Quantifying greenhouse gas emissions on a peat stockpile in the northern Alberta Oil Sands Region

by

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Author’s Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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Abstract

The Oil Sands Region (OSR) in Alberta, within Canada's boreal forest, is a combination of three recognized oil deposits. The boreal forest in the OSR can reach peatland coverage of over 50%. Peatlands are natural carbon sinks through a net uptake of atmospheric carbon dioxide (CO_2). The removal of peat for mining operations and the subsequent stockpiling of the peat under aerated conditions promote organic matter decomposition, potentially emitting significant amounts of carbon into the atmosphere. Peat stockpiles in the oil sands can stand for decades, often with actively introduced vegetation on the surface, leaving the actual decomposition rates largely unknown. Some studies suggest that all carbon is lost from peat in stockpiles during the initial stripping and stockpiling process, and final use as reclamation soil. This research aims to improve our accounting of wetland soil carbon losses for national emissions reporting by evaluating the carbon emissions on a peat stockpile at an in-situ oil sands lease across different vegetation treatments, locations, and soil moisture contents. To evaluate peat decomposition and carbon emissions, a laboratory incubation with peat samples from the stockpile was conducted over 5 weeks, and in-field carbon fluxes were measured weekly over 4 months using the closed chamber technique for both CO_2 and methane (CH_4) exchange. The incubation study included peat samples from bare organic, fen, and grass locations on the stockpile. Different soil moisture contents, as well as the presence of roots, were analyzed. The interaction between soil moisture and root presence moderately affected respiration from the peat samples, with the fen sample respiring the most. However, CH_4 flux was weakly affected by the same interaction. All wet samples (high soil moisture treatment) produced more CH_4 than their dry counterparts. These results give some insight into how the in-field processes of soil moisture and vegetation presence may affect decomposition and respiration. To confirm these results, in-field flux measurements were conducted on the stockpile. Fluxing collars with intact vegetation, clipped vegetation, and trenching were set up along a transect to compare soil respiration and net ecosystem exchange. Each collar treatment was set up in four elevated, dry locations dominated by shrubs and grasses, and four depression locations, with high soil moisture and with mainly sedges present. Biomass was collected to determine the total addition of new organic matter. The net carbon balance of the stockpile treatments was estimated as the difference between soil respiration, CH_4 flux, and carbon accumulation in biomass to determine how large a carbon source the stockpile has become. Results suggest no significant difference between stockpile locations (depressions vs elevations) for ecosystem respiration, gross ecosystem production, or net ecosystem exchange, but CH_4 emissions were significantly higher at depressions on the top of the stockpile. Depression locations had a greater range in net ecosystem exchange, gross ecosystem production, and ecosystem respiration due to the dense vegetation at these locations and optimal soil moisture contents. The significant increase in CH_4 flux at these wet locations, and the greater range in CO_2 produced and consumed, align with the findings in the incubation experiment. However, the effects were more pronounced in the in-field data. Utilizing the flux data and the biomass data, the net carbon balance of the stockpile is approximately 539 g C m^{-2} yr^{-1}. This value indicates that even after a standing duration of 6 years, the stockpile is still a large source of carbon to the atmosphere. All carbon was not lost during the initial construction processes, and serves to be a continuous carbon source in the future. Therefore, large peat stockpiles on oil sand leases have substantial implications for carbon emissions, and accurate emission reporting is needed. This study highlights the importance of studying peat stockpiles since they are large carbon sources and understudied overall. This data will be utilized for annual estimates of peat stockpile-related carbon losses, which will add to our limited knowledge of national-scale estimates of carbon losses from organic soils disturbed by oil sands operations and other infrastructure.

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Chapter 1

Introduction

Alberta, Canada has a surface area comprised of 20% wetland ecosystems, and 90% of these ecosystems are peatlands (Alberta Wetland Policy, 2013). Peatlands are areas of land that are responsible for storing substantial amounts of organic soil carbon and are termed carbon sinks (United Nations Environment Programme, 2022). Currently, industries are disrupting peatland function due to land use changes and are shifting them to long-term sources of carbon dioxide (CO_2) (Lehan et al., 2022). This is common practice in northern Alberta, as peatlands are becoming increasingly disturbed due to the expanding oil and gas industry (Alberta Wetland Policy, 2013). As of 2016, it is estimated that there are approximately 39,000 km^2 of land in Alberta being impacted by the oil and gas industry (ABMI, 2018). The amount of disturbed land will continue to increase in the coming years, as thousands more square kilometres of land have already been leased to oil sands operators (ABMI, 2018). A common practice on oil sands leases includes the removal of the surface layer of peat to construct infrastructure such as processing facilities and access roads (Lemmer et al., 2022). This surface peat is then stored in an expansive stockpile where the greenhouse gas (GHG) emissions from the peat are relatively unknown due to the vastly different conditions that disturbed peat is stored in compared to an undisturbed peatland (Rooney et al., 2012; ECCC, 2021). The stockpiling of peat has the potential to affect variables such as peat temperature, moisture content, and the presence of vegetation, among other variables, which can impact the rate of peat decomposition (Cleary et al., 2005). It is suggested that as peat is transported from water-saturated conditions in its natural environment to an aerated, dry stockpile, organic matter decomposition resulting in the release of that carbon to the atmosphere, likely as carbon dioxide (CO_2; Cleary et al., 2005; ECCC, 2021). Due to the decade-long standing duration of peat stockpiles, vegetation appears or is planted by industries to reduce erosion (Alberta Environment and Water, 2012). Peat from stockpiles is often used during reclamation, where it is combined with mineral soil and deposited in areas that have been disturbed (Wadu and Chang, 2018). The Alberta oil sands industry is continuously impacting pristine peatlands and is altering the ability of continued carbon storage to occur (Rooney et al., 2012).

To provide background on carbon dynamics in peatlands, peatland significance will be discussed along with CO_2 uptake and release, and methane (CH_4) production, consumption and transport. The practice of peat stockpiling including best management practices and the justifications for this will be analyzed. Controls on organic matter decomposability such as nutrient content, litter type, and priming will be described in the context of natural peatlands. The controls on soil and ecosystem respiration (ER) in the field including temperature, soil moisture, oxygen availability and microbial communities will also be discussed in the context of natural peatlands. The overall role of vegetation in carbon uptake will also be looked at. To tie these topics together, the impacts of these variables for peat carbon emissions under stockpile conditions will be analyzed. The gaps in the literature and proposed objectives to fill these gaps will then be discussed.

1.1 Peatland Importance and Carbon Dynamics

Peatlands are wetlands that contain a decomposed layer of plant material at least 30 cm deep (Lai, 2009, Strack et al., 2022). These areas cover about 4.16 x 10^6 km^2 worldwide, with most peatlands located in temperate-cold climates, mainly in Russia, Canada and the United States (Limpens et al., 2008). Although peatlands cover less than 3% of Earth's total land area (United Nations Environment Programme, 2022), globally, peatlands store a range of 450 – 650 Pg C (Food and Agriculture Organization, 2020), with northern peatlands storing approximately 415 Pg C (Hugelius et al., 2020). This equals around 33% of the world's soil carbon (Strack et al., 2006; United Nations Environment Programme, 2022). Yearly carbon accumulation is the result of carbon inputs from plant production exceeding the export of carbon from peatlands in gases, such as CO_2 and CH_4, or dissolved organic carbon, which are all the results of plant and organic matter decomposition (Chapin et al., 2006; Moore and Basiliko, 2006; Harris et al., 2020). Methane emission rates within peatlands are largely explained by the difference between CH_4 production and consumption (Bubier et al., 1993; Le Mer and Roger, 2001).

1.2 Carbon Dioxide Uptake and Release

Peatlands are characterized by a slow accumulation of organic matter resulting from anoxic conditions, low temperatures, and slowing decomposing organic matter and litter that together limit activity of the decomposer community (Moore and Basiliko, 2006). The main carbon input comes from plants fixing CO_2 from the atmosphere through photosynthesis and storing it within living and dead plant biomass (Bubier et al., 1993; Vasander et al., 2006; Baird et al., 2009). Photosynthesis is an environmental process that is fueled by sunlight and a carbon source of CO_2 (Vasander et al., 2006). Although peatlands are a major carbon sink, some carbon is still lost to the atmosphere in the form of CO_2 (Baird et al., 2009). Eventually, some of the carbon stored within plants returns to the atmosphere as CO_2 through heterotrophic respiration, as microbes decompose to get energy (Vasander et al., 2006; Baird et al., 2009). In addition to this, some of the fixed carbon is released back into the atmosphere as CO_2 during autotrophic respiration processes (Chapin et al., 2006), supporting the growth and maintenance of aboveground and belowground plant parts and heterotrophic organisms (Vasander et al., 2006). These processes mainly occur within the aerobic zone, with some occurring in the anaerobic zone due to the presence of oxygen from plant roots being able to oxidize CH_4 and transport it to the atmosphere as CO_2 (Lai, 2009; Bridgham et al., 2013). Whatever carbon is not lost to the atmosphere during photosynthesis and autotrophic respiration is turned into plant structures, mainly the belowground parts of plants, and eventually deposited as litter on the surface of and in the soil (Saarinen, 1996).

1.3 Methane Production, Oxidation and Transport

In addition to the release of CO_2, wetlands are the largest source of terrestrial atmospheric CH_4 (Gorham, 1991; Bubier et al., 1993; Le Mer and Roger, 2001; Strack et al., 2006; Baird et al., 2009). Wetlands produce, on average, 159 – 165 Tg $year^{-1}$ of CH_4 (Saunois et al., 2025). The production of CH_4 occurs largely in the anoxic, part of the peat, where decomposition is slow (Vasander et al., 2006). The position of the water table largely determines the release of CO_2 vs. CH_4 due to its determination of the boundary between oxic and anoxic conditions within the peatland (Bubier et al., 1993;

Lai, 2009). The populations of methanogens (CH_4-producers) and methanotrophs (CH_4-consumers) and the ability of the peat to provide adequate substrate to produce gases also play an important role in net emissions (Bubier et al., 1993). Litter inputs to the soil contain organic carbon that needs to be broken down before it is usable by methanogens (Bridgham et al., 2013), a group of microorganisms that produce CH_4 (Lai, 2009). This is a process of fermentation and can have multiple steps depending on the makeup of the initial substrate (Le Mer and Roger, 2001; Bridgham et al., 2013). Through the fermentation process, the organic matter is broken down and depending on the results, CH_4 can be generated by two different groups of methanogens (Le Mer and Roger, 2001; Lai, 2009; Bridgham et al., 2013). The acetate pathway occurs when acetate is directly deposited into the peat through root exudates or produced in the fermentation process (Bridgham et al., 2013). Acetoclastic methanogens use acetate (CH_3COOH) as a substrate to produce CH_4 and CO_2 (Lai, 2009; Bridgham et al., 2013). The hydrogen pathway occurs after the fermentation process when the product is H_2 and CO_2 (Lai, 2009; Bridgham et al., 2013). H_2 and CO_2 are used as a substrate by hydrogenotrophic methanogens to produce CH_4 and water (Lai, 2009; Bridgham et al., 2013). Acetoclastic methanogenesis is the dominant pathway in upper peat layers with labile organic material, and hydrogenotrophic methanogenesis is the dominant pathway in the lower peat layers with recalcitrant organic material (Lai, 2009). Despite only a small number of methanogenic species being able to use acetate as a carbon and energy source, the acetate pathway produces about two-thirds of CH_4 in peatlands (Le Mer and Roger, 2001). New research suggests that methylotrophic methanogenesis is another form of CH_4 production. Hanna et al. (2020) determined rates of CH_4 production using methylated substrates, such as methanol, to see if microbes could use it as a substrate for CH_4 production. Results showed that CH_4 production occurred using methanol at all sites and all peatland depths (Hanna et al., 2020). This study suggests that methylotrophic methanogenesis may be responsible for up to 11% of total CH_4 production in northern peatlands (Hanna et al., 2020).

CH_4 production can be limited due to the presence of alternative terminal electron acceptors (TEAs), such as nitrate, iron, and sulphate. The end products of the fermentation process used by methanogens can also be used by microbes present in the peat that use other TEAs in their metabolism (Bridgham et al., 2013). For example, sulphate-reducing bacteria can outcompete methanogens for hydrogen because of their increased affinity for this to be used as substrate (Bridgham et al., 2013). This competition amongst microorganisms reduces the ability of hydrogen to be used as a substrate for methanogenesis, which decreases CH_4 production (Bridgham et al., 2013).

Before CH_4 is transported to the atmosphere, methanotrophs —a subset of eubacteria that utilize single-carbon compounds, such as CH_4, for growth and maintenance —can oxidize it, primarily in the oxic layer (Lai, 2009). Methanotrophs use oxygen as a TEA to oxidize CH_4 and transform it into CO_2 (Le Mer and Roger, 2001; Limpens et al., 2008; Lai, 2009). Some studies estimate that approximately 40–70% of CH_4 produced is oxidized before reaching the atmosphere (Megonigal et al., 2004), while others say that up to 90% of CH_4 becomes oxidized as it moves through the peat profile (Fechner and Hemond, 1992; Le Mer and Roger, 2001). Methanotrophic activity is most prevalent in the areas closest to the water table. This is the overlap area between the oxic and anoxic zones where there is sufficient oxygen and CH_4 (Lai, 2009).

CH_4 is transported to the atmosphere in three ways: diffusion through the peat profile, plant-mediated transfer, and bubbles released as ebullition (Baird et al., 2009; Lai, 2009; Bridgham et al., 2013). Due to the large production of CH_4 in the anoxic zone, there is a concentration gradient between the peat and the atmosphere, which drives diffusion (Lai, 2009). Transport to the atmosphere through plant-mediated CH_4 flux through aerenchymous tissue is an important pathway because it allows the gases to bypass aerobic methanotrophy (Bridgham et al., 2013). Some studies suggest that plant-mediated CH_4 flux accounts for between 38 – 51% of total transport (Dorodnikov et al., 2011), while others estimate plant-mediated fluxes are responsible for approximately 88% of CH_4 transport to the atmosphere (Cheng et al., 2006). Lastly, ebullition occurs when CH_4 bubbles form in peat pore water and are transported to the peat surface (Lai, 2009; Ramirez et al., 2015).

1.4 Peat Stockpiles

Stockpiles are required to store peat that has been stripped from areas in an oilsands lease that are being developed for mining infrastructure (Rooney et al., 2012). Operators clear the land and store different soil types, such as peat and upland soil, in separate stockpiles so decisions can be made regarding the use of peat (Alberta Environment and Water, 2012). During future land reclamation, stockpiled peat is often mixed with mineral soil to form what is known as a peat-mineral mix (Wadu and Chang, 2018). This is deposited in areas affected by oil sands operations and helps to reverse degradation and convert the land back to its original productivity by enhancing water retention and plant growth (Wadu and Chang, 2018).

These large piles of peat remain for long periods of time, often decades, due to the lengthy duration of mining processes. Studies have found that stockpiling peat alters its quality and the viability of the seeds present, even when stockpiled for shorter durations (Rokich et al., 2000). Studies further suggest that stockpiling peat alters properties such as pore structure, and stockpile height and storage duration affect overall peat function (Lehan et al., 2022). In the Alberta Oil Sands Region, large stockpiles, greater than 6 m high, were shown to significantly reduce the viability of various boreal plant roots and seeds when studied after being stored for eight months (Alberta Environment and Water, 2012). The quality of the peat itself in stockpiles has not been extensively researched. Some studies advise that nutrient contents in peat stockpiles are similar to those in natural peatlands; however, if mixed with mineral soil, the rates of peat decomposition could increase due to the shift in chemical properties (Kong et al., 1980).

The formation of peat stockpiles is imprecise and dependent on mining companies, so soil type and age within stockpiles can become inconsistent due to their initial formation. Stockpiles should be constructed in multiple, small batches, between 1–3 m tall, with maximum surface area to ensure soil quality is consistent with undisturbed areas (Alberta Environment and Water, 2012). The revegetation of these smaller stockpiles, with increased surface area, can also help to retain beneficial soil microorganisms (Alberta Environment and Water, 2012). As a result of exposing peat to an environment that is drier and more aerated than its initial conditions, decomposition is likely to increase, subsequently increasing overall emissions from the stockpile (Cleary et al., 2005; ECCC, 2021). When peat is disturbed in this way, there are initial fundamental shifts in the water table, which increase the diffusivity of pore gases, one of the outlets for increased emissions (Moore and Dalva, 1993). Without the ability to retain water in these dry conditions, irreversible peat deformation can occur, and the ability to be utilized as reclamation soil diminishes (Lehan et al., 2022).

Peat stockpiles in the oil sands are different compared to those present at peat extraction sites. The site is manually drained, surface vegetation is removed, and the upper layers are milled to dry out the peat (Waddington et al., 2009). Small stockpiles are then created after the vacuum harvester collects the newly dried peat and lets it sit for anywhere between 5 – 6 months, where they are a major source of GHG emissions (Waddington et al., 2009). Even smaller stockpiles are created using the acrotelm transplant technique, which stores a small volume of peat for a couple of days between each step of drying in the factory (Waddington et al., 2009). After the stockpiling period, the peat is then processed and bagged in a factory for its eventual sale and use in the horticultural industry (Waddington et al., 2009). This extraction and stockpiling process can occur for up to 20 – 30 years, until the site is no longer economically profitable (Waddington et al., 2009). Horticultural peat stockpiles differ from those in the oil sands mainly because of their significantly shorter standing duration (days or months vs. multiple decades), their composition (surface layer peat vs. mixture of materials), and soil moisture (manually dried out vs. higher moisture content).

