036** *
	Interaction	48	1.5	0.81	0.806

Table 3.6 Leaf chemical compositions of 17 species across disturbance levels in a rich fen in Alberta, Canada. Leaf chemical compositions were analyzed using log transformation to meet ANOVA assumptions. Listed values represent the mean of actual data, with standard errors of transformed data in brackets. Group letters denote Tukey's HSD test results where disturbance levels are significantly different if they do not share a letter.

Leaf chemical	New	Re-disturbed	Old	Undisturbed
Total N (%)	1.34 (0.08) a	1.39 (0.08) a	1.38 (0.08) a	1.35 (0.08) a
Total C (%)	**46.17 (0.46) a**	**44.93 (0.54) b**	**45.94 (0.44) a**	**45.6 (0.45) a**
P (µg/g)	1482.54 (113.53) a	1393.97 (99.65) a	1413.09 (86.2) a	1457.22 (112.66) a
K (µg/g)	**8519.85 (969.11) c**	**9091.7 (977.46) bc**	**10182.71 (999.5) a**	**10520.12 (1251.58) ab**
Ca (µg/g)	**7519.35 (431.97) a**	**7996.33 (537.16) a**	**6349.86 (418.08) b**	**6488.56 (392) b**
S (µg/g)	**1010.32 (36.88) ab**	**1056 (44.12) ab**	**1067.02 (41.42) a**	**1008.81 (50.2) b**

Table 3.7 Leaf chemical compositions of 17 species across species in a rich fen in Canada. Leaf chemical compositions were analyzed using log transformation to meet ANOVA assumptions. Listed values represent the mean of actual data, with standard errors of transformed data in brackets. Group letters denote Tukey's HSD test results where disturbance levels are significantly different if they do not share a letter. Species full names can be found in List of Species Abbreviations.

Species	Total N (%)	Total C (%)	P (µg/g)	K (µg/g)	Ca (µg/g)	S (µg/g)
Andpol	1.48 (0.05) e	50.45 (0.14) ab	1183.21 (56.46) c	5713.16 (223.39) cde	6905.26 (413.73) cde	1053.89 (38.39) def
Aulpal	0.84 (0.03) gh	42.52 (0.62) fg	878.7 (64.81) d	4290.4 (365.93) fg	8591.35 (952.53) bcd	857 (36.76) fg
Betgla	1.47 (0.05) e	47.59 (0.27) d	1293 (56) bc	5268.15 (591.12) cdef	6281.6 (402.06) cdef	1017.75 (30.15) ef
Caraqu	1.64 (0.08) de	43.68 (0.35) ef	1655.25 (84.91) b	17213.9 (1506.39) b	2811.52 (388.23) g	1132.65 (63.25) cde
Chacal	1.63 (0.07) de	50.94 (0.42) ab	1582.15 (102.03) bc	6133.95 (583.06) cd	5945.05 (294.14) cdef	1331.75 (59.08) bc
Equflu	2.1 (0.06) bc	36.77 (0.26) h	3151.79 (187.35) a	33420.79 (1120.34) a	14986.58 (504) a	1563.26 (50.75) ab
Larlar	1.15 (0.04) f	48.5 (0.25) cd	1444.45 (66.03) bc	5769.1 (275.81) cde	2127.7 (132.67) g	739.85 (25.49) g
Maitri	2.5 (0.1) b	43.24 (0.25) efg	3196.84 (159.41) a	25605.79 (1534.98) a	4562.63 (287.46) f	1475.37 (84.87) ab
Mentri	3.11 (0.11) a	44.36 (0.22) e	3271.69 (183.53) a	27205.06 (1296.68) a	6223.69 (502.46) cdef	1737.69 (100.55) a
Picmar	0.54 (0.02) i	49.49 (0.15) bc	866.47 (54.26) d	3235.26 (224.69) g	7635.32 (393.49) cde	479.37 (21.83) h
Rhogro	1.43 (0.07) e	51.79 (0.17) a	1403.4 (79.8) bc	6344.75 (361.85) c	5182.98 (283.2) ef	1046.75 (40.88) def
Salped	1.81 (0.05) cd	47.98 (0.14) cd	1511.35 (69.02) bc	6429.55 (382.66) c	11429.3 (555.66) ab	1334.3 (79.02) bcd
Sphang	0.7 (0.02) h	41.84 (0.32) g	679.4 (37.38) de	4138.4 (257.63) fg	9209.65 (1310.04) cde	730 (25.15) g

Sphfus	0.79 (0.04) gh	43.41 (0.2) ef	580.4 (38.47) e	4503.7 (350.01) ef	6107.15 (666.21) def	703.3 (26.15) g
Sphwar	0.78 (0.06) gh	42.7 (0.49) fg	595.38 (57.84) e	4046.29 (289.26) fg	9075.57 (810.01) bc	751.19 (38.77) g
Tomnit	0.71 (0.02) h	41.94 (0.67) g	738.75 (44.25) de	4092.6 (214.83) fg	8353.35 (1047.55) cde	765.1 (25.18) g
Vacvit	0.89 (0.03) g	49.24 (0.16) bcd	879.22 (34.53) d	4539.78 (176.97) def	4520.83 (285.64) f	1063.83 (48) def

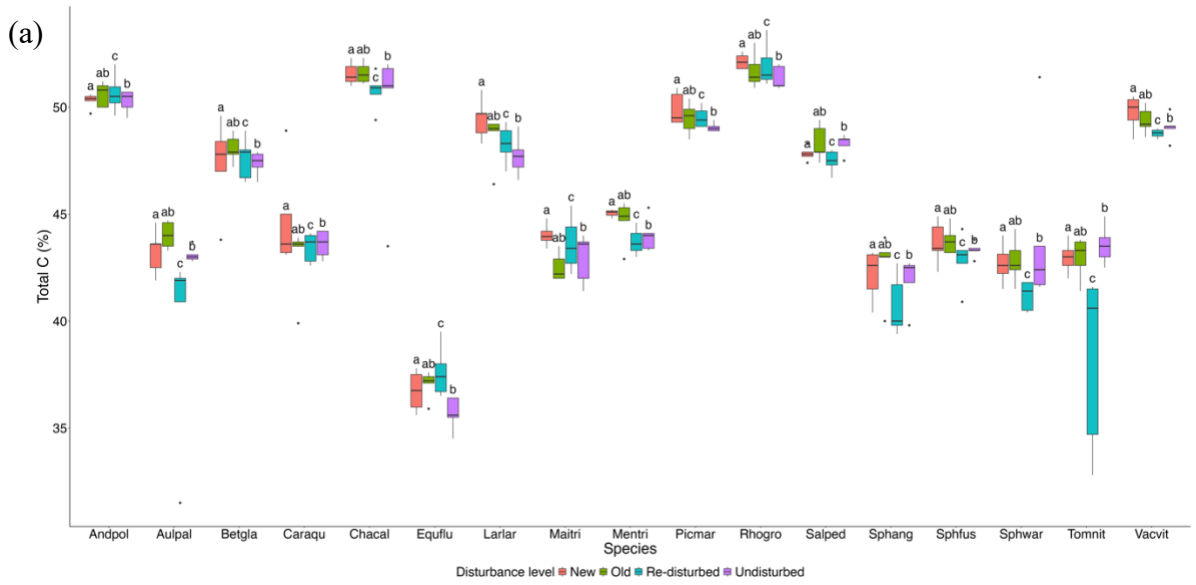


Figure 3.6 Variation in (a) leaf total C (%) across species and disturbance levels in a rich fen in Alberta, Canada.

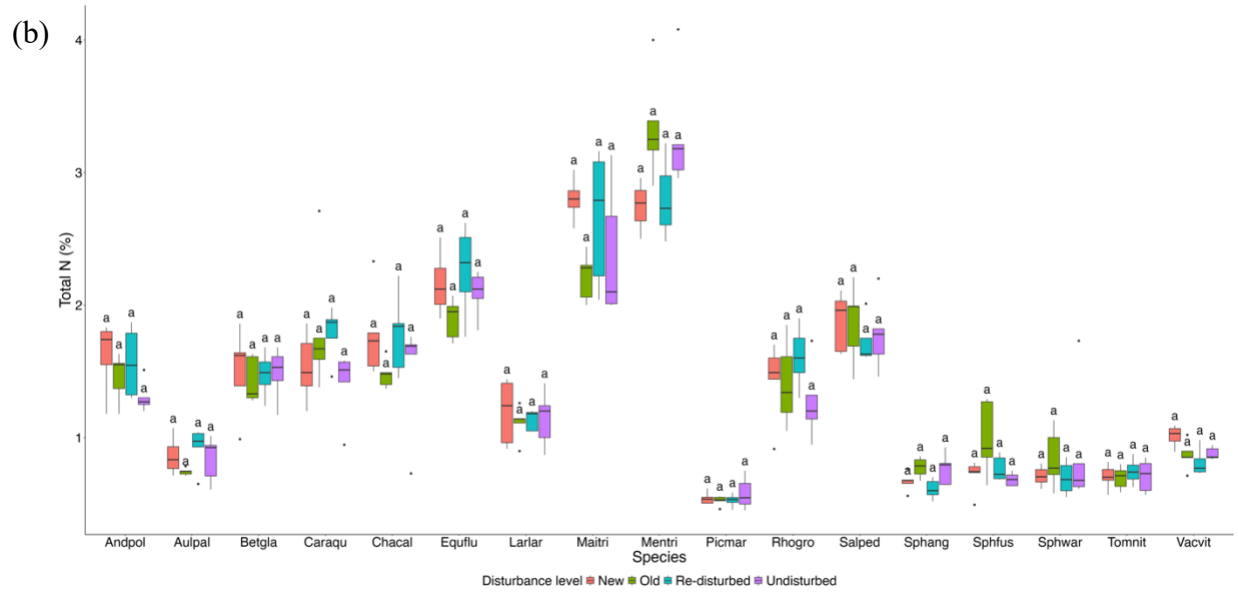


Figure 3.6 Variation in (b) leaf total N (%) across species and disturbance levels in a rich fen in Alberta, Canada.