To mitigate the negative impacts that stockpiles have on peat and its properties, introducing vegetation on the stockpile could be beneficial (Alberta Environment and

Water, 2012). An attempt should be made to introduce native peatland species on stockpiles to improve weed control, erosion, seed bank build-up, and reduce greenhouse gas emissions (Alberta Environment and Water, 2012), though the expected dry conditions on peat stockpiles may inhibit such growth. If native plant growth is possible, it will ultimately help keep the peat viable for use on its own or in a peat-mineral mix as future reclamation soil without significantly adding to the existing emissions resulting from oil sands operations (Rooney et al., 2012; Wadu and Chang, 2018).

1.5 Controls on Organic Matter Decomposability

Organic matter decomposability refers to how inherently decomposable peat material is and it changes within the peat profile (Moore et al., 2008; Leifeld et al., 2012). Variables such as substrate quality, litter type, and priming all affect the decomposability of peat. Although there are numerous controls, these are the ones that will be the focus of this literature review.

1.5.1 Substrate Quality

Substrate quality refers to the ability of organic material, in this case peat, to be decomposed by microorganisms (Rydin et al., 2006). Substrate quality in peatlands is primarily driven by its organic matter composition and the availability of nutrients. The quality of organic matter is in part related to its depth in the peat profile, chemical composition, and structure (Leifeld et al., 2012; Neubauer and Megonigal, 2022). Deeper in the peat profile is generally where older organic matter is found and it is termed as being recalcitrant, due to its chemical structure, and the waterlogged and anoxic conditions enhance its preservation (Leifeld et al., 2012; Neubauer and

Megonigal, 2022). Organic matter located shallower in the peat profile (near the surface) is termed labile, due to the availability of easy-to-breakdown compounds, with environmental conditions, such as greater oxygen availability, further enhancing decomposition (Leifeld et al., 2012; Neubauer and Megonigal, 2022). The chemical composition of organic matter in wetlands relies on its source material (Neubauer and Megonigal, 2022). Certain components of plants which make up the organic matter in peatlands tend to have varying carbon-nitrogen ratios which impacts their overall decomposability (Rydin et al., 2006).

Nutrient availability is key to substrate quality in peatlands and is impacted by vascular plant processes. Nitrogen is one of the most abundant nutrients within organic materials such as peat and plants, playing a key role in the decomposition process and is required to enhance the decomposability of the peat (Rydin et al., 2006). Nitrogen is often mentioned in terms of the carbon-to-nitrogen ratio, which examines the availability of nitrogen compared to carbon in determining the decomposability of a structure (Rydin et al., 2006). For example, nitrogen content is low in *Sphagnum spp.*, but high in sedges, so a sedge-dominated peatland would have higher decomposability overall (Rydin et al., 2006). In general, the carbon-to-nitrogen ratio decreases moving down the peat profile (Rydin et al., 2006). With no new additions of fresh organic matter and carbon lost due to decomposition, this forces a decrease in the carbon-to-nitrogen ratio as nitrogen remains similar throughout the profile (Rydin et al., 2006).

Substrate quality plays a large role in decomposability and carbon emissions (Neubauer and Megonigal, 2022). In response to certain environmental variables, poor substrate quality can decrease soil respiration, while in other scenarios this same substrate may increase soil respiration (Muhr et al., 2011). In terms of the stockpiling process, substrate quality will likely be unknown due to the mixing of the stripped peat and the range of peatland types affected. The peat within the stockpile will be subject to aerated conditions and the substrate will not be in its natural environment developing under usual conditions (Cleary et al., 2005; ECCC, 2021). The quality of the substrate in the peat stockpile will determine how the peat reacts to environmental variables acting upon the stockpile and can result in either an increase or decrease in carbon emissions (Leifeld et al., 2012).

1.5.2 Litter Type

Decomposability in peatlands varies due to numerous factors, but the type of litter present plays a key role (Moore et al., 2008). Peatlands can have slow decomposition due to the low decomposability of the litter within them (Moore et al., 2007; Moore et al., 2008). *Sphagnum* spp. and various other mosses found within peatlands exhibit low decomposability due to their low nutrient concentrations, particularly nitrogen, high lignin contents, and subsequent recalcitrant litters (Moore et al., 2008). Conversely, vascular plant litter results in quicker decomposition due to the availability of more nitrogen relative to carbon, and labile litter (Moore et al., 2007). Vascular plant litter is labile due to the low concentrations of lignin present and low carbon-to-nitrogen ratios (Moore et al., 2007). Even within vascular plants, there are varying rates of decomposability. Gingerich and Anderson (2011) analyzed five types of litter from common wetland species and discovered that broadleaf cattail and brookside alder had decomposition rates lower than the other types of litter analyzed. The rates at which mass decreases amongst litter types in peatlands vary among them (Gingerich and Anderson, 2011). Generally, physical structures of varying vascular plant types determine their decomposability (Rydin et al., 2006). Waxy, hard materials such as conifer needles or shrub leaves tend to have lower decomposability than other non-woody, herbaceous vascular plants (Rydin et al., 2006).

During the stockpiling process, all litter and plants are torn up and rearranged within the peat and are removed from the natural water table, therefore altering the decomposability of the peat (Alberta Environment and Water, 2012; Lehan et al., 2022). Even though many litter types within peatlands have low decomposability, such as *Sphagnum spp.*, these processes will shift when the plants are ultimately removed from their thriving environments or are destroyed in general (Moore et al., 2008). The introduction of common wetland species onto a peat stockpile aims to diminish these impacts by offsetting some of the carbon lost through enhanced decomposition (Alberta Environment and Water, 2012).

1.5.3 Priming Effects

The concept of priming effects in peatlands can be both positive and negative. A positive effect of priming is an increased release of carbon from the soil due to the addition of external easily decomposable substances (Kuzyakov et al., 2000). This causes increased decomposition and enhanced carbon emissions, faster than it would have occurred without the addition of a fresh organic substance (Kuzyakov et al., 2000). If there is an introduction of easily decomposable organic substances, it has the potential to accelerate microorganism turnover and therefore increase carbon emissions from the peat (Degens and Sparling, 1996). Some factors that may cause this effect include the addition of fertilizers, physically mixing the peat, or drying and wetting the peat (Kuzyakov et al., 2000). Root exudates have also been shown to enhance decomposition in deep peat layers where more recalcitrant organic matter is found (Basiliko et al., 2012). In general, the addition of priming material will have a positive effect; however, there are some scenarios where the addition of material will result in a negative effect (Kuzyakov et al., 2000). A negative priming effect means that the added material may cause immobilization of the added nutrients instead of mineralization, resulting in a decrease in soil organic matter decomposition (Kuzyakov et al., 2000).

In general, the priming effect is particularly important when it comes to the peat stockpiling process. During formation, older peat and plant litter of various ages are mixed with newer peat (Alberta Environment and Water, 2012). Due to the mixing of the peat and the addition of fresher plant materials (i.e., from mixing in fresh litter or plantings on the stockpile), microorganisms will be able to grow and decompose older peat material more easily (Degens and Sparling, 1996). Therefore, due to the priming effect, the stockpiling process could increase decomposition and enhance carbon emissions from peat material (Degens and Sparling, 1996; Cleary et al., 2005; ECCC, 2021).

1.6 Controls on Soil and Ecosystem Respiration

Significant amounts of carbon stored in peatlands are due to an imbalance between the input of carbon produced by plants and the peatland’s expulsion of carbon as gases such as CO_2 or CH_4 during respiration (Chapin et al., 2006; Moore and Basiliko, 2006; Harris et al., 2020). There are many established controls on soil and ecosystem respiration, but this literature review will only discuss soil temperature, moisture, and oxygen availability, and microbial communities as these have been identified as main drivers in many studies.

1.6.1 Soil Temperature, Moisture and Oxygen Availability

Temperature and moisture content impact oxygen availability, which in turn affects microbial activity within the peatland and leads to the production of greenhouse gases (Moore and Dalva, 1993). Decomposition in northern peatlands is limited due to colder temperatures and hydrological controls being water-saturated conditions from a shallow water table and lack of oxygen (Clymo, 1984). This results in a net accumulation of organic matter instead of the loss of organic matter to decomposition (Clymo, 1984). As climate change intensifies, warmer and drier conditions are increasing the aerobic mineralization of organic matter due to deeper water table and the increasing availability of oxygen (Laiho, 2006). When there is greater aeration in peatlands this results in decreased moisture and creates ideal conditions for aerobic decomposition to become the dominant process (Santruckova et al., 2004). When this occurs, it often shifts peatlands from a carbon sink to a carbon source (Harris et al., 2020). However, sometimes this drastic decrease in soil moisture can lead to moisture stress of the peat which reduces decomposition (Hunter et al., 2024). The relationship between temperature, moisture content, and oxygen availability in peatlands in terms of decomposition rates is complicated. Temperature increases will affect decomposition rates only when the moisture conditions are favourable (Laiho, 2006). As shown in Moore and Dalva's (1993) laboratory experiment, the relationship between water table position and CO_2 production is clearly established, as they discovered a decreased water table (i.e., drying) increases CO_2 fluxes. Similarly, there is a clear relationship between temperature and CO_2 fluxes (Moore and Dalva, 1993). They determined that the relationship between soil temperature and water table to CH_4 production was more complicated, as CH_4 production is more complex (Moore and Dalva, 1993). Though the overall pattern in CH_4 production is that the position of the water table largely determines the release of CO_2 vs. CH_4, because CH_4 is mainly produced in the anoxic part of the peat (Bubier et al., 1993; Vasander et al., 2006; Lai, 2009).

The relationship between soil temperature, moisture, and oxygen availability within a peat stockpile is complicated. Although we are not looking at the impacts of climate change in this scenario, the peat in the stockpile will be subject to warmer temperatures due to its enhanced sun exposure. The peat below the water table is completely stripped and left in a stockpile, impacting the moisture content within the peat itself (Alberta Environment and Water, 2012; Lehan et al., 2022). These lower peat layers that were previously under anoxic conditions will now be in oxic conditions and could see a significant increase in decomposition (Cleary et al., 2005; ECCC, 2021). Due to temperature and moisture shifts, these new conditions will enhance decomposition and heterotrophic respiration, leading to a large release of carbon from the stockpiled peat (Harris et al., 2020).

1.6.2 Microbial Communities

Carbon dioxide and CH_4 emissions are dependent on the microbial communities present within the peat (Moore and Dalva, 1993). CO_2 emissions from peat soils depend on the occurrence of aerobic and anaerobic production from root respiration and microbial activity, and the subsequent transfer of this gas to the peat surface (Moore and Dalva, 1993). In contrast, CH_4 emissions rely on the balance between aerobic CH_4

consumption and anaerobic CH_4 production in the peatland (Moore and Dalva, 1993). CH_4 emissions also depend on this gas being transferred to the peat surface by processes such as diffusion, ebullition and rooting systems within the peat (Moore and Dalva, 1993; Baird et al., 2009; Lai, 2009; Bridgham et al., 2013).

Peatland microbial communities shift with increasing depth (Andersen et al., 2013). Morales et al. (2006) discovered that peat samples taken at 1 m depth had higher bacterial counts, but a less diverse bacterial community than surface samples. Kip et al. (2011) suggest the presence of these microbial communities is also highly dependent on the vegetation types present within the peatland. Microbial communities are highly adapted to each peatland and can be significantly impacted by several variables, including chemical and hydrological changes (Andersen et al., 2013).

In oil sands operations, peat and its vegetation are stripped from its natural environment to make way for mining infrastructure (Rooney et al., 2012). Microbial communities within the peat profile are significantly decreased in post-disturbed sites, which may also occur in peat stockpiles (Andersen et al., 2006). This has serious implications in terms of oil sands stockpiles. Working in a peat extraction site, Andersen et al. (2006) identified that within three years of regrowing vegetation post-disturbance, the microbial communities did not return nearly as fast as the vegetation did. This suggests that, when planting vegetation on stockpiles in an attempt to return the peat to its natural function, microbial communities may not immediately be affected. Conversely, microbial communities could return to their original quantities if conditions follow those mentioned in Kip et al. (2011). The limitation or abundance of microbial communities due to multiple factors plays a role in how decomposition occurs in peatlands (Moore and Dalva, 1993).

1.7 Role of Vegetation in Carbon Uptake

Peatlands are significant areas of land that are responsible for storing substantial amounts of carbon and are termed carbon sinks (Cleary et al., 2005). Carbon storage occurs due to the continuous build-up of partially decomposed organic matter, usually *Sphagnum* mosses., which turns into peat (Bragazza et al., 2006). Vegetation, which mainly grows as a result of microtopography gradients within the landscape, plays a large role in the carbon sink properties of peatlands as they sequester large amounts of carbon through photosynthesis (Del Guidice and Lindo, 2017; Oke and Hager, 2020). Hummocks are drier, unsaturated, peat mounds that are situated above the water table, making them drier locations than their surroundings with a low pH, the presence of shrubs and the dominant mosses are *Sphagnum magellanicum* and *Sphagnum fuscum* (Johnson et al., 2015; Barreto and Lindo, 2018; Oke and Hager, 2020). Conversely, hollows are depressions; sometimes below the water table and overall wetter than hummocks, have a higher pH, and the dominant species are *Sphagnum fallax* and *Sphagnum angustifolium* (Johnson et al., 2015; Barreto and Lindo, 2018; Oke and Hager, 2020). Different vegetation types vary in their ability to sequester or release carbon, affecting the overall carbon cycle within the ecosystem (Dieleman et al., 2017).

Sphagnum spp. produce highly recalcitrant litter, meaning that it contributes to slow decomposition rates and helps keep carbon within peatlands (Pinsonneault et al., 2016). Vascular litter, such as graminoids, can enhance decomposition and the release of peatland carbon by producing labile, easily degradable litter (Bombonato et al., 2010). Vascular plants also alter belowground carbon processes, increasing decomposition (Dieleman et al., 2017). Sedges, in particular, have a transport system called aerenchyma that moves CH_4 from the anoxic zone below the water table to the peat surface (Vasander et al., 2006; Strack et al., 2006). Through this process, CH_4 can bypass oxidation in the oxic zone, enhancing overall CH_4 transport to the atmosphere (Vasander et al, 2006; Strack et al., 2006). Conversely, these transport systems can also bring oxygen to the rhizosphere, creating oxic areas (Vasander et al., 2006; Strack et al., 2006). Eventually, once enough oxygen is brought to the anoxic zone of the peat profile, the CH_4 flux will decrease due to it becoming oxidized before it is able to be transported (Vasander et al., 2006). A peatland community shifting from being *Sphagnum*-dominated towards being covered by vascular vegetation is not ideal for peatland carbon uptake and storage (Dieleman et al., 2017). Conditions conducive to vascular vegetation growth could be the drying of peat, which is a possibility on the stockpile. This would eliminate decay-resistant *Sphagnum spp.* and would replace it with easily decomposable vascular plants, which have an increasing effect on nitrogen availability and microbial respiration (Bragazza et al., 2006) and have the ability to transport CH_4 directly to the atmosphere by bypassing oxidation in the aerobic zone (Bridgham et al., 2013). This would potentially shift the peatland to become a carbon source and would impact its carbon sequestration capabilities (Dieleman et al., 2017).

Stockpiles on oil sands leases were formed by stripping the peat from the ground and removing its surface vegetation (Cleary et al., 2005; Alberta Environment and Water, 2012). All functions that these plants had within the natural peatland are altered as the plants are damaged, significantly affecting the carbon uptake in this area (Moore et al., 2008). The conditions on the stockpile will be extremely dry, and, although planting wetland common species can aid in carbon uptake, the conditions may still not be suitable for vegetation such as *Sphagnum* moss to successfully grow (Lehan et al., 2022). After analyzing plant function and the decomposability of its litter, it was determined that *Sphagnum spp.* play a large role in the carbon sequestration capabilities of peatlands (Pinsonneault et al., 2016). If *Sphagnum spp.* cannot thrive on the peat stockpile and only vascular vegetation can grow, the stockpile's net carbon emissions will be uncertain.

1.8 Gaps in the Scientific Literature and Proposed Objectives

Processes affecting decomposability and actual decomposition rates within natural, undisturbed peatlands are well-researched; several studies are discussed within this literature review. More work is required on peat stockpiles specifically as very little is known about them, especially those stockpiles that sit for decades on oil sands leases. Further, there are several studies on peat stockpiles in a horticulturally significant context. For example, Lehan et al. (2022) studied peat stockpiles that were only left standing for 3 to 14 months as the peat was used for reclamation in disturbed peatlands from the horticulture industry. Findings from their study suggest that stockpile duration can impact characteristics in stockpiled peat, such as pore size and the ability of *Sphagnum* moss regenerating from the stockpile to photosynthesize, as well as environmental growing conditions (Lehan et al., 2022). This study further suggests that drastically reducing peat stockpiling time will result in the greatest likelihood for the stockpiled peat to be viable for reclamation purposes (Lehan et al., 2022). The conditions found in the stockpiles studied by Lehan et al. (2022) may vary from stockpiles on oil sands leases due to them having shorter stockpile standing duration, varying sizes and construction methods.

Since carbon emissions and environmental conditions of peat stockpiles in an oil sands setting have not been extensively studied, my work aims to fill this gap by analyzing the different vegetation communities established following industry-led seeding for erosion control on a peat stockpile and how they impact the stockpile's net carbon emissions. Specifically, this study will (1) evaluate the carbon emissions on a stockpile at an in-situ oil sands lease in northern Alberta across different vegetation communities (Chapter 3); (2) analyze peat samples across vegetation treatments for indicators of decomposition and respiration rates to more effectively understand how vegetation affects organic matter decomposition (Chapter 2); (3) measure biomass accumulation to determine total plant inputs and calculate net carbon balance among the vegetation treatments (Chapter 3); (4) analyze how position (i.e., top vs. slope) on the stockpile impacts carbon emissions from the peat (Chapter 3); and (5) determine environmental controls on carbon emissions and if they vary with stockpile location (Chapter 3). My proposed study will provide useful data and information for the development of accurate oil sands lease-scale emissions reporting that incorporates the fate of peat stored in stockpiles. This research will also aid in the overall understanding of peat soil respiration dynamics and environmental controls on oil sands peat stockpiles.

Chapter 2

Understanding the Role of Vegetation in Stockpiled Peat Decomposition: An Incubation Experiment

2.1 Introduction

Wetland ecosystems cover 20% of Alberta, Canada’s land area with 90% of them categorized as peatland ecosystems (Alberta Wetland Policy, 2013). Peatlands are important land areas responsible for storing substantial amounts of organic soil carbon (Cleary et al., 2005). Currently, the oil and gas industry is disrupting peatland function in northern Alberta by altering land use, through the removal of peatlands and subsequent construction and use of mining infrastructure, transforming these areas into carbon sources (Alberta Wetland Policy, 2013; Lehan et al., 2022). Before oil sands infrastructure development, the removal of the surface layer of peat is a required first step to make way for construction of processing facilities and access roads (Lemmer et al., 2022). This surface peat is then stockpiled, where the peat is exposed to different environmental conditions than in a natural peatland, resulting in altered carbon storage and GHG emissions (Rooney et al., 2012; Environment and Climate Change Canada, 2021). The shift in environmental conditions and the physical mixing and aerating of peat can impact integral variables such as soil moisture, vegetation presence, and soil temperature, among many other variables, which can all impact the rate of peat decomposition and respiration processes (Cleary et al., 2005). It is suggested that as peat is transported from water-saturated conditions in its natural environment to an aerated, dry stockpile, organic matter decomposition will increase (Cleary et al., 2005; Environment and Climate Change Canada, 2021). Current knowledge suggests that all carbon emissions from the peat stockpiling process occur only during the stripping and stockpiling process, and when the stockpiled peat is used as reclamation soil (Rooney et al., 2012). No literature outlines the carbon uptake or release processes of peat stockpiles during their standing duration. Due to the decade-long standing duration of peat stockpiles, the introduction of wetland vegetation species is recommended to offset carbon emissions, assist in weed control, build a viable seed bank, and combat erosion (Alberta Environment and Water, 2012). Currently, the actual carbon emissions associated with peat stockpiles in the oil sands are relatively unknown, as well as the role that plants on stockpiles play in offsetting carbon loss from peat decomposition.

Organic matter decomposition in natural peatlands is relatively slow due to a high water table and resulting anoxic conditions through most of the peat profile (Moore and Basiliko, 2006). When peatlands are stripped of their peat layers and placed into a stockpile for expanding oil sands infrastructure construction, decomposition will increase and depend on varying factors. Decomposition varies with soil moisture content, with literature stating that optimal conditions are around 60% volumetric water content, with a decline at both higher and lower contents (Husen et al., 2014). The substrate quality of stockpiled peat also affects the decomposition. In general, the substrate quality in natural peatlands is driven by the presence of vegetation, including *Sphagnum* spp. (Moore et al., 2008). In the case of peat stockpiles, *Sphagnum* spp. may make up a lot of the peat within the stockpile, but likely do not have a dominant living presence, and the industry-planted graminoid mix makes up the majority of vegetation cover. Graminoids can enhance decomposition by producing labile, easily degradable litter onto the stockpile (Bombonato et al., 2010) and due to their size, they can produce more litter, than compared to mosses. This addition of fresh organic matter to the stockpile could result in the process of priming. Priming in peatlands is an increased release of carbon from the soil resulting from the addition of easily decomposable materials, such as vascular litter (Kuzyakov et al., 2000). This increase in easily decomposable materials can accelerate microorganism turnover, increasing GHG emissions (Degens and Sparling, 1996).

To better understand the issues of peat stockpiling and stockpile GHG emissions, the objective of this study is to measure decomposition rates in peat samples across vegetation treatments on a subsoil peat stockpile to better understand how vegetation affects organic matter decomposition. This was analyzed during a 5-week-long laboratory incubation experiment using peat cores from areas of different vegetation communities on a peat stockpile; the incubation was conducted under controlled moisture conditions at 40 and 60% volumetric moisture content. One hypothesis is that treatments with increased vegetation and roots will experience more decomposition and increased respiration. Another hypothesis is that the wet treatments will experience significantly higher CH_4 flux than the dry treatments.

2.2 Methods

2.2.1 Study Site

Imperial Oil’s Aspen Lease is approximately 120 km northeast of Fort McMurray, Alberta. The organic subsoil stockpile is located at the end of the access road on this lease (57°06'50.3"N 111°01'10.1"W, Figure 2.1). On an initial walk-through of the stockpile during Summer 2023, three main vegetative cover types were identified: Bare Organic, Fen and Grass, which pertain to the dominant vegetation type established following revegetation using standard seed mixes by industry partners. Large areas representing each cover type were selected for sampling. The Bare Organic area had no vegetation establishment present and had bare peat at its surface.

Figure 2.1 Map of Imperial Oil's Aspen Lease in relation to Fort McMurray, Alberta.

The Fen area had common wetland species present, dominated by sedges, such as *Carex aquatilis*, *Carex utriculata*, and *Carex media*, as it was in a depression on the stockpile and was overall wetter than the other two locations. Lastly, the Grass area was a dry, slightly elevated location and had grass species present, such as *Poa pratensis*, *Poa palustris*, and *Calamagrostis canadensis*.

2.2.2 Peat Sampling

Peat samples were taken in the Summer of 2023 to be incubated in a laboratory setting in Fall of 2023. A polyvinyl chloride (PVC) pipe with the dimensions of width = 7 cm, height = 20 cm was extracted in triplicates from each of the designated areas on the stockpile (Bare Organic, Fen and Grass) for a total of nine peat cores. After extracting each core, they were placed in a plastic bag and frozen until the time of analysis.

2.2.3 Laboratory Incubation

We conducted a full-factorial laboratory incubation experiment investigating the effect of moisture content and peat substrate on CO_2 and CH_4 emissions. To begin the laboratory incubation, the peat samples were thawed, and a 15 mL subsample of each core was removed, weighed, and dried at 60°C for 48 hours. Once the subsample was dry, the dry weight was obtained. The dry and wet bulk densities were calculated for each subsample by dividing each sample's volume (mL) by their wet or dry weights. The values were used to calculate gravimetric water content (%) and adjust mass of jars to the desired volumetric water contents for the incubation treatments. To set up each jar, between 25 – 50 g of dry peat was added to each 500 mL jar to obtain a target weight of approximately 15 g of dry peat. The amount of wet peat per jar was divided by the wet bulk density and then multiplied by the dry bulk density to obtain the target weight per jar. After the desired dry weight of peat was determined, the amount of water per jar could be calculated using the target volumetric water content of 40% (dry treatment) and 60% (wet treatment, optimal respiration; Husen et al. 2014). The exact weights used for each jar are summarized in Table A-1.

To accurately determine the impact that vegetation had on organic matter decomposition we incubated peat both with roots from established vegetation intact and removed. As Bare areas had no roots, this surface type had only the no-root treatment. This resulted in five different substrate types: Bare organic, Fen with roots intact (Fen

Roots), Sedge roots removed, Grass with roots intact (Grass Roots) and Grass roots removed. Each substrate–moisture content condition was incubated in triplicate resulting in 30 incubation jars after each treatment was applied.

Before the initial measurement of the jars, the lid on each jar was left off to allow the contents of the jars to reach the desired water contents. When the desired water contents were below their target, additional deionized water was added to reach the desired water content. After the incubation experiment began, the jars were maintained at ambient room conditions (~21 °C) in the lab for the duration of the study. Lids were loosely placed on top of each jar between measurement times to prevent major evaporation events and a build-up of gases. During the five-week incubation, each of the 30 jars was re-weighed and re-wetted twice per week to bring them back to the desired water content and sample weight. CO_2 and CH_4 emissions were measured twice per week using a trace gas analyzer approximately 24 hours after the re-weighing and re-wetting of the jars (LI-COR; LI-7810; Lincoln, NE, USA). Before the flux measurements, lids on the incubation jars were completely removed to allow for the release of any accumulated gases. Each flux was measured over a 3-minute interval, and room temperature and humidity were recorded at the start of each flux measurement. Fluxes were measured based on the accumulation of gases within each jar attached to the analyzer with a custom lid and tubing attachment. Actual volumetric water content based on the weight of the jar was calculated at the start of each flux to account for any small evaporative losses from the sample over the 24 hours after the re-wetting of the jars. CO_2 and CH_4 flux were calculated using a linear fit through the change in gas concentration in the jar headspace measured by the LI-COR over the 3-

minute time interval. The program PEDRO (Peatland Equipment Data Re-Organizer)(Newton, 2023) was used to clip the concentration of both CO_2 and CH_4 to choose the linear portion of the flux. The fluxes were converted to units of µg CO_2 – C g dry peat^{-1} hr^{11} and ng CH_4 – C g dry peat^{-1} hr^{11} by using the ideal gas law (PV=nRT) and mass of dry peat in the incubation jar. The headspace volume was determined for each jar by subtracting the volume of peat in each jar (Table A1) from the total volume of the jar (500 mL).

2.2.4 C:N Analysis

Solid materials were analyzed for total carbon and total nitrogen content for the 30 peat samples from the incubation done in Fall 2023. This analysis was conducted at the Environmental Isotope Lab at the University of Waterloo using a 4010 Elemental Analyzer (Costech Instruments, Italy) coupled to a Delta Plus XP (Thermo-Finnigan, Germany) continuous flow isotope ratio mass spectrometer (CFIRMS) (Environmental Isotope Lab, 2024). Materials were tested against international reference materials and in-house standard materials including ammonium sulfate, sucrose, cellulose, L-glutamic acid, and sediment (Environmental Isotope Lab, 2024). The peat from inside each incubation jar was dried in the oven, and then a small sub-sample was taken for processing. This sub-sample was ground into a fine powder using a ball mill with approximately 1-1.1 mg weighed into a tin capsule.

2.2.5 Data Analysis

Statistical analyses were completed in R version 4.2.3 (R Core Team, 2023). Statistical significance was assessed based on p-value <0.05 and considered the framework for strength of evidence presented by Muff et al. (2022) and discussed using the language of evidence (Figure 2.2). To determine the effect of moisture and vegetation treatments on carbon emissions (CO_2 and CH_4), a linear mixed effects model was used with the function ‘lme’ in the package nlme (Pinheiro and Bates, 2000), with vegetation treatment and moisture set as fixed effects and jar set as a random effect. Statistical significant was assessed based based on the ANOVA type marginal output, and if there was a statistical significance at $p<0.05$, the ‘emmeans’ function in the emmeans package (Lenth, 2025) was used to complete a Tukey test for a pairwise comparison among vegetation and moisture treatments.

To determine the effect of roots on the C:N ratio (log-transformed), a linear model was run on the data using the function ‘lm’ in base R with an ANOVA type II output. The ‘emmeans’ function in the emmeans package (Lenth, 2025) was used to complete a Tukey test for a pairwise comparison among root treatments.

To determine the effect of the C:N ratio (log-transformed) on carbon emissions (CO_2 and CH_4), a linear model was run on the data using the function ‘lm’ in base R, with C:N ratio (log-transformed) set as a fixed effect and jar set as a random effect (R Core Team, 2023). These were assessed using the ANOVA type II output, the MuMIn package (Bartoń, 2025) used to calculate the marginal and conditional R^2 values. All graphs were created using the ggplot2 package in R (Wickham et al., 2016).

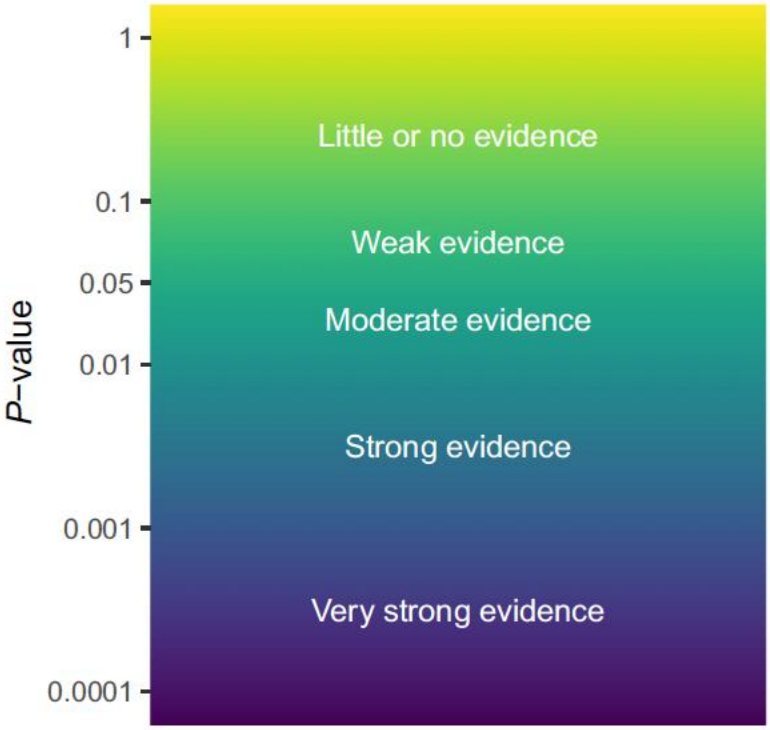

Figure 2.2 Muff et al. (2022) language of evidence thresholds.

2.3 Results

2.3.1 Incubation Treatments and Carbon Fluxes

The average respiration was highest at the Fen Roots treatment throughout the incubation (14.8 µg CO_2-C g dry peat hr^{-1}), while the lowest average respiration occurred at the Bare Organic No Roots Treatment (1.73 µg CO_2-C g dry peat hr^{-1}). The average respiration among dry treatments was 2.89 µg CO_2-C g dry peat hr^{-1}, while the average respiration among wet treatments was 7.44 µg CO_2-C g dry peat hr^{-1}. The overall range in respiration during the incubation experiment was 0.158–226.0 µg CO_2-C g dry peat hr^{-1}. There was moderate evidence for an effect of the interaction between soil moisture and treatment on respiration in the incubation experiment ($F_{4,20}$=3.12, p=0.04) and no evidence for the individual effects of moisture and substrate type for explaining variation in respiration (Table 2.2). Respiration was higher in the wet treatment for the Fen Roots, and minimally higher in the Fen No Roots and Grass Roots. There was little difference between moisture treatments for Grass No Roots and Bare Organic.

The average CH_4 flux was highest at the Grass Roots treatment throughout the incubation (1.09 ng CH_4-C g dry peat^{-1} hr^{-1}). The lowest average CH_4 flux was at the Fen No Roots treatment (0.0049 ng CH_4-C g dry peat hr^{-1}). The average CH_4 flux among dry treatments was -0.073 ng CH_4-C g dry peat hr^{-1}, indicating net CH_4 consumption, while the average CH_4 flux among wet treatments was 0.774 ng CH_4-C g dry peat hr^{-1}. The overall range in CH_4 fluxes during the incubation experiment was -1.93 – 7.57 ng CH_4-C g dry peat hr^{-1}. There was weak evidence for the effect of the interaction between moisture and treatment on CH_4 flux in the incubation experiment ($F_{4,20}$=2.53, p=0.07) while their individual effects were not statistically significant (Table 2.2). CH_4 emissions were higher at every wet treatment compared to the dry treatment, with the most notable difference between moisture contents at the Grass Roots jars.