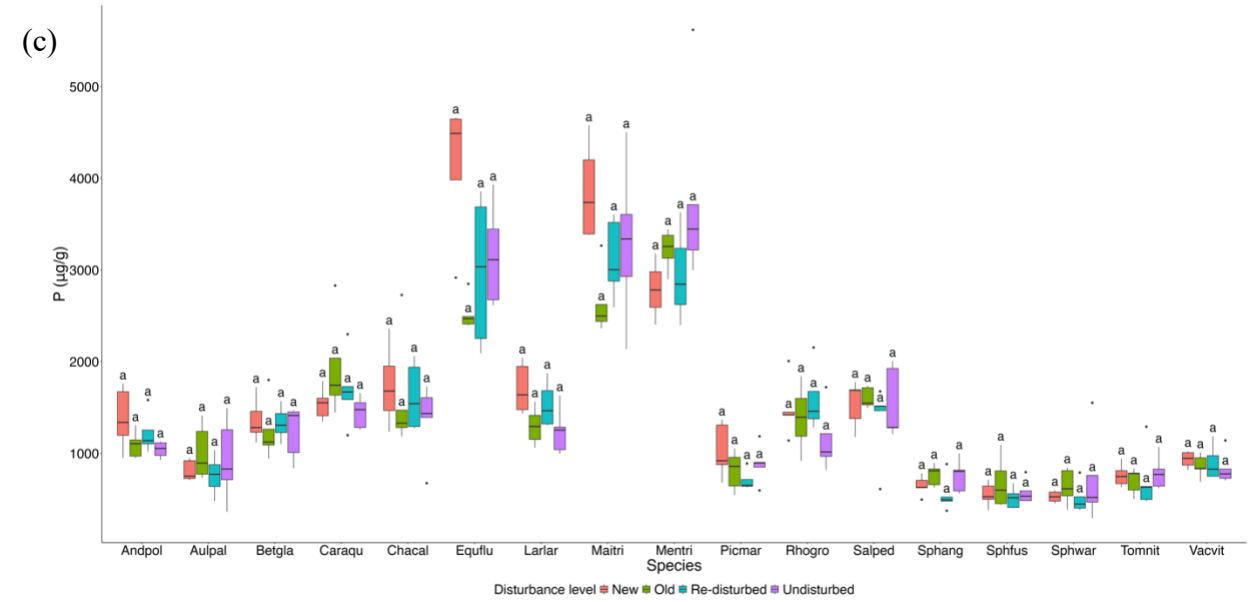


Figure 3.6 Variation in (c) leaf P (µg/g) across species and disturbance levels in a rich fen in Alberta, Canada.

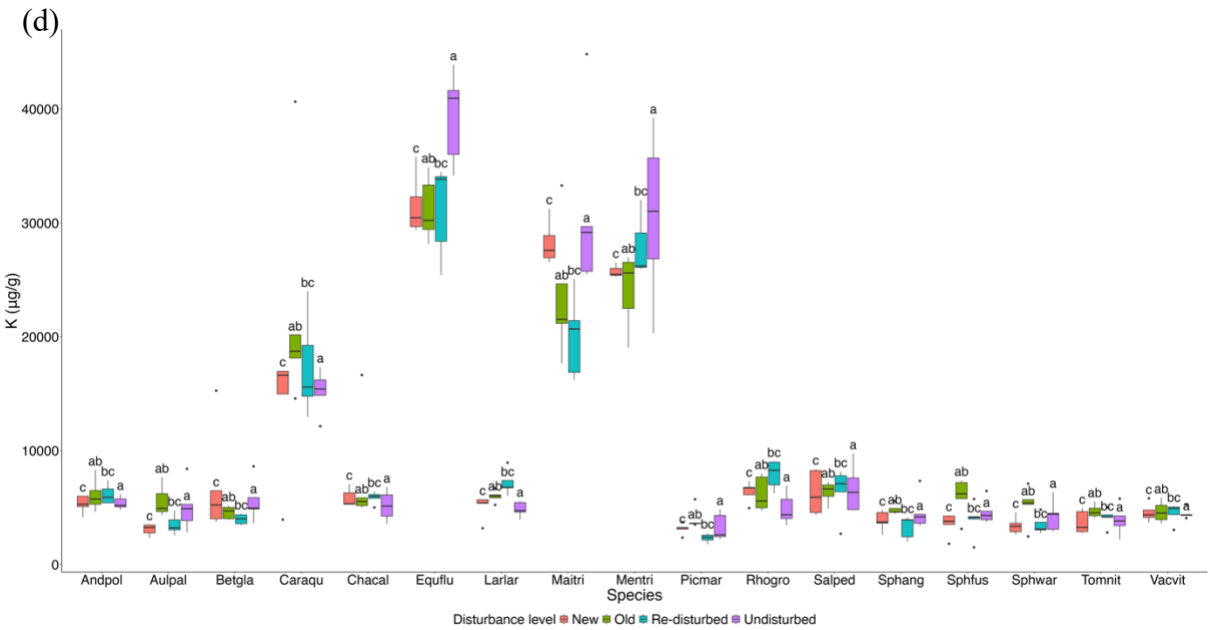


Figure 3.6 Variation in (d) leaf K (µg/g) across species and disturbance levels in a rich fen in Alberta, Canada.