Table 2.1 Main effect of moisture and location on CO_2 and CH_4 (incubation).

	numDF	**denDF**	**F-value**	**p-value**
CO_2				
Intercept	1	230	0.25	0.62
Moisture	1	20	0.005	0.95
Location	4	20	0.24	0.91
Moisture*Location	4	20	3.12	**0.04**
CH_4				
Intercept	1	240	0.46	0.50
Moisture	1	20	0.60	0.47
Location	4	20	0.46	0.76
Moisture*Location	4	20	2.53	0.07

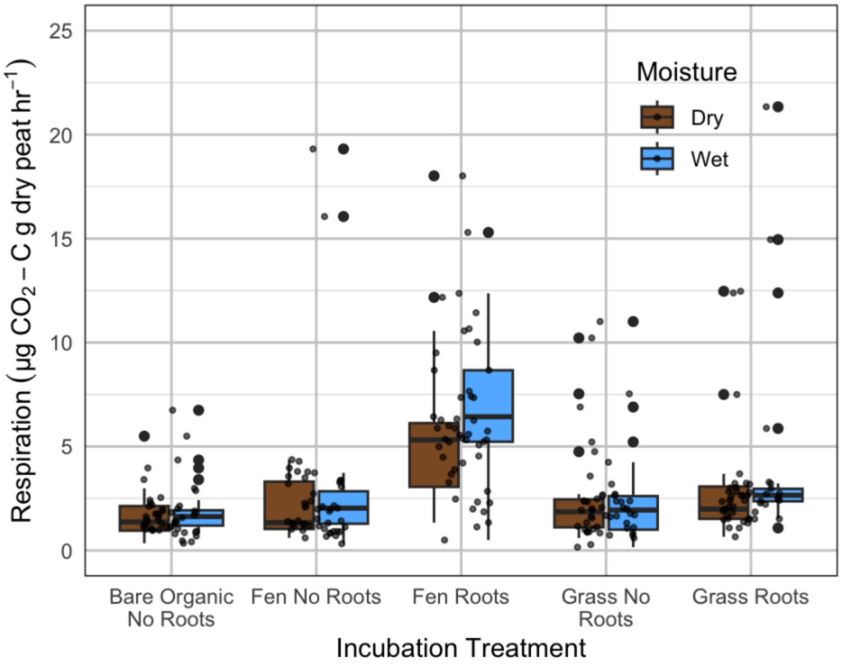

Figure 2.3 Boxplot showing CO_2 flux for each incubation treatment.

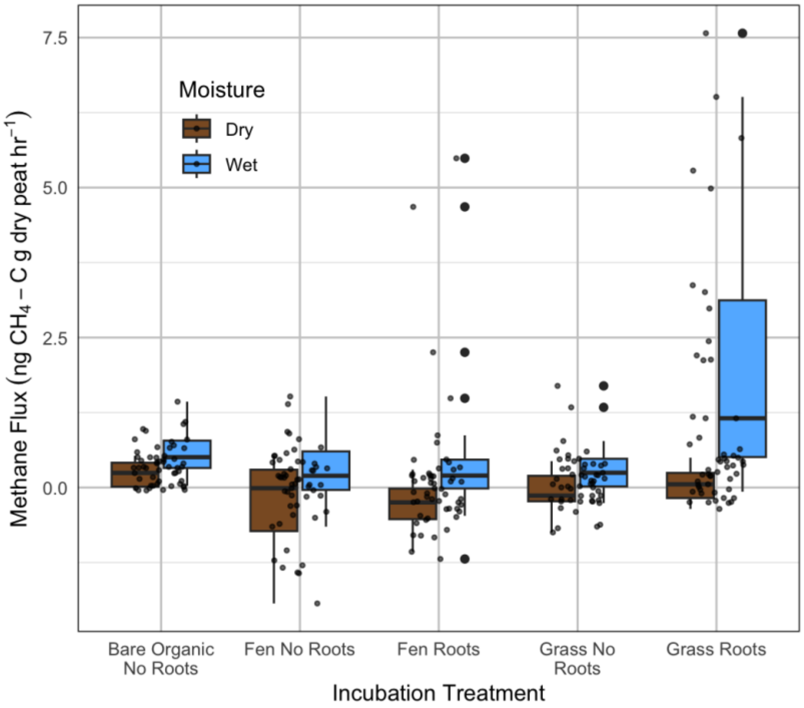

Figure 2.4 Boxplot showing CH_4 flux for each incubation treatment.

2.3.2 C:N Ratio and Roots

The highest average C:N ratio was from the Bare Organic No Roots samples (39.1:1), while the lowest average C:N ratio was from the Fen Roots samples (28.0:1). Both Fen treatments (Roots and No Roots) had statistically lower C:N ratios than the Bare Organic No Roots treatment, while both Grass treatments (Roots and No Roots) had no significant differences from either group (Figure 2.4). For both Fen and Grass treatments C:N ratio was similar among their Root and No Roots samples. There was very strong evidence for a negative effect of root presence on the C:N ratio in the incubation ($F_{4,}$=7.02, p=0.000622).

Table 2.2 Summary of average %C, %N and C:N Ratio for each incubation treatment.

Treatment	%C	%N	C:N Ratio
Bare Organic No Roots	13.6	0.34	39.1:1
Fen No Roots	17.9	0.60	30.0:1
Fen Roots	16.2	0.58	28.0:1
Grass No Roots	20.3	0.56	34.4:1
Grass Roots	19.1	0.57	32.9:1

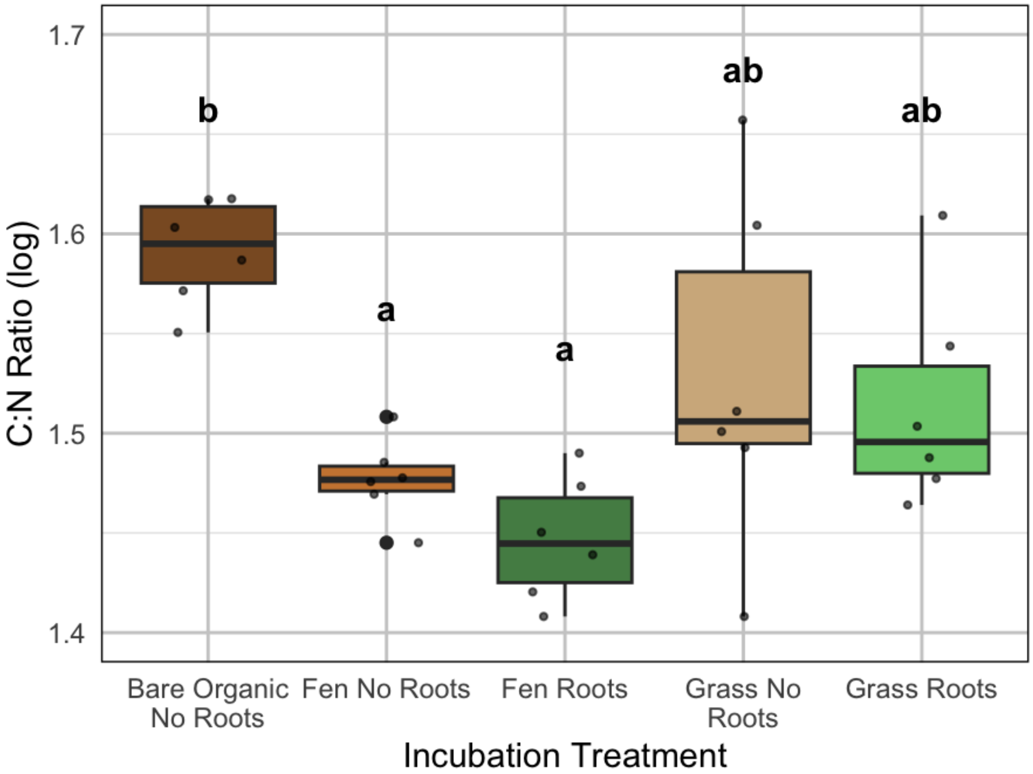

Figure 2.5 Boxplot showing the log-transformed C:N ratios for each incubation treatment.

2.3.3 C:N Ratio and Carbon Fluxes

There was moderate evidence for a negative effect of C:N ratio on respiration in the incubation, indicating that higher C:N ratios are associated with lower respiration during the incubation experiment ($F_{1,28}$=6.77, p=0.015). Conversely, there was no evidence that the C:N ratio had an effect on CH_4 fluxes in the incubation ($F_{1,28}$=0.02, p=0.88).

Table 2.3 The relationship between carbon fluxes and C:N ratio.

	numDF	**denDF**	**F-value**	**p-value**
CO_2				
Intercept	1	28	7.84	0.0092
CN Ratio (log)	1	28	6.77	**0.015**
CH_4				
Intercept	1	28	0.06	0.80
CN Ratio (log)	1	28	0.02	0.88

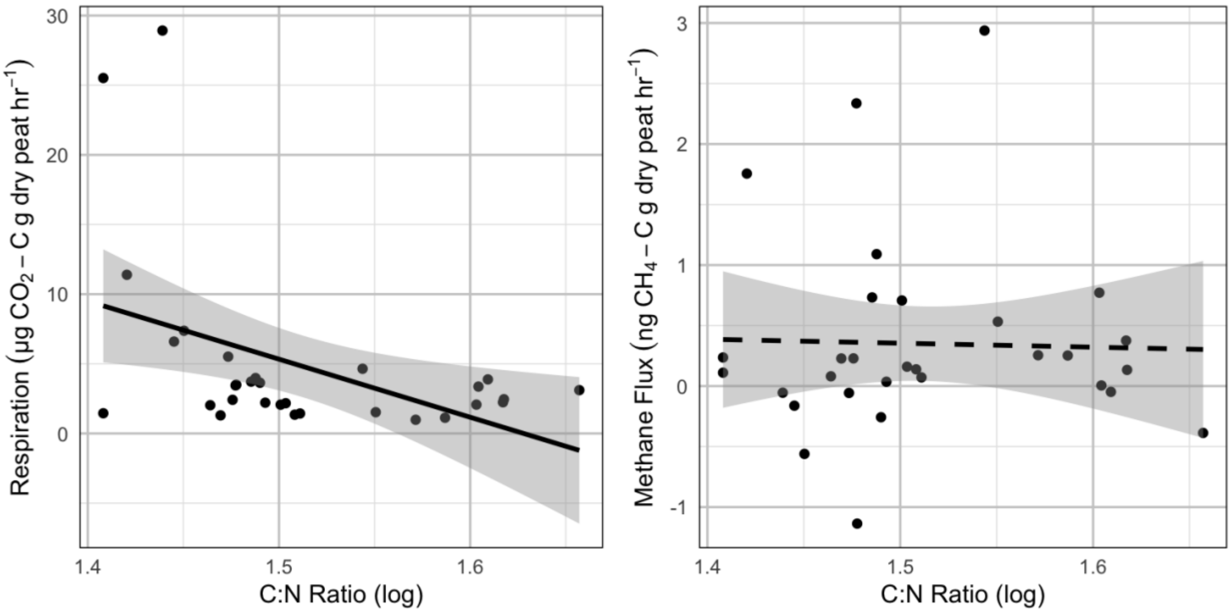

Figure 2.6 Left: The relationship between respiration and log-transformed C:N ratio (F1,28=6.77, p=0.0146)(y= 67.85 - 41.68 * x). Right: The relationship between CH_4 flux and log-transformed C:N ratio (F1,28=0.02, p=0.88)(y = 0.00085 - 0.00033 * x).

2.4 Discussion

2.4.1 Incubation Treatments and Carbon Fluxes

Incubation CO_2 fluxes were moderately affected by the interaction of moisture and location (Figure 2.3). Figure 2.3 shows that treatments Bare Organic No Roots, Fen No Roots, Grass No Roots and Grass Roots all had similar respiration among wet and dry treatments. The Fen Roots treatment shows the highest respiration among locations, with more respiration coming from the wet treatment, but the dry treatment still has higher respiration than the rest of the locations. The higher respiration experienced from the Fen Roots treatment could be explained by more labile carbon within the initial incubation sample. The Fen areas on the stockpile were more densely vegetated than the Grass locations (or Bare Organic), which is why the effect of root presence is most pronounced at the Fen Roots treatment. This added vascular plant material is easily decomposable and adds to respiration measured from the sample (Oke and Hagar, 2020). The high respiration experienced from the wet Fen Roots samples is also likely because of the water content chosen to represent the wet treatments in this incubation. Husen et al. (2014) reported that respiration increased when peat samples were moist, and the water content was around 60%, which is the water content chosen for the wet samples in this incubation. The effect of the wet versus dry treatment was most pronounced at the Fen Roots treatment, whereas all other treatments had similar respiration among their wet and dry treatments. Overall, the incubation results suggest that areas of the stockpile with more plant material and an ideal moisture content will experience an increase in respiration. Although it is generally assumed that moving peat to aerated stockpile conditions will enhance respiration rates, lower rates observed at 40% moisture content suggest that excessive drying of the surface could result in reduced decomposition due to moisture stress (Hunter et al. 2024).

Incubation CH_4 fluxes were weakly affected by the interaction of moisture and location (Figure 2.4). Figure 2.4 shows that amongst all treatments, the CH_4 flux was consistently higher in the wet treatments versus the dry treatments. This was expected since within a peatland, the position of the water table determines whether CO_2 or CH_4 is released (Bubier et al., 1993; Lai, 2009). With a high water table, or wet soil conditions as experienced in the incubation, water-filled pores increase the chance of anoxic conditions developing, which allows for CH_4 production and transport (Bubier et al., 1993; Lai, 2009). The increase in CH_4 flux under higher moisture content was predominantly experienced at the Grass Roots treatment. Although it was determined that the Fen Roots treatment had more labile carbon in its sample, the Grass Roots treatment seemed to be affected the most by the availability of roots for CH_4 production. Similar to the CO_2 fluxes, this added carbon to the sample was broken down and due to the high moisture content of the wet samples, CH_4 was able to be produced and released. The Grass Roots treatment had a lower average wet bulk density, potentially increasing pore space able to release CH_4 within the jar. This combination of labile organic material as well as increased pore space could explain the large flux of CH_4 seen at the Grass Roots treatment. Overall, the incubation results suggest that areas of the stockpile with more plant material and wetter conditions will experience an increase in CH_4 fluxes. The wet conditions in the incubation experiment were controlled at 60% water content, which probably allowed for the production and transport of CH_4 to begin occurring, but in the field, the soil moisture content will likely be higher in certain areas and could allow for higher actual CH_4 emissions. Measured CH_4 consumption under the dry treatment (40% moisture content) suggests that the stockpile could act as a CH_4 sink under dry conditions.

2.4.2 C:N Ratio and Roots

The C:N ratio was significantly impacted by the presence of roots in the incubation samples (Figure 2.5). It was indicated that there was a negative relationship between C:N ratio and root presence, suggesting that if the sample had roots present the C:N ratio was lower than if no roots were present. This is evident in Figure 2.5 as both Fen Roots and Grass Roots have lower C:N ratios than their counterparts without roots and the Bare Organic No Roots sample. However, each of the Fen and Grass samples had statistically similar C:N ratios and were statistically different from the Bare Organic No Roots sample. As the peat stockpile consisted of mixed subsoil peat, these difference likely reflected changes in the peat matrix from the presence of plants on the stockpile after construction. The Fen samples were collected from an area that was sedge-dominated, while the Grass samples were collected in an area with grasses and had less vegetation overall. The availability of nitrogen is what increases or decreases the carbon-to-nitrogen ratio. Nitrogen is one of the most abundant nutrients in organic materials, like plants, and it plays a large role in decomposition and is required to enhance the decomposability of peat (Rydin et al., 2006). Sedge roots grow deep into the peat profile (Strack et al., 2006) and release root exudates, which provide easily decomposable litter (Vasander et al., 2006; Basiliko et al., 2012), and this was likely captured in the Fen samples. These root exudates also alter the microbial community within the soil, which indirectly affects different processes within the nitrogen cycle, increasing nitrogen availability in the soil (Ahmad et al., 2021). The increased nitrogen likely remained in the Fen samples, which is how Fen No Roots still has a relatively low C:N ratio, but the added nitrogen from the roots themselves in the Fen Roots sample is how it had the lowest overall C:N ratio. This same effect is seen in both Grass treatments, where the Grass No Roots treatment has a slightly higher C:N ratio than the Grass Roots treatment. The highest C:N ratio among treatments was the Bare Organic No Roots treatment. If the C:N ratios only relied on how decomposed the sample was, then it would be expected that the Bare Organic treatments would have the lowest C:N ratio. But this is not the only variable that affects C:N ratios. The C:N ratio at the Bare Organic treatments is likely higher due to there being no root exudates or plant material to add nitrogen or enhance the nitrogen cycle in the area where the samples for this treatment were collected. Overall, it is evident that root exudates and root availability in the peat samples affected the carbon-to-nitrogen ratios, with the sample with no roots present having the highest C:N ratio to the sample with the most roots present having the lowest C:N ratio.

2.4.3 C:N Ratio and Carbon Fluxes

A negative relationship existed between the C:N ratio and respiration in the incubation experiment, meaning that when the C:N ratio was low, respiration rates were higher. This is because microbes in the peat require low C:N ratios, around 20-30:1 in the substrate, to effectively decompose material (Kendall et al., 2021). When nitrogen is scarce, as observed primarily in the Bare Organic No Roots treatment (Figure 2.6), the C:N ratio increases, leading microbes to compete with one another for the available nitrogen (Kendall et al., 2021).

There was no relationship between the C:N ratio and CH_4 fluxes in the incubation experiment. There was not much difference between treatments in terms of CH_4 emissions, except for the wet Grass Roots treatment. However, even though the wet Grass Roots treatment had higher emissions, all emissions were relatively close to 0 ng CH_4-C g dry peat hr^{-1}, making it unlikely for a significant relationship to occur.

2.5 Conclusion

The results of this incubation indicate that interaction between moisture content and the presence of roots within the incubation treatments weakly affected CH_4 fluxes, and moderately affected respiration. However, there was no significant effect of the individual treatments (moisture and root presence) on carbon fluxes. This was unexpected as it was hypothesized that having roots in the treatment would enhance decomposition and respiration. The data shows that wet treatments produced more CH_4, but this relationship was not significant.

It was also determined that the C:N ratio was significantly related to incubation treatment, with the Grass and Fen Roots treatments having significantly lower C:N ratios than the Bare Organic No Roots treatment while being statistically similar to their No Roots counterpart. Therefore, the presence of plants on the stockpile alters the peat substrate quality in the near surface and should be considered when estimating peat stockpile respiration.

There was a relationship between the C:N ratio and respiration, with increased respiration coming from samples with lower C:N ratios. However, the same relationship was not found for CH_4 emissions. This was because there was little variation in CH_4 emissions, with the average being around 0 µg CH_4-C g dry peat hr^{-1}, but there are different C:N ratios for each sample. If the incubation experiment was conducted with different controlled water contents, there would be the potential for anoxic conditions, which are favourable for CH_4 production and transport. In general, this suggests that C:N ratio could be a good predictor of stockpile peat CO_2 emissions.

The results from this incubation experiment highlight the need for increased field-based flux measurements on peat stockpiles. Environmental conditions, such as soil temperature and soil moisture, that cannot be controlled like in this experiment, may result in different carbon emissions, C:N ratios and their interactions in a peat stockpile. As vegetation plays a role in altering peat substrate quality, it is important to determine its effect on field-level fluxes to advance our understanding of overall stockpile carbon dynamics and how environmental variables impact them.

Chapter 3

Carbon Emissions from a Large Organic Subsoil Stockpile in the Alberta Oil Sands: Offset Potential of Biomass Accumulation in the First 5 Years

3.1 Introduction

The province of Alberta is approximately 20% wetland cover, with the majority of this area, around 90%, being peatland ecosystems (Alberta Wetland Policy, 2013). Peatlands are a subset of wetlands that are characterized by having a layer of decomposed plant material of at least 30 cm thick, with 40 cm used as the cutoff in Alberta (Lai, 2009; Strack et al., 2022). These areas are termed carbon sinks as they store substantial amounts of soil carbon (Cleary et al., 2005). Northern peatlands store approximately 415 Pg C (Hugelius et al., 2020). Thus, protecting this peatland carbon stock could be an important nature-based climate solution, especially important now and for future climate change (Strack et al., 2022). However, peatlands in northern Alberta are becoming increasingly impacted due to the expanding oil and gas industry (Alberta Wetland Policy, 2013; ABMI, 2018). The amount of disturbed peatlands is set to increase in the coming years, as thousands more square kilometres have already been leased to oil and gas companies (ABMI, 2018). The increase in oil and gas leases means there will be an increase in the construction of peat stockpiles on the landscape. This includes the stripping of peat from the natural environment and relocation to a stockpile for future reclamation use (Rooney et al., 2012).

When peatlands become impacted in this way, it disrupts their natural ability to store carbon. Variables such as soil temperature, soil moisture, oxygen availability, and microbial communities all affect peat decomposition and respiration processes (Moore and Dalva, 1993) and are all affected through oil and gas lease expansion and exploration. The main focus of this study is on peat stockpiles, which are a byproduct of oil sands infrastructure construction. This requires removing peat from its natural environment, where there is likely an above-surface water table and a significant presence of wetland species, to an aerated, dry stockpile (Cleary et al., 2005; ECCC, 2021). When peat is moved into these dry, aerated conditions, there are significant shifts in moisture and the water table, which increases the diffusivity of pore gases, therefore increasing GHG emissions from the peat (Moore and Dalva, 1993). These conditions also prohibit the peat from retaining water, which can lead to irreversible peat deformation and therefore affect the ability for stockpiled peat to be used as future reclamation soil (Lehan et al., 2022). It is believed that all carbon lost from stockpiled peat occurs during the initial stripping and stockpiling process, and finally when the peat is used for reclamation soil (Rooney et al., 2012). Peat stockpiles will remain on the landscape for several decades, while the infrastructure is in use; however, during this period, actual carbon emissions are relatively unknown.

A potential way to diminish the GHG emissions from peat stockpiles is to add wetland-specific vegetation to aid in carbon uptake (Alberta Environment and Water, 2012). Vegetation can sequester significant amounts of carbon through photosynthesis (Oke and Hager, 2020). The role that plants play in carbon uptake differs among vegetation types. *Sphagnum spp.* would slowly add add biomas to the pile but produce recalcitrant litter, and subsequently slow decomposition rates, overall keeping carbon in peatlands (Pinsonneault et al., 2016). While vascular vegetation, particularly graminoids, produce large quantities of biomass that enhances decomposition processes due to nitrogen deposition and increases the loss of carbon due to their labile, easily decomposable litter (Moore et al., 2007; Bombonato et al., 2010). Sedges can also transport CH_4 directly from below the water table in the anoxic zone to the atmosphere, allowing it to bypass oxidation in the oxic zone of the peatland (Vasander et al., 2006; Strack et al., 2006). Due to the expected increase in decomposition and carbon emissions resulting from the planting of vascular vegetation, incorporating *Sphagnum spp.* on the peat stockpile could be beneficial for carbon sequestration. However, it is expected that the conditions on the peat stockpile may not be suitable for the successful growth of *Sphagnum spp*. due to increased aeration (Lehan et al., 2022). Overall, due to the unknown conditions on the peat stockpile and most of the industry-planted vegetation being vascular, it is uncertain whether the plants will play a role in carbon uptake or will produce significant quantities of labile litter that enhance overall carbon emissions from the peat stockpile.

To better understand overall carbon dynamics, the role that plants play in carbon storage and respiration/decomposition, and how environmental variables affect emissions, the objectives of this study are to (1) evaluate the carbon emissions on a stockpile at an in-situ oil sands lease in northern Alberta across different vegetation communities; (2) measure biomass accumulation to determine total plant inputs and calculate net carbon balance among the vegetation treatments; (3) analyze how position on the stockpile impacts carbon emissions from the peat; and (4) determine environmental controls on carbon emissions and if they vary with stockpile location. This study will contribute to a deeper understanding of peat soil respiration dynamics and the effect of environmental variables on emissions from oil sands peat stockpiles. This study will produce useful data and information for the development of accurate oil sands lease-scale emissions reporting.

3.2 Methods

3.2.1 Site Location and Description

Imperial Oil’s Aspen Lease is approximately 120 km northeast of Fort McMurray, Alberta. This study analyzes an organic subsoil stockpile that was constructed in 2019 at the end of the access road on this lease (57°06'50.3"N 111°01'10.1"W, Figure 2.1). On the stockpile, carbon flux locations were separated into slope, elevation and depression. To characterize emissions of CO_2 and CH_4 from the stockpile slopes, measurement plots were established on each of the stockpiles’ four sides (north, south, east, west) with two collars on each slope, one in the middle and one at the bottom. These two collars were established in bare organic soil and do not have any vegetation inside, and thus represent peat respiration only (Figure 3.1). The elevation and depression areas were established on top of the stockpile but lined up with the north, south, east and west slopes. At each of these locations, we established a paired elevation and depression carbon flux location. Elevation and depression locations were chosen based on their perceived height relative to their surrounding area and plant community composition. At each location, carbon gas fluxes were measured at an intact collar which had all the vegetation and roots present, a clipped collar which had the vegetation clipped out, but the roots still intact, and a trenched collar which had all surface vegetation and their roots pulled out and a tarp installed in a square around the collar to prevent lateral root growth into the measurement area (Figure 3.1). Net ecosystem exchange of CO_2 and CH_4 was measured at intact collars, soil respiration at clipped collars and peat only respiration and CH_4 release at trenched collars, with the latter comparable to measured fluxes from the slope collars. This study design resulted in a total of 32 carbon flux collars across the entirety of the stockpile.

Mid Slope

Bottom Slope

Intact Elevation

Clipped

Trenched

Intact Depression

Figure 3.1 Photos of different collar types, including an intact elevation and depression showing the different vegetation types.

3.2.2 Carbon Fluxes – CO_2 and CH_4

Carbon dioxide and CH_4 fluxes were measured using the closed chamber method (Saraswati et al., 2020). There were a total of 11 carbon flux measurements between May 24 and September 28, 2024. The concentration of these gases within the chamber was measured simultaneously using a trace gas analyzer and an accompanying tablet to view carbon fluxes in real time and aid in the accuracy of flux measurements (LI-COR; LI-7810; Lincoln, NE, USA). Carbon fluxes were conducted weekly, except for an early and mid-season disruption due to wildfires near the study site. Each flux ran for 3 minutes and only began after the gas concentrations levelled out after placing the chamber on the collar. A clear chamber with the dimensions of diameter = 20 cm, height = 40 cm with an approximate volume of 12.5 L was utilized. All intact collars were measured in the light by leaving the chamber uncovered and allowing light to pass through to reach the vegetation and in the dark by putting a neoprene cover over the chamber for complete darkness. Light fluxes measured net ecosystem exchange (NEE) at the intact collars across the stockpile. A positive NEE value represents a release of CO_2, while a negative value represents an uptake of CO_2. Dark fluxes measured ecosystem respiration (ER). Gross ecosystem productivity (GEP) was then calculated by subtracting the ER values from NEE. All remaining collars, clipped, trenched and mid and bottom slope collars, were only measured in the dark to analyze respiration. The total chamber volume was also obtained. Before starting a carbon flux measurement, the difference between the ground surface in the collar and the collar rim was measured, and the chamber volume was corrected based on this value. The chamber was fitted with a small computer fan at the top to aid in the mixing of air within the chamber to avoid a buildup of gas at the top and altering the carbon flux results. The chamber also had a thermocouple wire inserted into the top, which was connected to a temperature reader to provide internal chamber temperature at the start and end of each carbon flux measurement. A handheld photosynthetic active radiation (PAR) sensor was used during the light fluxes at the intact collars to capture a PAR reading at the start and end of each flux. At the start of each flux, the chamber was aired out to bring internal air temperature and gas composition back to ambient. After this, the chamber was placed onto the collar and the flux was ready to begin after the CO_2 and CH_4 concentration stabilized on the tablet screen.

All data was visually inspected and the linear portion of the concentration change selected using PEDRO (Newton, 2023). The majority of R^2 values for the CO_2 concentrations are above 0.80, except for a few fluxes where the R^2 values were lower as the concentration only rose <5 ppm over the entirety of the flux. Any fluxes with a low R^2 value where the concentration rose more than 5 ppm over the 3 minutes were removed from the dataset, resulting in a loss of 0.45% of the data. Most of the R^2 values for the CH_4 concentrations are above 0.80, except for a few fluxes where the R^2 values were lower as the concentration only rose <10 ppb over the entirety of the flux. Any fluxes with a low R^2 value where the concentration rose more than 10 ppb over the 3 minutes were removed from the dataset, resulting in a loss of 0.45% of the data. Fluxes of CO_2 and CH_4 were then calculated using the slope of change in concentration over time and converted to units of g CO_2-C m^{-2} d^{-1} or mg CH_4-C m^{-2} d^{-1} using the ideal gas law (PV=nRT) and the chamber volume adjusted for temperature and collar height.

To partition soil organic matter-derived, plant-derived, and root-derived respiration from the stockpile, the different collar types were utilized. Soil organic matter-derived respiration is equal to the trenched collars that isolate for peat respiration, with no vegetation within or around the collars. Plant-derived respiration was calculated by subtracting the clipped collar respiration from the intact collar respiration, to isolate for plants only. The root-derived respiration was calculated by subtracting the trenched collar respiration from the clipped collar respiration, to isolate for roots only.

3.2.3 Environmental Variables

The water table was measured at each elevation and depression location on the stockpile. On May 31, 2024, h = 1.5 m, d = 2.5 cm PVC pipe wells were installed 1 m into the peat at 4 elevations and 4 depressions. The water table was measured each time a carbon flux measurement was taken until the water table fell deeper than the bottom of the wells.

Soil temperature at 2 cm, 5 cm, 10 cm, 20 cm, 25 cm, and 30 cm below the peat surface was measured adjacent to each collar using a 30 cm Digi-Sense WD-93758-02 thermocouple immersion probe (Cole-Palmer Instrument Company, Illinois, USA) and a TME MM2020 Dual Input Thermocouple Thermometer (TME, West Sussex, UK).

Volumetric Water Content (VWC %) was measured adjacent to each collar using a Campbell Scientific Hydrosense II Handheld Soil Moisture Sensor (Campbell Scientific, Edmonton, Alberta, Canada). Due to inaccurate readings on this sensor for organic soils, a soil moisture calibration was completed to adjust the readings. A PVC pipe with diameter of 7 cm and length of 20 cm was extracted at each elevation, depression, and slope for a total of 12 peat cores. These cores were brought back to the field house and were immediately weighed before being saturated. A wetted weight and a VWC and period (PER) reading from the Hydrosense sensor were obtained after this step. From June 19, 2024, to July 24, 2024, each core was weighed, and a VWC and PER reading were recorded daily. After the soil cores dried for just over one month, final weights were obtained, and the height of the peat within the core was calculated by subtracting the space at the top of the core from the entire height of the core. Once the peat was removed from the cores, each PVC pipe was weighed. Utilizing the individual heights and radius, the volume for each PVC pipe was calculated. To calculate the actual volumetric water content for each measurement of this calibration, the following equation was used:

$$Actual\ VWC = \frac{Sample\ Weight - PVC\ Weight - Final\ Weight * 1000}{PVC\ Volume * 100}$$

Where sample weight is the weight of each sample on individual sampling days. The final weight is the weight that was obtained for each sample on July 24, 2024. Once the actual VWC values were calculated, a scatter plot was created using the actual VWC values on the y-axis and the PER values on the x-axis. A second-degree polynomial trendline was fitted to the graph, and the equation of the line was obtained ($y = -8.7458x^2 + 84.997x - 97.483$, $R^2 = 0.6039$)(Figure A-2). This equation was then applied to all field-measured VWC values to obtain more accurate VWC values for organic soil.

3.2.4 Biomass Sampling and Net Primary Production Estimates

Biomass and litter sampling was conducted to determine the net primary production on the stockpile and estimate C stored by vegetation since its construction. Aboveground biomass sampling took place on August 1, 2024. There were two sampling plots on each slope, one sampling plot at each elevation and depression carbon flux sampling location, and then four additional replicate elevations, and four replicate depressions selected across the top of the stockpile. At each sampling location, a 1 m x 1 m quadrat was used to assess percent cover of litter, vegetation and bare organic. Of the vegetation present, the percentage of functional group (forb, graminoid, horsetail, liverwort, moss and shrub) was determined. Within the 1 m x 1 m quadrat, a smaller 25 cm x 25 cm quadrat was placed randomly along one of the edges and was used for biomass and litter collection. All vegetation was clipped at the soil surface and was put into paper bags and separated by plant functional group. All litter was also collected and placed in a separate bag. These biomass and litter samples were sorted and weighed within 24 hours of collection, dried at 70 °C for 48 hours, and then weighed in grams.

Belowground biomass sampling was conducted to help determine the total carbon content within root biomass in the stockpile. It took place on August 1, 2024. A PVC pipe with a diameter of 7.62 cm and a length of 50 cm was extracted from each elevation and depression, for a total of 8 belowground biomass cores. During processing, the 50 cm core was separated into the top 15 cm, middle 15 cm, and bottom 20 cm to isolate which locations the plant roots originated from in the core. Each core was emptied into a tin tray, where all large roots were pulled out and separated into a new tray. Dry weight was determined for the roots from each core after drying at 70 °C for 48 hours.

A brief tree survey was completed at the stockpile on August 2, 2024. A total of 18 plots with a 2 m radius were placed systematically across the top of the stockpile. All trees within the 2 m radius were identified and their height recorded. A VWC measurement was taken using a Campbell Scientific Hydrosense II Handheld Soil Moisture Sensor (Campbell Scientific, Edmonton, AB).

To determine the carbon content stored within trees on the stockpile, tree height equations adapted from Huang et al. (2013) and Chojnacky et al. (2014) were used for Black Spruce, Tamarack, Jack Pine, and Trembling Aspen. To obtain an average of carbon stored in trees in g m^{-2} across the stockpile, the total carbon stored in each plot was added and then divided by the plot area (each plot was 12.566 m^{2}).

Table 3.1 Summary of height to biomass equations (Huang et al., 2013; Chojnacky et al., 2014).

Tree Type	**Height to Biomass Equation**
Black Spruce	$g\ C = (0.140969194 * Tree\ Height^{2.3233}) * 1000 * 0.5$
Tamarack	$g\ C = (0.114444576 * Tree\ Height^{2.3853})$ * 1000 * 0.5
Jack Pine	$g\ C = (0.086834515 * \ Tree\ Height^{2.4638})$ * 1000 * 0.5
Trembling Aspen	$g\ C = (0.08680422 * \ Tree\ Height^{2.4561})$ * 1000 * 0.5

To determine the total carbon stored in ground layer plant biomass and litter on the stockpile, the total weight (g) of dried biomass was multiplied by 0.43 because the carbon content in vegetation is approximately 43% of its total weight, as reported by Thormann and Bayley (1997). Total carbon stored in biomass is presented in g C m^{-2}. Note that the equations adapted from Huang et al. (2013) and Chojnacky et al. (2014) estimate that the carbon content in tree biomass is approximately 50%.