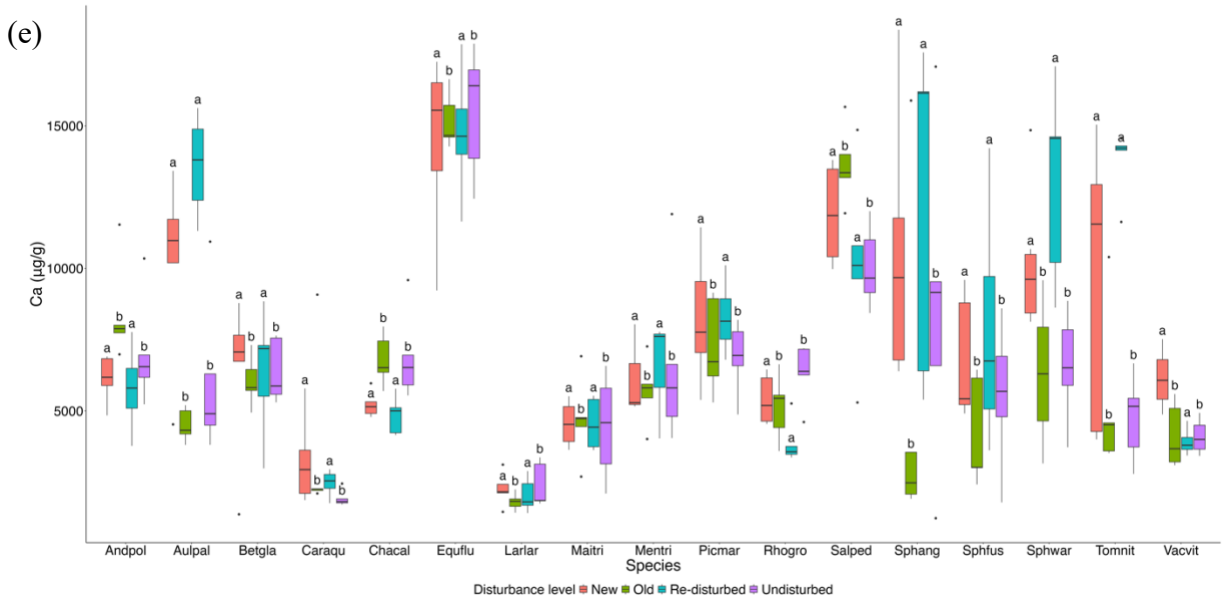


Figure 3.6 Variation in (e) leaf Ca (µg/g) across species and disturbance levels in a rich fen in Alberta, Canada.

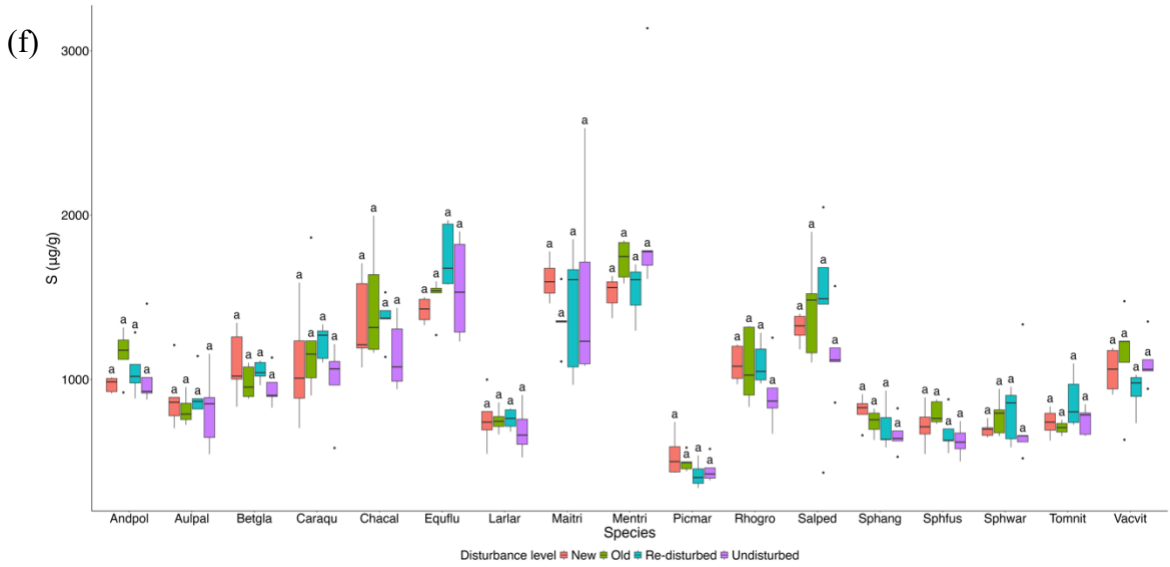


Figure 3.6 Variation in (f) leaf S (µg/g) across species and disturbance levels in a rich fen in Alberta, Canada.

3.4 Discussion

3.4.1 Moss responses to seismic line disturbance

Mosses, particularly *Sphagnum* spp., generally showed resilience to seismic line disturbance, with LDMC remaining almost consistent across disturbance types (Figure 3.5e). However, different moss species showed slightly different responses in LDMC. For instance, *S. warnstorfii* maintained almost consistent LDMC in all sites, whereas *T. nitens* showed a significant increase in undisturbed sites, potentially indicating a lower tolerance to seismic line disturbance. These differences suggest that even within a resilient group like mosses, some species are better suited to cope with disturbed environments depending on their specific water retention capabilities (Adessi et al., 2021).

Unlike LDMC, mosses showed significant variation in leaf C (Figure 3.6a). Specifically, *T. nitens*, showed a notable variation in leaf C, especially in re-disturbed sites, where leaf C was significantly lower than other sites. This variation suggests that *T. nitens* is highly adaptable, potentially adjusting its carbon allocation based on environmental conditions. The decrease in leaf C content as a percentage of total mass for *T. nitens* can suggest a compositional shift within the plant tissue. This shift is likely due to an increase in elements such as Ca and S, or possibly in organic compounds rich in oxygen, given that N content remained relatively unchanged (White & Broadley, 2003). These changes in chemical composition may represent physiological adjustments aimed at enhancing structural integrity and stress resistance (Kraigher et al., 2002). The role of Ca in structural stability and cellular signaling underscores its potential in bolstering plant resilience against physical disturbances and alterations in water chemistry (White & Broadley, 2003). Additionally, the importance of S in amino acid and protein synthesis highlights its role in supporting plant health under environmental stress (Khan et al., 2014). The reduction

in C allocation to structural compounds can decrease the growth and reproductive strategies of *T. nitens*, potentially reducing its competitive ability within disturbed peatlands (Belyea & Malmer, 2004; Turetsky et al., 2000).

In contrast to *T. nitens*, other bryophytes, such as *S. angustifolium* and *A. palustre* showed little variation in leaf C across disturbed and undisturbed sites. It might suggest that these species are more resilient to changes in their environment compared to *T. nitens.* The consistency in leaf C implies that they can maintain their biochemical balance and structural integrity despite external disturbances.

3.4.2 Graminoid responses to seismic line disturbance

Graminoid species, such as *C. aquatilis*, showed varying responses to seismic line disturbance. The SLA of *C. aquatilis* often increases with increased water table level (Gold, 2000). The increase in SLA often allows plants to optimize photosynthesis and recover biomass more efficiently (Hollister & Flaherty, 2010).

This strategy can help *C. aquatilis* regrow from underground rhizomes in disturbed peatlands. In contrast, *E. fluviatile* showed higher LS and SLA in undisturbed areas. With both high LS and SLA, *E. fluviatile* efficiently captures light in undisturbed woody peatlands where light availability is likely lower than on the open seismic lines. Although *E. fluviatile* lacks true photosynthetic leaves, its photosynthetic branches allow for maximum exposure to sunlight. The photosynthetic branches can help maximize light capture and photosynthesis in shaded environments.

The variation in leaf K was different for these two species (Figure 3.6d). *E. fluviatile* had a significantly higher leaf K in undisturbed sites, whereas *C. aquatilis* had less variation in leaf K than *E. fluviatile*. *Equisetum spp.* typically have a high water-uptake efficiency and nutrient absorption in saturated soils (Marsh et al., 2000). The deep rhizomatous system of *Equisetum* allows it to penetrate waterlogged areas and efficiently absorb soluble nutrients such as potassium, which is critical for osmotic regulation and water transport (Husby, 2013). In undisturbed wetlands, where nutrient availability is stable, *Equisetum* species tend to have significantly higher K level compared to disturbed areas. On the other hand, *Carex* spp. can regulate nutrient uptake in a way that minimizes fluctuations, even when environmental conditions change (Pérez-Corona & Verhoeven, 1996). While *Carex* spp. also grow in wet environments, their ability to maintain consistent K levels across different disturbance regimes suggests that it is less reliant on external K availability (Øien, 2004). This suggests that it may possess mechanisms to buffer against external changes in nutrient availability, allowing it to conserve and efficiently use available nutrients without becoming overly dependent on fluctuating K levels in the environment (Bernard et al., 1988).

3.4.3 Forb responses to seismic line disturbance

Forbs, such as *M. trifoliata,* demonstrated considerable plasticity in response to seismic line disturbance. *M. trifoliata*, with its big leaves, showed a significant reduction in LS in old and re-disturbed areas, whereas *M. trifolium* did not show significant reductions in LS in any disturbed sites (Figure 3.5b). The significant reduction in LS of *M. trifoliata* on seismic lines points to its higher plasticity, meaning it can adjust its traits in response to changing environmental conditions. This plasticity can be a strategy to cope with stress, such as increased

competition in disturbed areas (Menichino et al., 2016). In contrast, the lack of significant changes in LS of *M. trifolium* may suggest either a lower degree of plasticity or a resilience to these specific environmental shifts, potentially due to better strategies to disturbances (Gold, 2000).

Although the leaf P levels of *M. trifolium* do not differ significantly across disturbance levels, they are the highest in new sites (Figure 3.6c). Higher P levels often improve the plant's overall metabolic efficiency, supporting processes such as cell division and tissue repair that are essential after a disturbance (Khan et al., 2023). The highest leaf P level in new sites suggests that *M. trifolium* is adapting to take advantage of the newly available resources to build its biomass and maintain its competitive position in the disturbed environment. In contrast, *M. trifoliata* had the highest leaf P level in undisturbed sites (Figure 3.6c). The differences in leaf P levels between *M. trifolium* and *M. trifoliata* may be explained by variations in their root systems, nutrient uptake mechanisms, and competitive strategies.

M. trifoliata likely has a deeper, more established root system in undisturbed sites, allowing it to efficiently access P stored deeper in the soil or via mycorrhizal associations (Khan et al., 2023). On the other hand, *M. trifolium* may possess a more opportunistic root system that allows it to quickly exploit newly available surface nutrients, such as P, released from organic matter decomposition after a disturbance (Nadeem et al., 2022). Additionally, the nutrient uptake mechanisms of *M. trifoliata*, facilitated by mycorrhizal fungi, may be more efficient in undisturbed environments, while *M. trifolium* likely adjusts its root architecture or enhances P transporter activity to cope with sudden nutrient fluxes (Dissanayaka et al., 2020). In undisturbed conditions, *M. trifoliata* can outcompete other species through its ability to maintain high P levels, giving it a physiological edge in growth and reproduction. In fluctuating environments,

M. trifolium's rapid nutrient uptake and adaptability make it more competitive, enabling faster regeneration after a disturbance (Han et al., 2021).