3.2.5 Soil Properties: Organic Matter and Carbonate Content

Organic matter and carbonate content in the stockpile soil was determined by loss on ignition analysis conducted in the Ecology Lab at the University of Waterloo. Soil samples from the eight cores collected for belowground biomass soil (roots removed), were used in this analysis (three depths per core for a total of 24 samples analyzed). Crucibles were cleaned, dried, and weighed before adding dry soil, filling the crucible around three-quarters full. The weight of the crucible with the soil was recorded. All 24 crucibles were then placed into the muffle furnace for 5 hours, 1 hour for heat up to 550°C, and 4 hours at the selected temperature. The muffle furnace was shut off after 5 hours, and the samples cooled overnight.

After cooling, the crucibles were weighed again with the remaining soil sample and recorded. The crucibles were put back into the muffle furnace, and the temperature was set to 950°C for 5 hours. There was a 3-hour heat-up time and 2 hours at the selected temperature. After 5 hours, the muffle furnace was turned off, and the samples cooled overnight. Final crucible and soil weights were recorded after the last cooling period.

In the first step, organic matter is combusted to ash and CO_2 at 550°C (Heiri et al., 2001), loss on ignition is calculated using:

$$LOI_{550} = \frac{DW_{105} - DW_{550}}{DW_{105}} * 100$$

Where LOI_{550} is LOI at 550 °C (as a percentage), DW_{105} is the dry weight of the sample before combustion, and DW_{550} is the dry weight of the sample after combustion at 550 °C, both in g (Heiri et al., 2001).

In the second step, CO_2 is released from carbonate, leaving oxide (Heiri et al., 2001), loss on ignition is calculated using:

$$LOI_{950} = \frac{DW_{550} - DW_{950}}{DW_{105}} * 100$$

Where LOI_{950} is the LOI at 950 °C (as a percentage), DW_{550} is the dry weight of the sample after combustion at 550 °C, DW_{950} is the dry weight of the sample after combustion at 950 °C, and DW_{105} is the initial dry weight of the sample before combustion, all represented in g (Heiri et al., 2001). Results from this process are reported as a mass of carbonate (CO_3).

3.2.6 Stockpile Net Carbon Balance

To determine the net carbon balance on the stockpile, emission values were determined with a weighted average of peat CO_2 and CH_4 and subtracted NPP. Both the top of stockpile and slope values were multiplied by their relative areas, and then divided by the entire stockpile area.

$$(1)\ Net\ Carbon\ Balance\ (g\ C\ m^2\ year)$$

$$= \frac{((R_{top} - NPP_{top}) * Top\ Area)\ +\ ((R_{slope-}\ NPP_{slope}) * Slope\ Area)}{Total\ Stockpile\ Area}$$

To determine respiration on top of the stockpile during the growing season, average ER from the trenched collars and average CH_4 from the intact collars at elevations and depressions were added together and then multiplied by their stockpile coverage (elevations = 45%, depressions = 55%). The majority of bare peat areas were located within elevations, so they were accounted for in the areal weighting. Proportional coverage of elevations and depressions was determined by a walking survey on top of the stockpile, manually noting every 30 m whether or not the location was an elevation or depression. Two surveys conducted, one running north to south and the other running east to west on top of the stockpile. These values were added together then multiplied by 151 days in the growing season where fluxes were collected (May 1 – September 28, 2024).

$$(2)\ R_{top}GS = ((Proportion_{el} * (ER_{trenched\ el} + CH4_{intact\ el})) + (Proportion_{dep} * (ER_{trenched\ dep} + CH4_{intact\ dep})) * Growing\ Season$$

To determine respiration on top of the stockpile during the non-growing season, the value obtained for the growing season was multiplied by 0.15, assuming that non-growing season fluxes account for 15% of those during the growing season (Saarnio et al., 2007).

$$(3)\ R_{top}NGS = R_{top}GS * 0.15$$

To determine the total peat respiration from the top of the stockpile, the growing season value from equation 2 and the non-growing season value from equation 3 were added together.

$$(4)\ R_{top} = R_{top}GS + R_{top}NGS$$

Net primary production on the top of the stockpile was calculated by obtaining the average g C m^{-2} stored in elevations and depressions and multiplying them by their areal weights, and then adding the average g C m^{-2} stored in trees to this value. The total was divided by the years since stockpile construction.

$$(5)\ NPP_{top} = \frac{(Elevation\ Biomass * 0.45) + (Depression\ Biomass * 0.55) + Tree\ Biomass}{Years\ since\ contruction}$$

Respiration on the slope during the growing season was calculated by adding the average ER and CH$_4$ values together. These values were then multiplied by 151 days in the growing season where fluxes were collected (May 1 – September 28, 2024).

$$(6)\ R_{slope}GS = \left(ER_{slope} + CH4_{slope}\right) * Growing\ Season$$

Respiration on the slope during the non-growing season was calculated by multiplying the growing season value obtained from equation 6 by by 0.15, assuming that non-growing season fluxes account for 15% of those during the growing season (Saarnio et al., 2007).

$$(7)\ R_{slope}NGS = R_{slope}GS * 0.15$$

To determine the total respiration from the slopes for the entire year, the values from equation 6, growing season, and equation 7, non-growing season, were added together.

$$(8)\ R_{slope} = R_{slope}GS + R_{slope}NGS$$

To determine net primary production on the slope, belowground biomass was estimated since actual measurements did not occur at these locations. Vegetation on the slopes was similar to that of the elevation locations. A ratio of belowground biomass to aboveground biomass was calculated for the elevation locations. This ratio was then used to multiply the average aboveground biomass at the slopes by to obtain an estimated average belowground biomass. This estimated value was then added to the average aboveground biomass value and then divided by years since stockpile construction.

$$(9)\ NPP_{slope} = \frac{Slope\ Biomass}{Years\ since\ contruction}$$

3.2.7 Statistical Analysis

All statistical analysis was completed in R (R Core Team, 2023). Statistical significance was assessed based on p-value <0.05 and considered the framework for strength of evidence presented by Muff et al. (2022) and discussed using the language of evidence (Figure 2.2). To determine the effect of vegetation community (i.e., depression and elevation) on carbon emissions (NEE, GEP, ER, CH_4), a linear mixed effects model was run on the data using the function ‘lme’ in the package nlme (Pinheiro and Bates, 2000), with vegetation community set as a fixed effect and collar set as a random effect. These were tested using the ANOVA type marginal output, and the ‘emmeans’ function in the emmeans package (Lenth, 2025) was used to complete a Tukey test for a pairwise comparison among vegetation treatments.

To determine the effect of stockpile location on aboveground and belowground biomass, a linear model was run on the data using the function ‘lm’ in base R with an ANOVA type II output, and the ‘emmeans’ function in the emmeans package (Lenth, 2025) was used to complete a Tukey test for a pairwise comparison among locations.

To analyze the effect of stockpile elevation (bottom, middle, top) on carbon emissions from the peat, a linear mixed effects model was run on the data using the function ‘lme’ in the package nlme (Pinheiro and Bates, 2000), with collar treatment set as a fixed effect and collar set as a random effect. The only vegetation treatments used in this model are bottom, middle, and trenched to analyze carbon emissions solely from peat, making them, in this instance, collar treatments to capture the three elevations of the study design. These were tested using the ANOVA type marginal output.

To determine the effect of location on organic matter content and carbonate content, a linear model was run on the data using the function ‘lm’ in base R with an ANOVA type II output, the ‘emmeans’ function in the emmeans package (Lenth, 2025) was used to complete a Tukey test for a pairwise comparison among locations.

To determine the effect of location and respiration type on calculated respiration, a linear model was run on the data using the function 'lm' in base R with an ANOVA type II output. This dataset used averages of each plant-derived, root-derived, and soil organic matter-derived respiration value from all elevations and depressions. Due to combing all the different collars by averaging values, a linear mixed effects model with a random effect could not be run on the data, therefore a linear model was used instead.

To determine the effect of environmental controls on carbon emissions and if they vary by vegetation treatment, a linear mixed effects model was run on the data using the function 'lme' in the package nlme (Pinheiro and Bates, 2000), with soil temperature (at 10 cm below surface), soil moisture, and location set as a fixed effects and collar set as a random effect. The MuMIn package (Bartoń, 2025) was used to calculate the marginal and conditional R^2 values. All graphs were created using the ggplot2 package in R (Wickham et al., 2016).

3.3 Results

3.3.1 Environmental Conditions

Historical weather data from the station at the Fort McMurray International Airport (https://climate.weather.gc.ca/index_e.html) recorded that the summer (May to August 2024) average air temperature was approximately 21.5 °C, and the total precipitation was 152.5 mm.

Among all bare organic collars on the stockpile, the average soil temperature at 10 cm throughout the study period was 13.0 °C, with a range of 5.3 – 23.2 °C. (Table 3.3) The average soil temperature at 10 cm was higher at the depression bare organic collars compared to the elevation between May 24 – June 8, 2024, but then was similar amongst the elevation and depression bare organic collars for the rest of the summer. Similarly, at all intact collars on the stockpile, the average soil temperature at 10 cm throughout the study period was 12.5 °C, with a range of 4.0 – 23.0 °C. Early in the season, soil temperature at 10 cm rotated from being higher at both the depressions and the elevations, until mid-summer, when soil temperature was consistently higher at the elevation until the end of the season (Figure 3.2).

Across all bare organic collars on the stockpile, the average volumetric water content throughout the study period was 70.5%, ranging from 30.1 – 94.5% (Table 3.2) Overall, volumetric water content was consistently higher at the depression bare organic collars than at the elevation bare organic collars throughout the summer (Figure 3.2). Among all intact collars on the stockpile, the average volumetric water content throughout the study period was 69.7%, ranging from 37.4 – 97.4%. Overall, volumetric water content was consistently higher at the depression intact collars than at the elevation intact collars throughout the summer.

Table 3.2 Summary of VWC (%) and Soil Temperature (°C) across collar types.

Collar Type	Vegetation Community	Minimum	Maximum	Average
Volumetric Water Content (%)				
Intact	Elevation	37.4	74.9	55.6
Intact	Depression	69.9	97.4	83.8
Bare Organic	Elevation	30.1	80.4	57.2
Bare Organic	Depression	68.5	94.5	83.7
Soil Temperature at 10 cm (°C)				
Intact	Elevation	4.3	23.0	13.0
Intact	Depression	4.0	21.0	11.9
Bare Organic	Elevation	5.3	23.2	12.8
Bare Organic	Depression	6.5	20.6	13.2

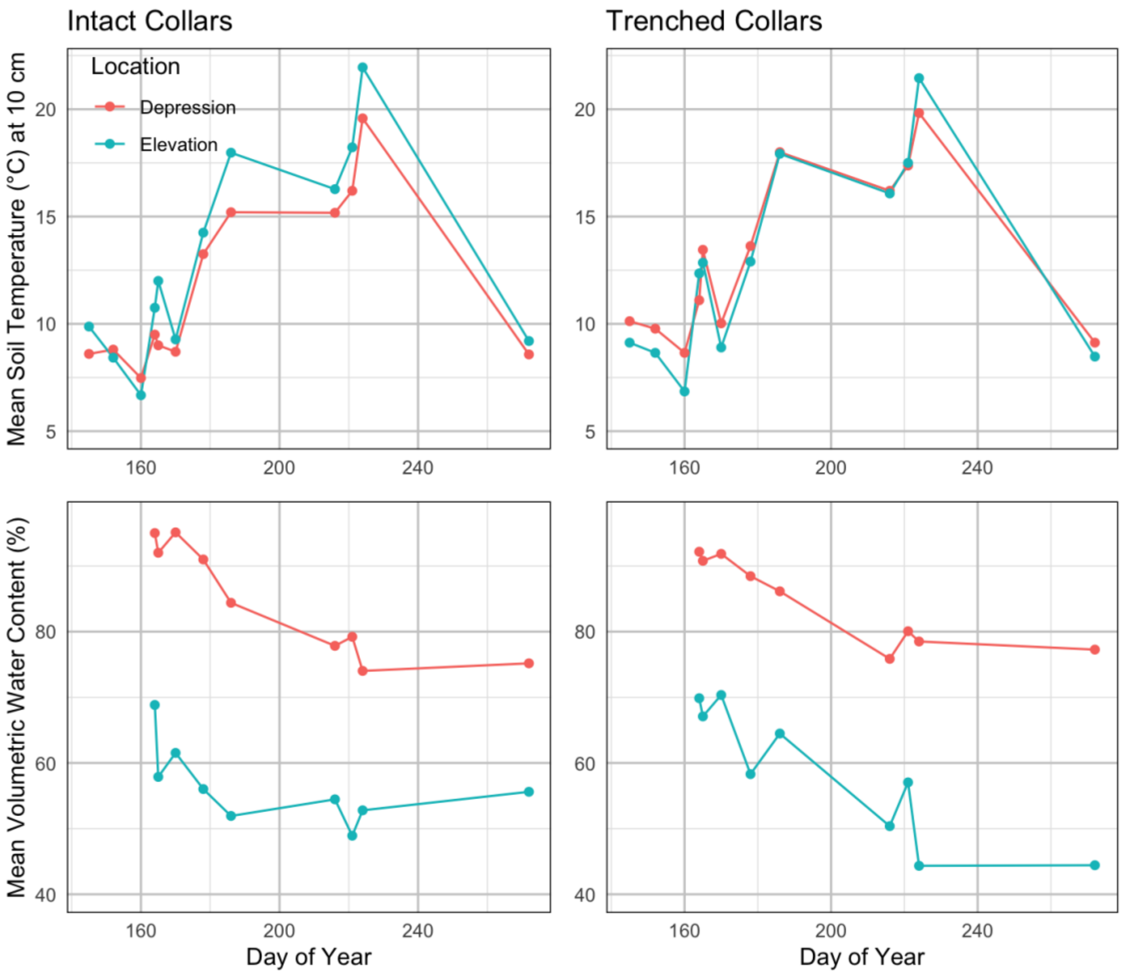

Figure 3.2 Average soil temperature and VWC across intact and trenched collars for the study period.

3.3.2 Soil Properties: Organic Matter and Carbonate Content

For the loss on ignition analysis, the average organic matter content in the depression samples was 33.7%, while the elevation samples were 48.6%. The average organic matter content amongst core depths in depression samples increased with depth from the top (26.7%) to middle (33.8%), and bottom (40.6%). The average organic matter content amongst core depths in elevation samples was: top (41.7%), middle (56.1%), and bottom (48.1%). There was no evidence that depth (F_2=0.71, p=0.50) or the interaction between depth and location (F_2=0.27, p=0.77) had an effect on organic matter content. However, there was weak evidence that location had an effect on organic matter content (F_1=3.25, p=0.09). Although the evidence for the significance was weak, there was still large variability in organic matter content, especially in the elevation samples. The range of organic matter content in the elevation samples was 19.4 – 84.9%, while the range in the depression samples was 10.2 – 62.8%. The elevation samples had a greater organic matter content overall.

The average mass of carbonate in the depression samples was 1.21%, while the elevation samples were 1.84%. The average mass of carbonate amongst core depths in depression samples was: top (1.23%), middle (1.17%), and bottom (1.23%). The average mass of carbonate amongst core depths in elevation samples was: top (1.58%), middle (2.10%), and bottom (1.84%). There was no evidence that depth (F_2=0.40, p=0.68), or the interaction between depth and location (F_2=0.67, p=0.52) had an effect on the mass of carbonate. However, the data revealed very strong evidence that location (F_1=9.15, p=0.0073) has a positive effect on the mass of carbonate, with a higher mass of carbonate content in the elevation samples than the depression samples.

Table 3.3 Main effect of depth and location on organic matter content and carbonate content.

	Degrees of freedom	**Sum of squares**	**F value**	**p-value**
Organic Matter Content				
Depth	2	583.2	0.71	0.50
Location	1	1332.6	3.25	0.09
Depth*Location	2	219.2	0.27	0.77
Carbonate Content				
Depth	2	0.2071	0.40	0.68
Location	1	2.3935	9.15	**0.0073**
Depth*Location	2	0.3521	0.67	0.52

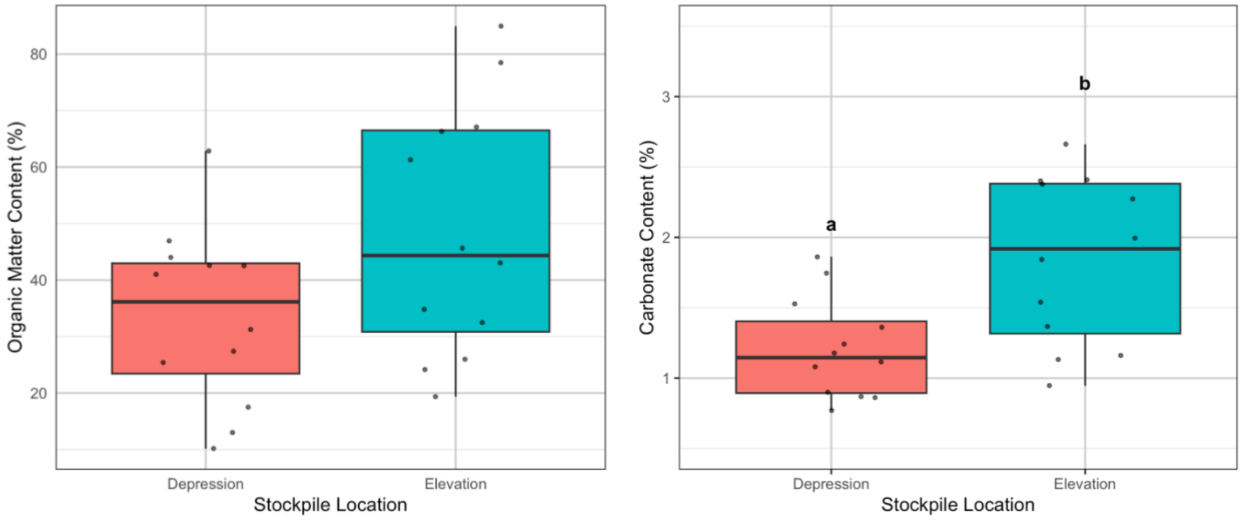

Figure 3.3 Boxplots depicting organic matter content (left) and carbonate content (right) amongst soil samples from depression and elevation locations.