3.4.4 Shrub responses to seismic line disturbance

The contrasting responses of shrub species to seismic line disturbance reflect their differing ecological roles and strategies in disturbed peatland environments. *B. glandulosa* showed a notable increase in height and a slight increase in LDMC in old sites (Figure 3.5a and e), indicating its ability to take advantage of the more stable conditions in these mature peatlands. This response aligns with its successional role as a dominant species in later stages of succession (Chazdon & Guariguata, 2016). The increased resource availability allows for greater investment in structural components, such as stems (Davidson et al., 2021). The slight increase in LDMC is associated with a higher investment in long-lived tissue, which can enhance drought tolerance and nutrient retention (Poorter et al., 2009). The ability of *B. glandulosa* to respond positively to older sites suggests that it is well-adapted to capitalize open light availability following disturbance and then contribute to the gradual recovery of peatland ecosystems.

In contrast, *V. vitis-idaea* showed lower plasticity and maintained relatively low LDMC and small stature across all sites (Figure 3.5a and e). This may reflect its conservative growth strategy, which is typical of stress-tolerant species that are adapted to low-nutrient, acidic conditions (Grime, 1988). *V. vitis-idaea* can grow in nutrient-poor environments without requiring significant changes in biomass allocation or leaf structure (Grime, 2001). Its consistent LDMC and small size may indicate that it relies on a slow, resource-conserving strategy, optimizing for long-term survival rather than rapid growth (Reich et al., 2001). These differences

in responses between the two species suggests that *B. glandulosa* plays a more dynamic role in post-disturbance regeneration, while *V. vitis-idaea* is more suited to maintaining stability in nutrient-limited environments.

The leaf N levels in some shrubs, such as *B. glandulosa, A. polifolia*, and *C. calyculata*, are higher in more recently disturbed sites (Figure 3.6b). Machinery cutting and vegetation removal can lead to increased N availability as plant materials are broken down. The organic nitrogen released into the soil is converted into plant-available forms like NH4 and NO3 (Bejarano-Castillo et al., 2015; Perakis et al., 2015). Additionally, vegetation removal often reduces competition for nutrients, as there are fewer plants present. This allows shrubs to absorb more N during early succession, thereby increasing their leaf N levels, even if the overall amount of N in the ecosystem remains constant (Tu et al., 2022; Zhou et al., 2022).

This higher N content reflects the species' ability to take advantage of newly available nutrients in disturbed environments, enhancing metabolic activities such as protein synthesis and photosynthesis. This is particularly important in early successional stages, where rapid growth provides an advantage for recolonizing disturbed areas (Bejarano-Castillo et al., 2015)

3.4.5 Tree responses to seismic line disturbance

L. laricina and *P. mariana* showed notable species-specific responses to seismic line disturbance (Figure 3.5a and e). *L. laricina* showed a substantial increase in height and a slight increase in LDMC in old sites. This suggests that *L. laricina*, as a faster growing species, capitalizes on post-disturbance resource availability, such as increased light and nutrients, to enhance growth (Poorter et al., 2007). In contrast, *P. mariana* demonstrated more conservative

growth across all sites, with shorter height and lower LDMC in old sites. This aligns with its role as a slow-growing, shade-tolerant climax species, which adopts a more resource-conserving strategy, optimizing for stable, low-nutrient conditions (Reich et al., 2001; Poorter et al., 2009). The difference in growth responses suggests that *L. laricina* has a higher plasticity that allows it to exploit favorable conditions following seismic line disturbance, whereas *P. mariana* maintains a consistent, conservative growth approach, focusing on long-term survival under stable, low-light environments (Grime, 2006).

L. laricina and *P. mariana* showed notable differences in leaf Ca variation, with *P. mariana* having greater variation than *L. laricina* (Figure 3.6e). This can be attributed to their different nutrient uptake strategies to environmental conditions. *P mariana,* a slow-growing, shade-tolerant evergreen species typically adapted to low-nutrient environments may show greater variation in leaf Ca (Morris, 2000). This is likely due to its conservative nutrient strategy, where it adjusts Ca uptake based on environmental conditions (Greenway et al., 1992). This variation likely reflects its need to optimize nutrient acquisition in response to disturbances that alter soil composition (Aerts & Chapin, 2000). In contrast, *L. laricina* showed more stable leaf Ca levels. The role of Ca in maintaining leaf structure could mean that *L. laricina* focuses on maintaining stable Ca levels to ensure steady growth, while *P. mariana* adjusts its Ca content in response to varying environmental stresses (White & Broadley, 2003). These species-specific responses highlight the contrasting ecological strategies of the same plant functional group in adapting to nutrient availability and disturbance (Poorter et al., 2009).

3.4.6 Community-level shifts and the effect of ITV

At the community level, the CWM of traits across disturbance levels showed a trend toward resource acquisition in new and re-disturbed sites, whereas older sites exhibited traits that point towards resource conservation. Species with higher ITV, such as *B. glandulosa* and *M. trifoliata*, contributed to community-level shifts by adjusting their traits to cope with environmental changes. In new and re-disturbed sites, species like *M. trifoliata* showed plasticity in LS, which facilitated rapid growth and resource acquisition under disturbed conditions. Conversely, in older sites, species like *V. vitis-idaea* maintained a more conservative strategy by investing in carbon-rich tissues. This strategy supports resource conservation and long-term survival (Grime, 2006; Wright et al., 2004).

Species-specific responses, driven by ITV, played an important role in shaping community-level patterns. For example, the ability of *B. glandulosa* to increase LDMC in older sites suggests a shift toward greater tissue investment and drought tolerance as resource competition intensifies during succession (Champagne et al., 2012). On the other hand, the lower ITV in *P mariana* and *A. palustre*, which maintained almost consistent trait values across all sites, indicated a more conservative growth strategy that limits their adaptability to changing conditions (Poorter et al., 2009). Species with high ITV can modulate trait expression, which are important in maintaining ecosystem resilience and its ability to recover after disturbances (Violle et al., 2012).

The community-level shifts in plant functional traits highlight the importance of both inter- and intraspecific variation in response to seismic line disturbance. Species with higher ITV, such as *B. glandulosa* and *M. trifoliata*, contribute more dynamically to changes in functional

composition, facilitating ecosystem recovery, while other species take a more conservative, slower approach to regeneration.

3.5 Conclusion

In conclusion, the variation in plant traits across disturbance levels highlights the significant influence of seismic lines on plant community composition and ecosystem functions. Undisturbed sites served as the reference for comparison, showing stable conditions with plant traits that support long-term survival and resource conservation. Old sites, which have experienced about 30 years of natural regeneration, demonstrated a transition toward late-successional stages with traits favoring taller plants and strategies for conserving resources, such as higher SLA and greater plant height.

Conversely, new and re-disturbed sites reflected responses to more dynamic environments, with a shift in traits towards resource acquisition, such as bigger leaves and lower LDMC. These traits are advantageous in early succession but may come at the cost of long-term ecosystem resilience. At the community level, the CWM of traits showed a trend towards resource acquisition in new and re-disturbed sites, whereas older sites showed traits moving towards resource conservation. Species with higher ITV, such as *B. glandulosa* and *M. trifoliata*, contributed to these community-level shifts by adjusting their traits to cope with environmental changes. For example, *M. trifoliata* showed plasticity in LS, facilitating rapid growth in disturbed environments, while species like *V. vitis-idaea* maintained a more conservative strategy in older sites by investing in carbon-rich tissues for long-term survival.

Species-specific responses, driven by ITV, also contributed to shaping community-level patterns. *B. glandulosa*, for instance, had a higher LDMC in older sites, suggesting a shift towards greater tissue investment as competition intensifies during succession. On the other hand, species with lower ITV, such as *P. mariana* and *A. polifolia*, maintained relatively consistent trait values across all sites, indicating a more conservative growth strategy that limits their adaptability to changing environments.

The relationship between plant traits and ecosystem functions indicates that disturbance level plays a crucial role in shaping survival strategies. In older sites, plant traits promote nutrient uptake efficiency and ecosystem resilience, while in more recently disturbed sites, traits that support rapid resource utilization dominate. While this strategy facilitates immediate regeneration, it may compromise long-term ecosystem recovery. Nevertheless, the rapid growth of species such as *B. glandulosa* contributes to recreating shady ground-layer conditions, which can potentially help the ecosystem move towards a structure and function more similar to undisturbed conditions, even at the cost of slower-growing species like *P. mariana* requiring longer regeneration periods.

Overall, both shifts in community composition and ITV in response to disturbance are important in shaping peatland plant community functions following seismic line disturbance. These complex interactions underline the importance of understanding both inter- and intraspecific trait responses to different disturbance levels for the successful restoration and management of peatland ecosystems.

Chapter 4 Conclusions

4.1 Summary of main findings

This study investigates the ecological shifts in a rich fen following seismic line disturbance and provides insights for restoration strategies and environmental policy. It highlights how seismic lines cause long-lasting changes to plant community composition and ecosystem functions, but also emphasizes that natural regeneration processes are at play. In old sites, traits favoring long-term survival and resource conservation emerge over time, suggesting that peatlands have the capacity to gradually move towards recovery.

New and re-disturbed sites are characterized by traits that favor rapid growth and resource acquisition, but these strategies may compromise long-term resilience. However, species like *B. glandulosa*, through their rapid growth, help recreate the necessary environmental conditions that promote recovery, illustrating how species-specific responses can contribute to ecosystem stability.

The study emphasizes the important role that both community composition shifts and ITV play in peatland recovery. Disturbance levels strongly influenced plant community composition and plant traits, with undisturbed and old sites showing successful progression towards later successional stages, where traits favored resource conservation and long-term resilience. In contrast, plants on newly disturbed and re-disturbed sites adapted to dynamic conditions by favoring rapid growth and resource acquisition. The extent of ITV varied among plant functional groups and species. While ITV played a role in shaping plant traits and functions following disturbance, changes in CWM of traits were more significant than shifts in mean traits alone. This suggests that interspecific differences and shifts in species composition are the

primary drivers of changes among disturbance levels. The balance between natural processes and targeted restoration interventions is important for effective peatland management. The insights gained from this research have important implications for guiding conservation policies and land-use strategies that promote both ecological resilience and sustainable restoration of disturbed peatland ecosystems.