3.3.3 Carbon Fluxes

3.3.3.1 NEE, GEP, ER, CH_4 flux

Average GEP was lower in the depressions (-7.24 g CO_2-C m^{-2} d^{-1}) than elevations (-5.22 g CO_2-C m^{-2} d^{-1}), suggesting greater uptake by plants in the depression areas of the stockpile. The depression locations, on average, also had higher ecosystem respiration (12.20 g CO_2-C m^{-2} d^{-1}), while the elevation locations had a lower ecosystem respiration on average (7.31 g CO_2-C m^{-2} d^{-1}). Average NEE indicated that both elevations and depressions were net sources of CO_2 with lower net emissions at the elevation locations (2.10 g CO_2-C m^{-2} d^{-1}) than depression locations (3.52 g CO_2-C m^{-2} d^{-1}). Statistically, there was no evidence that location had an effect on GEP ($F_{1,6}$=0.65, p=0.45), NEE ($F_{1,6}$=0.20, p=0.67), or ER ($F_{2,6}$=1.79, p=0.23).

The average CH_4 flux was greater at the depressions when compared to elevations. The average CH_4 flux at the depression locations was 446 mg CH_4-C m^{-2} d^{-1}, with a range of -0.573 – 3190 mg CH_4-C m^{-2} d^{-1}. In contrast, elevations only averaged emissions of 2.83 mg CH_4-C m^{-2} d^{-1}, with a range of -3.07 – 109 mg CH_4-C m^{-2} d^{-1}.

There was very strong evidence for an effect of location on log-transformed CH_4 with significantly higher emissions from depressions ($F_{1,6}$=67.09, p=0.0002) (Table 3.5, Figure 3.4).

Table 3.4 Main effect of location on carbon fluxes.

	numDF	**denDF**	**F-value**	**p-value**
GEP				
Intercept	1	76	23.14	**<.0001**
Location	1	6	0.97	0.36
NEE				
Intercept	1	77	1.97	0.16
Location	1	6	0.17	0.69
ER				
Intercept	1	80	22.45	**<.0001**
Location	2	6	1.79	0.23
CH_4 (log)				
Intercept	1	165	276.19	**<.0001**
Location	1	6	62.35	**0.0002**

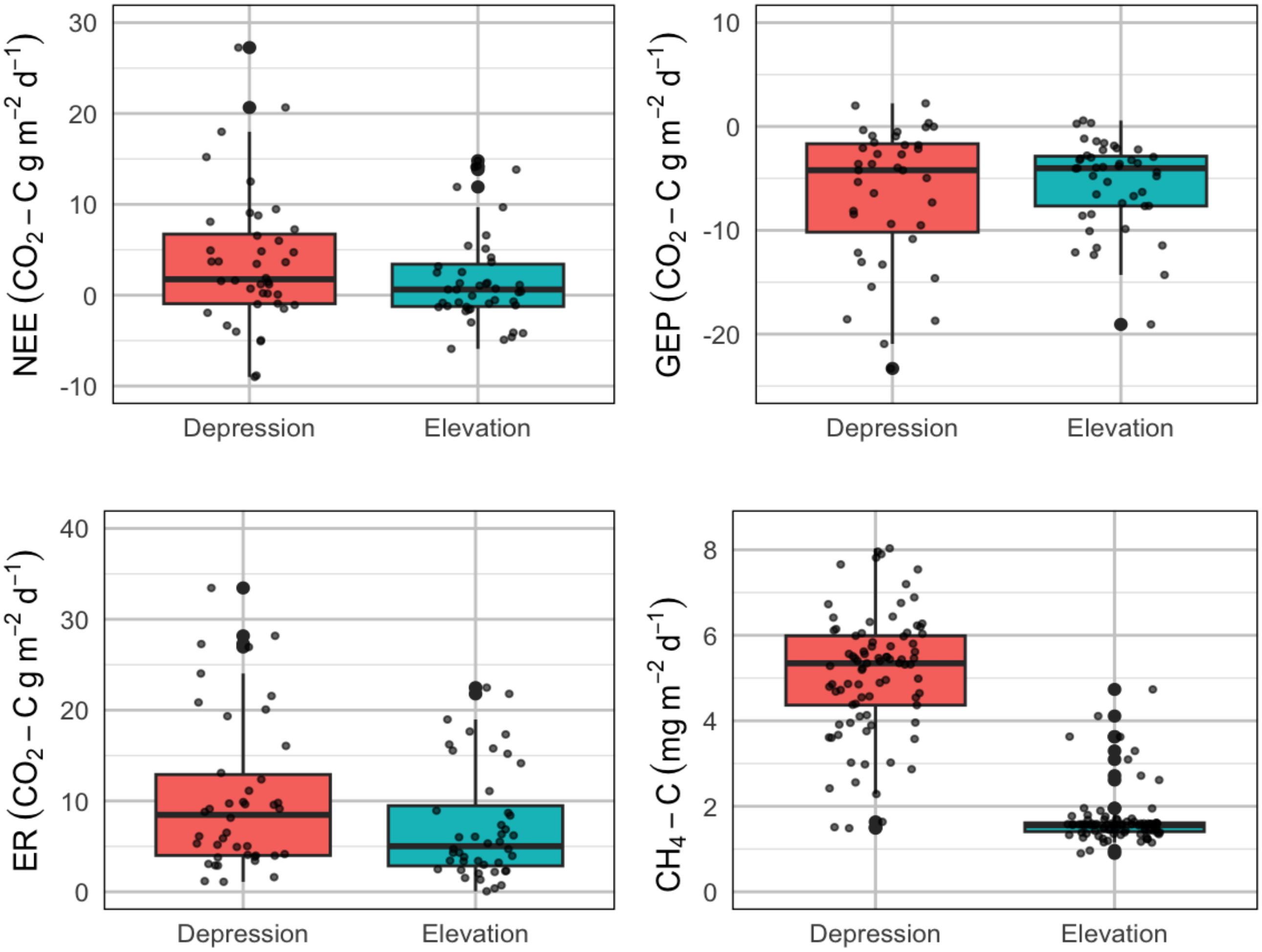

Figure 3.4 Boxplots depicting NEE (top left), GEP (top right), ER (bottom left), and CH_4 (bottom right) from depression and elevation locations.

3.3.3.2 Respiration Partitioning

At the elevations, the largest average respiration came from the peat (soil organic matter-derived), with the lowest average respiration coming from the roots (root-derived). At the depressions, the largest average respiration came from the plants (plant-derived), with very similar respiration amounts coming from the peat and the roots. At both locations, the plants had the largest variation in respiration, with the roots having the least variation in respiration. At the depressions, the average partitioned respiration was 3.43 g CO_2-C m^{-2} d^{-1}, 4.59 g CO_2-C m^{-2} d^{-1}, and 3.45 g CO_2-C m^{-2} d^{-1} from soil organic matter, plant-derived and root-derived respiration, respectively. At the elevations, the average partitioned respiration from each section was 3.59 g CO_2-C m^{-2} d^{-1} from soil organic matter, 2.94 g CO_2-C m^{-2} d^{-1} from plants, and 1.81 g CO_2-C m^{-2} d^{-1} from roots. Although there were differences in average partitioned respiration among the stockpile plant communities, the data did not show any evidence that location (F_1=2.20, p=0.14), respiration type (F_2=0.96, p=0.39) or their interaction (F_2=0.73, p=0.49) had an effect on calculated respiration (Table 3.6, Figure 3.5).

Table 3.5 Main effects of location and respiration type on calculated respiration.

	Degrees of freedom	**Sum of squares**	**F-value**	**p-value**
Location	1	18.08	2.20	0.14
Respiration Type	2	15.70	0.96	0.39
Location*Respiration Type	2	11.91	0.73	0.49

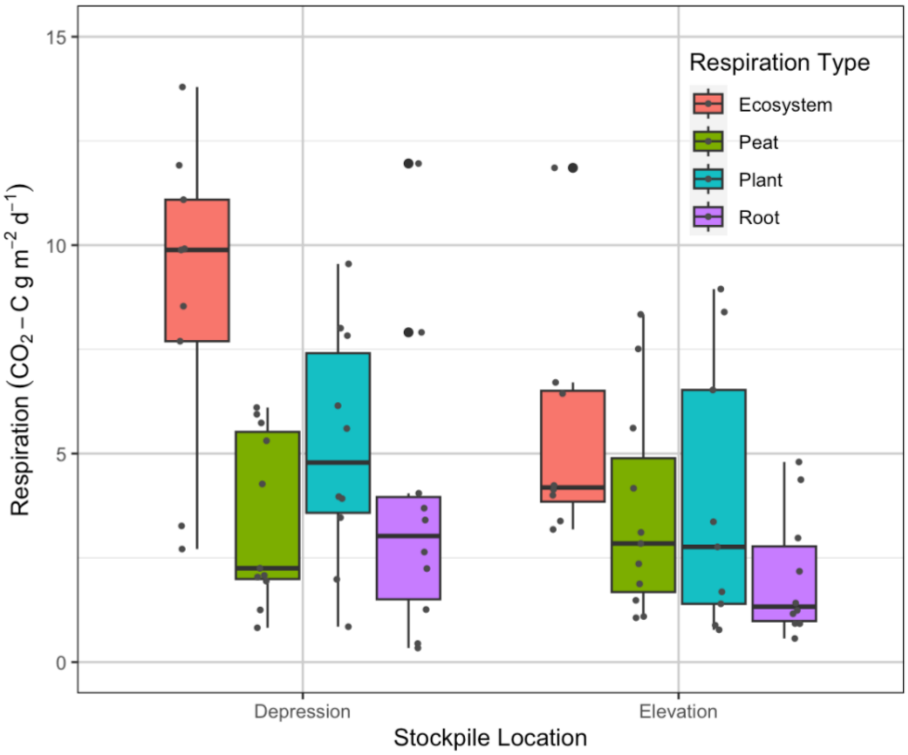

Figure 3.5 Boxplot depicting respiration partitioning among stockpile components. Ecosystem respiration is shown as the total of all components.

3.3.3.3 Environmental Controls on Ecosystem Fluxes

In an initial complex model of environmental variables' effect on intact collar fluxes, there was very strong evidence that the three-way interaction between soil temperature, volumetric water content and location explained variation in ecosystem respiration ($F_{1,114}$=10.14, p=0.0025) and CH_4 flux ($F_{1,114}$=12.27, p=0.0007). Due to the significance of the three-way interactions, the data was split into elevation and depression locations to investigate the effect of environmental conditions within each plant community.

In the simpler model, there was weak evidence that the interaction between soil temperature and volumetric water content had an effect on ecosystem respiration at intact collars at elevation locations ($F_{1,25}$=3.56, p=0.071). There was also weak evidence that volumetric water content individually had a negative effect on ecosystem respiration at elevation locations ($F_{1,25}$=3.06, p=0.093). There was moderate evidence that soil temperature ($F_{1,25}$=6.76, p=0.02) and volumetric water content ($F_{1,25}$=7.65, p=0.01) had a positive effect on ecosystem respiration at depression locations with their interaction also important ($F_{1,25}$=6.07, p=0.02).

In the simpler model, there was moderate evidence that soil temperature ($F_{1,57}$=4.19, p=0.05) had a positive effect on CH_4 emissions at intact collars at elevation locations (Figure 3.7). The interaction between soil temperature and volumetric water content ($F_{1,57}$=5.52, p=0.02) had moderate evidence for an effect on CH_4 emissions at intact collars at elevation locations. However, there was very strong evidence that volumetric water content had a positive effect on CH_4 emissions at intact collars at elevation locations ($F_{1,57}$=12.31, p=0.0009). Conversely, there was only moderate evidence that the interaction between soil temperature and volumetric water content had an effect on CH_4 emissions at intact collars at depression locations ($F_{1,57}$=7.08, p=0.01).

Table 3.6 Main effects of soil temperature and volumetric water content on ER and CH_4 at elevation and depression (intact collars).

	numDF	**denDF**	**F-value**	**p-value**
Elevation ER				
Intercept	1	25	1.63	0.21
Soil Temperature at 10 cm	1	25	0.66	0.42
Volumetric Water Content	1	25	3.06	0.09
Soil Temperature at 10 cm*Volumetric Water Content	1	25	3.56	0.07
	R^2m - 0.57		R^2c - 0.57	
Depression ER				
Intercept	1	25	7.05	**0.01**
Soil Temperature at 10 cm	1	25	6.76	**0.02**
Volumetric Water Content	1	25	7.65	**0.01**

Soil Temperature at 10 cm*Volumetric Water Content	1	25	6.07	**0.02**
	R^2m - 0.18		R^2c - 0.33	
Elevation CH_4				
Intercept	1	57	1.44	0.23
Soil Temperature at 10 cm	1	57	4.19	**0.05**
Volumetric Water Content	1	57	12.31	**0.0009**
Soil Temperature at 10 cm*Volumetric Water Content	1	57	5.52	**0.02**
	R^2m - 0.33		R^2c - 0.41	
Depression CH_4				
Intercept	1	57	0.000099	0.99
Soil Temperature at 10 cm	1	57	3.46	0.07
Volumetric Water Content	1	57	0.18	0.67
Soil Temperature at 10 cm*Volumetric Water Content	1	57	7.08	**0.01**
	R^2m - 0.52		R^2c - 0.64	

3.3.3.4 Peat Respiration and CH_4 across Stockpile Elevations

Considering only peat respiration (i.e., using the bare organic, trenched ER for the top of the stockpile) all stockpile elevations (bottom, middle, top) had similar ranges in peat respiration (Figure 3.6). The average peat respiration at the bottom of the stockpile was 2.92 g CO_2-C m^{-2} d^{-1}, at the middle of the stockpile, it was 4.14 g CO_2-C m^{-2} d^{-1}, and at the top of the stockpile, it was 3.51 g CO_2-C m^{-2} d^{-1}. There was no evidence that stockpile elevation had an effect on peat respiration ($F_{2,13}$=0.54, p=0.59; Table 3.8, Figure 3.6).

The bottom and middle stockpile locations had little variability in their CH_4 emissions, while the top of the stockpile has a large range of variability in CH_4 emissions. Although the emission range differs across stockpile elevations, average log-transformed CH_4 emissions were similar. The bottom of the stockpile had an average of 1.96 mg CH_4-C m^{-2} d^{-1} while the middle of the stockpile has an average of 1.61 mg CH_4-C m^{-2} d^{-1}. The range in CH_4 emissions from the top of the stockpile was 0.50–7.73 mg

CH_4-C m^{-2} d^{-1}, while the average was 2.49 mg CH_4-C m^{-2} d^{-1}. There was no statistical evidence that stockpile elevation had an effect on CH_4 emissions ($F_{2,13}$=1.26, p=0.32; Table 3.8, Figure 3.6).

Table 3.7 Main effect of stockpile elevation on peat respiration and CH_4.

	numDF	denDF	F-value	p-value
Peat Respiration				
Intercept	1	160	12.43	**0.0006**
Elevation	2	13	0.54	0.59
CH_4				
Intercept	1	158	0.0057	0.94
Elevation	2	13	1.26	0.32

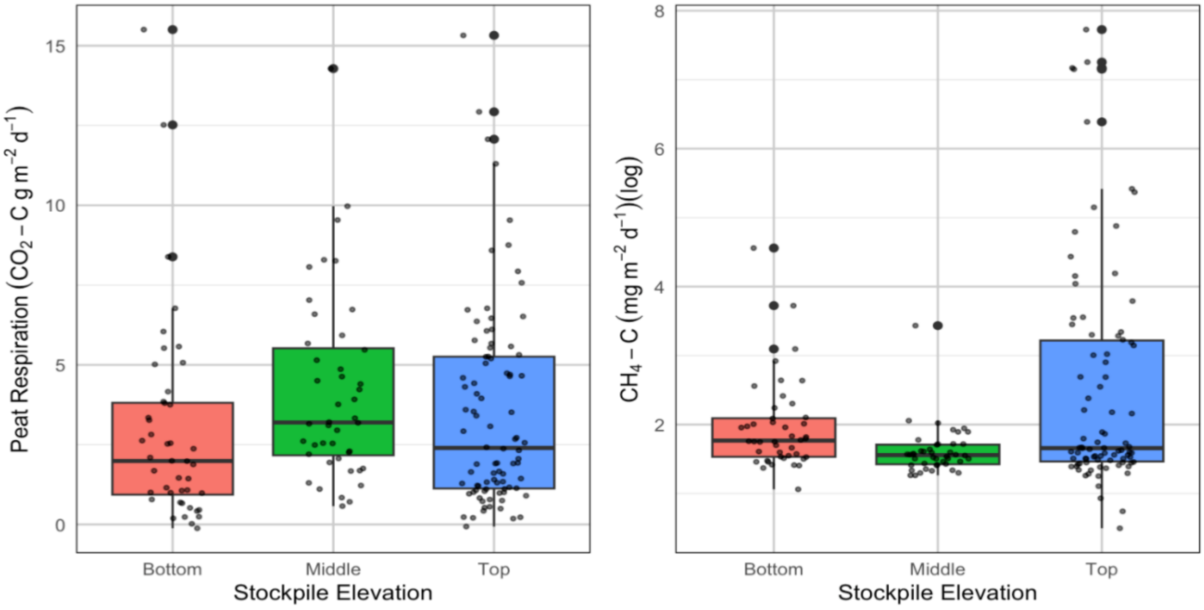

Figure 3.6 Boxplots depicting peat respiration (left) and CH_4 flux (right) among stockpile elevations (bottom of stockpile, middle of stockpile, and top of stockpile).