4.2 Significance of study

The study on the impact of seismic line disturbance in peatlands makes important contributions to ecological understanding, restoration practices, and environmental policy. It investigates the shifts in plant community composition following seismic line disturbance, revealing a trend towards species that thrive in wetter conditions typically found on seismic lines in peatlands. Moreover, the research identified key environmental factors, such as DTW, pH, and EC, as primary drivers of community composition, highlighting the importance of peatland type over the disturbance itself. While some species, such as trees, require more time to regenerate, natural regeneration, overall, is sufficient for peatland recovery following seismic line disturbance. Older sites demonstrated that natural processes, given enough time, can facilitate the regeneration of key species and ecosystem functions without the need for extensive interventions. However, targeted efforts are still beneficial to accelerate the establishment of the slower-growing species. Restoration efforts should aim to maintain the functional integrity of these reestablished communities while recognizing that some areas are already progressing toward a pre-disturbance state.

These findings have important implications for policy and conservation, providing evidence-based insights that can help policymakers and conservationists formulate more

effective land-use policies and conservation strategies. By promoting a better understanding of the long-term impacts of seismic lines, the study supports the need for management strategies that consider both ecological and environmental complexities. This approach can lead to more robust and effective conservation efforts, ensuring the preservation of peatland ecosystems in the face of ongoing disturbances.

4.3 Future research needs

Future research should address several outstanding questions and expand on the findings from this study. A deeper investigation into nutrient cycling and the relationships between leaf and soil chemistry is necessary to resolve these discrepancies. Expanding the study to include a wider range of peatland types, such as bogs and poor fens, would also enhance the applicability of the findings.

Bogs are nutrient-poor and typically dominated by *Sphagnum* mosses and acid-loving plants. Their low nutrient availability and reliance on precipitation make them particularly sensitive to disturbances, which can disrupt their delicate hydrological balance and nutrient cycling. As a result, bogs tend to recover slowly after disturbances, sometimes taking decades or even centuries (Lavoie et al., 2003). Following disturbance, bog vegetation may shift towards more nutrient-demanding species, potentially altering the ecosystem in fundamental ways (Limpens et al., 2008). In contrast, poor fens receive some nutrient input from groundwater, making them more nutrient-rich than bogs. This allows fens to support a more diverse plant community, including sedges and grasses, and they often show different recovery patterns. Fens tend to be more resilient to disturbances due to their ability to draw on external nutrient sources,

which can accelerate vegetation recovery. However, changes in water table levels and nutrient inputs from disturbances can still lead to shifts in species composition, often favoring fast-growing, nutrient-demanding species (Klimkowska et al., 2019). Expanding the study to include these peatland types would allow for a more comprehensive understanding of how peatland ecosystems as a whole respond to seismic line disturbance. Previous studies have shown that bogs and fens respond differently to disturbances in terms of recovery speed, species composition, and hydrological stability (Caners & Lieffers, 2014; Clarke et al., 2014; Guêné Nanchen et al., 2021). Including them in future research will enhance the applicability of the findings by accounting for these variations, providing more robust insights into peatland restoration and management strategies (Pellerin et al., 2015). This broader perspective will help determine whether the patterns observed in this study are unique to specific peatland types or represent generalized responses across a range of peatland ecosystems.

Furthermore, future studies should incorporate additional functional traits such as root length and photosynthetic rate to offer a more detailed view of how plants adapt and contribute to ecosystem recovery. Root length is a critical trait that determines a plant's ability to access water and nutrients (Liu & von Wirén, 2022), especially in disturbed environments where soil may be compacted. Including root traits can provide insights into how different species adapt to fluctuating water tables or soil nutrient levels, particularly in peatlands where hydrology plays a central role in ecosystem functioning. Photosynthetic rate is another important trait that reflects how efficiently a plant can convert light into energy, directly impacting growth rates and carbon sequestration (Loisel et al., 2012). Measuring these traits can reveal how species adapt to changes in light availability following seismic line disturbance.

Moreover, while this study inferred plant community functions based on traits, future research should focus on directly measuring ecosystem functions, such as carbon cycling, nutrient cycling, and litter production. For instance, measuring carbon fluxes can help quantify how well peatlands recover their role as carbon sinks post-disturbance. Similarly, understanding changes in nutrient cycling can reveal how seismic line disturbance alter soil nutrient dynamics and the availability of essential elements. By tracking litter production, we can assess how well plant species contribute to the organic matter accumulation necessary for peat formation. By incorporating these direct measurements of ecosystem functions alongside a broader range of plant traits and peatland types, future research can provide a more comprehensive understanding of how peatlands recover and function after seismic line disturbance. This approach will also enhance our understanding of the ecological dynamics that govern the resilience and sustainability of peatland ecosystems, ultimately guiding more effective conservation and restoration strategies.

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Appendix A: methodological details on DTW measurements

Depth to water (DTW) measurements were conducted as part of the larger Boreal Ecosystem Recovery and Assessment (BERA) program. Using drone-acquire imagery of the study sites, supervised classification was performed on the orthomosaic to identify surface water, utilizing the canopy height model (CHM) to exclude any areas with canopy coverage over 0.2 m, ensuring only visible water bodies were classified. Training sites for surface water, ground, and shadowed ground were manually digitized to train a classification model using the *rpart* package (Therneau & Atkinson, 2023). Following classification, the derived surface water raster was used to mask the digital terrain model (DTM), and the elevations of these water pixels formed the base data for interpolating a water table surface using ordinary kriging with the *gstat* package (Pebesma, 2004). The kriging was calibrated specifically for this study's peatland conditions, employing a Matern semivariogram model. This interpolation, combined with DTM, produced a DTW raster, highlighting the water table's spatial variation relative to the ground surface. In areas classified as open water, the DTW was set to zero, reflecting the methodological limitation of near-infrared LiDAR in detecting submerged ground surfaces.