3.3.3.5 Environmental Controls on Peat Respiration

In an initial complex model of environmental variables' effect on peat respiration, there was moderate evidence that the three-way interaction between soil temperature, volumetric water content and location had an effect on peat respiration ($F_{1,50}$=6.98, p=0.01). Due to the significance of the three-way interaction, the model was simplified by separating the data by location. At elevations, there was moderate evidence that soil temperature had a positive effect on peat respiration ($F_{1,25}$=5.77, p=0.02). At the depressions, there was strong evidence that both soil temperature ($F_{1,25}$=9.04, p=0.0059) and volumetric water content ($F_{1,25}$=8.304, p=0.008) had a positive effect on peat respiration. There was also very strong evidence that their interaction ($F_{1,25}$=9.11, p=0.0058) had an effect on peat respiration.

Table 3.8 Main effect of soil moisture and volumetric water content on peat respiration at elevation and depression.

	numDF	denDF	F-value	p-value
Elevation Peat Respiration				
Intercept	1	25	0.04	0.84
Soil Temperature at 10 cm	1	25	5.77	**0.02**
Volumetric Water Content	1	25	0.14	0.71
Soil Temperature at 10 cm*Volumetric Water Content	1	25	2.68	0.11
	R^2m - 0.26		R^2c - 0.77	
Depression Peat Respiration				
Intercept	1	25	7.13	**0.01**
Soil Temperature at 10 cm	1	25	9.04	**0.0059**
Volumetric Water Content	1	25	8.30	**0.008**
Soil Temperature at 10 cm*Volumetric Water Content	1	25	9.11	**0.0058**
	R^2m - 0.21		R^2c - 0.35	

In an initial complex model of environmental variables' effect on CH_4, there was no evidence that the three-way interaction between soil temperature, volumetric water content and location had an effect on CH_4 emissions ($F_{1,48}$=0.0088, p=0.93). As no fixed effects were significant, a model simplification was conducted; first, the three-way interaction was removed from the model and only individual variables and two-way interactions were analyzed. There was no evidence that soil temperature had an effect on CH_4 emissions ($F_{1,49}$=0.24, p=0.63). A new model was created by removing soil temperature and its two-way interactions. There was very strong evidence that volumetric water content ($F_{1,52}$=24.97, p=<0.0001) by itself had a positive effect on CH_4 emissions at bare organic collars. While there was moderate evidence that location ($F_{1,52}$=11.86, p=0.01) by itself had a positive effect on CH_4 emissions at bare organic collars. The interaction between these two variables had an effect on CH_4 emissions at bare organic collars ($F_{1,52}$=16.75, p=0.0001), suggesting that the relationship differs amongst locations. Considering each vegetation community separately, there was moderate evidence that volumetric water content ($F_{1,27}$=6.07, p=0.02) had a positive effect on CH_4 emissions at the bare organic collars at elevation locations. At depression locations, there was very strong evidence that volumetric water content ($F_{1,25}$=12.20, p=0.0018) had a positive effect on CH_4 emissions at the bare organic collars.

Table 3.9 Main effect of volumetric water content on CH_4 fluxes at elevations and depressions.

	numDF	**denDF**	**F-value**	**p-value**
Elevation CH_4				
Intercept	1	27	27.09	**<.0001**
Volumetric Water Content	1	27	6.07	**0.02**
	R^2m - 0.12		R^2c - 0.49	
Depression CH_4				
Intercept	1	25	5.34	**0.029**
Volumetric Water Content	1	25	12.20	**0.0018**
	R^2m - 0.26		R^2c - 0.41	

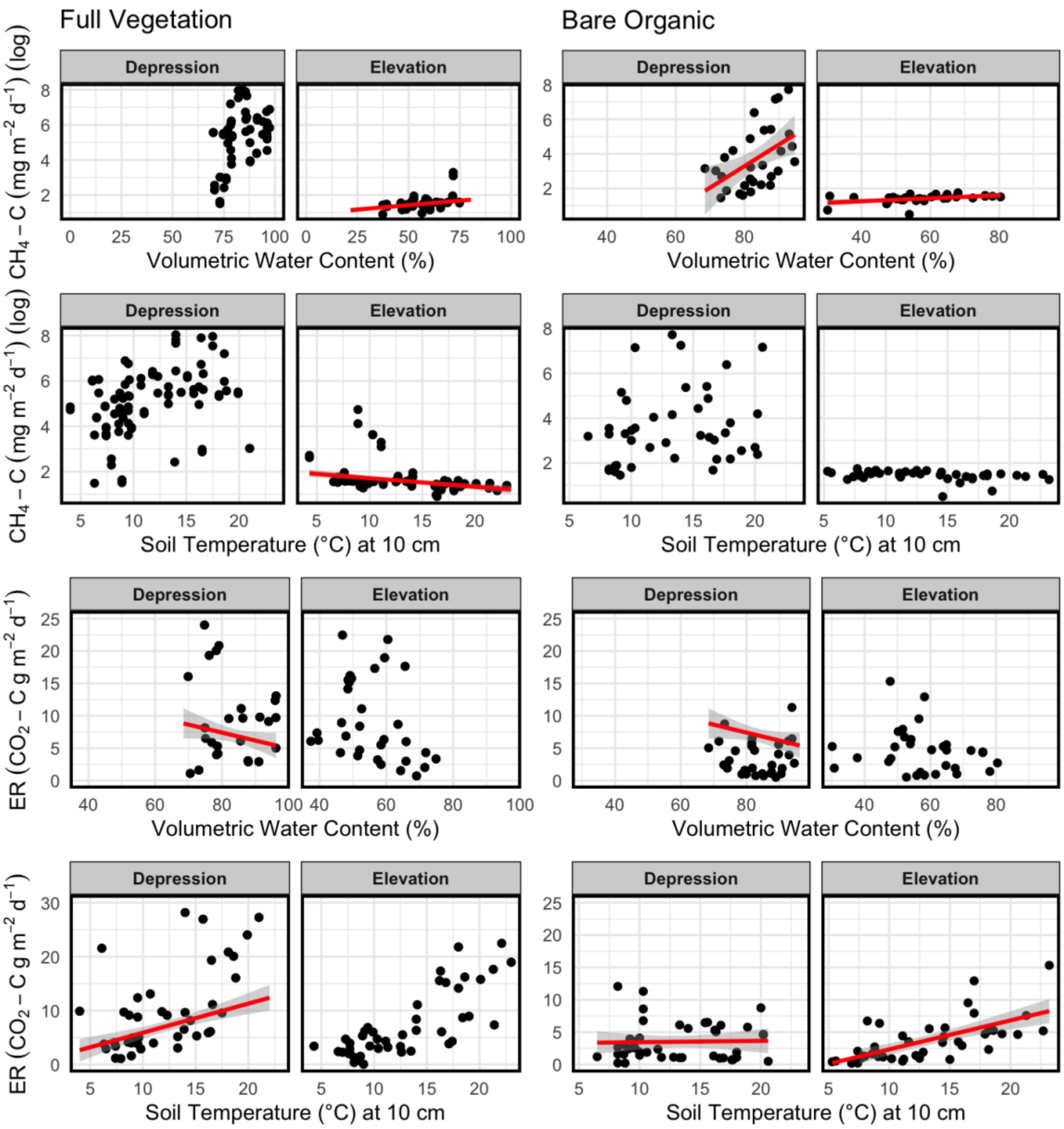

Figure 3.7 Scatterplots depicting the relationship between volumetric water content and CH_4 flux, soil temperature and CH_4 flux, volumetric water content and ER, and soil temperature and ER all at full vegetation (intact) collars and bare organic (trenched) collars.

3.3.4 Biomass and Net Primary Productivity

The average aboveground biomass and litter at the depression locations was 199 g C m^{-2}, while the average at elevation communities was 142 g C m^{-2} (Figure 3.8). . Aboveground biomass was statistically similar across vegetation community types

($F_{1,14}$=1.27, p=0.28). Average aboveground biomass at the slopes was 177.4 g C m^{-2}, and the average carbon stored in tree biomass was 2.9 g C m^{-2}. Trees on the stockpile were a mixture of industry-planted as well as natural regeneration. The average height of trees measured was 0.51 m, with a density of 3 trees per plot.

Belowground biomass had greater storage than aboveground biomass with depression locations having an average of 641 g C m^{-2}, while the average stored in elevation locations was 269 g C m^{-2} (Figure 3.8). There was moderate evidence that more carbon was stored in belowground biomass at depressions versus elevations ($F_{1,6}$=7.39, p=0.03).

We assumed that this biomass had been accumulating since stockpile construction in 2019. Assuming a constant rate of biomass accumulation over those 6 years results in an estimated NPP of 108.3 g C m^{-2} yr^{-1} across the entire top of the stockpile.

Table 3.10 Average C stored in biomass by location and type.

Biomass Type	**Location**	**Average g C m^{-2}**
Aboveground	Elevation	142.4
Aboveground	Depression	198.6
Aboveground	Slope	177.4
Belowground	Elevation	269.0
Belowground	Depression	641.5
Trees	All Stockpile	2.9

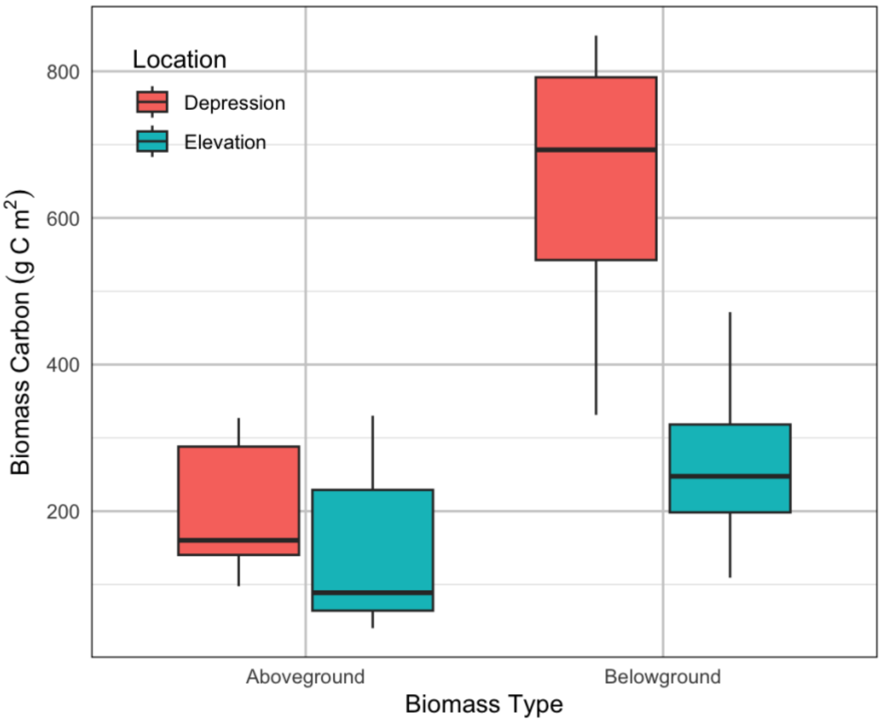

Figure 3.8 Boxplot depicting carbon stored in aboveground and belowground biomass per m^{-2} at the elevation and depression locations.

3.3.5 Stockpile Net Carbon Balance

Per year, the top of the stockpile emitted approximately 652.7 g C m^{-2} from peat organic matter decomposition, while plant NPP only offset approximately 108.3 g C m^{-2} annually. Similarly, the slopes of the stockpile emitted approximately 612.8 g C m^{-2} as peat respiration (CO_2 + CH_4), while plants only offset 85.4 g C m^{-2}. The weighted average of these values combined results in a stockpile-wide net carbon balance of 539.6 g C m^{-2} yr^{-1}.

3.4 Discussion

3.4.1 Stockpile Soil Composition among Vegetation Communities

Organic matter content was not affected by the different vegetation communities (Figure 3.3). Organic matter content was lower in the depression communities and higher at the elevation communities, where there was a larger range in values. It was hypothesized that the depressions would have a greater percentage of organic matter content due to the above-surface water table present and the density of vegetation at these locations. Due to the high water table at these spots, it was expected that decomposition would be slow (Clymo, 1984), maintaining a higher amount of organic matter in these locations. Also, the increased vegetation cover, particularly sedges, at these locations was expected to increase organic matter. However, as the field season progressed, the water table was not above the surface, but soil moisture was still high and labile litter deposition likely increased decomposition rates in these locations. This can be seen in the higher average ecosystem respiration experienced at the depressions versus the elevations (Figure 3.4). Less vegetation, and conditions likely too dry for most of the season to drive high ecosystem respiration, led to the preservation of organic matter in the elevation samples, resulting in a higher organic matter percentage. It is also possible that a lower percentage of organic matter is what created the depressions on the stockpile. With a higher percentage of mineral soil mixed with the peat in certain areas of the stockpile, greater subsidence due to factors such as soil compaction could have created the depression areas.

There were significant differences between the carbonate content in the depression and elevation communities. The elevation locations had significantly higher carbonate content than the depression locations. This likely has to do with the construction of the stockpile. The particular stockpile in this study is constructed of deep, catotelmic peat, some of which was once located at the peat-mineral interface in the ground. During construction, operators could have potentially scraped off part of the top layer of mineral soil as well as peat. This mineral soil likely got mixed in with the peat stockpile. The elevations had a larger percentage of carbonate and a higher percentage of organic matter than the depressions, which resulted in slightly higher soil organic matter-derived respiration than the depressions (Figure 3.5). This does not align with what was found in Kong et al. (1980), where it was suggested that added mineral soil would enhance decomposition. However, Kong et al. (1980) do not explicitly say how much mineral soil or what percentage of carbonate was present in the conditions for increased decomposition.

3.4.2 Carbon Fluxes

3.4.2.1 CO_2 dynamics for in-field fluxes

NEE, GEP, and ER were not significantly different between the vegetation communities (Figure 3.4). The average NEE among both vegetation communities, the grass and shrub-dominated elevations, and the sedge-dominated depressions, indicated that both locations were a source for CO_2. This implies that even though plants were present at these locations, autotrophic respiration and heterotrophic respiration (i.e., peat decomposition), exceeded any carbon uptake by plants and carbon storage in biomass. As previously mentioned, vascular vegetation, which is the dominant type of vegetation on the stockpile, produces highly labile litter and is not a desired vegetation type for carbon sequestration in peatlands (Bombonato et al., 2010; Wilson et al., 2021). The elevation locations had a slightly lower NEE value, indicating a bit more net uptake, versus the depression locations. This could be due to how densely vegetated the depression locations were. More overall plant cover could lead to increased litter and decomposable plant material, increasing GHG emissions, or an increase in autotrophic respiration. The sedges present at the depressions could have also enhanced oxygen transport to the rhizosphere, introducing oxic areas within the anaerobic layer and increasing CO_2 emissions (Vasander et al., 2006; Strack et al., 2006). This increased plant cover at depressions also results in greater productivity and increased carbon uptake (Del Guidice and Lindo, 2017; Oke and Hager, 2020). The difference in NEE between the two locations was not significant, although there was a greater range in NEE at the depression locations (Figure 3.4). The depressions had a lower GEP (i.e., greater productivity), but had a higher average ecosystem respiration than the elevations. This indicates that even though the depressions are experiencing greater carbon uptake, due to the increased vegetation presence and photosynthesis, they are also experiencing greater ecosystem respiration, due to increased autotrophic respiration (Figure 3.4).

Volumetric water content, soil temperature and their interaction significantly affected ecosystem respiration at the intact plots at depressions, and nearing significance at the elevations (Table 3.7). High soil moisture is usually associated with lower ecosystem respiration in wetlands, which is still the case in this study, but we still observed high ecosystem respiration values at high volumetric water contents. At the depression locations, there was consistently high soil moisture throughout the study period. Since the depression locations were dominated by sedges, oxygen transport to the water-saturated soil by aerenchyma likely increased aerobic decomposition and

CO_2 output, to a certain extent (Le Mer and Roger, 2001; Strack et al., 2006; Limpens et al., 2008; Lai, 2009). Soil moisture was also likely within an optimal range for ecosystem respiration at these locations during the study period. With the help of the vegetation at these locations, high volumetric water content is responsible for some of the high ecosystem respiration at the depressions, and oftentimes, respiring similar amounts to the elevations, which have lower volumetric water contents. A negative relationship is also seen at the depression locations in the bare organic collars. At depressions, the interaction between soil temperature and volumetric water content, as well as these variables individually, had a significant effect on peat respiration (Table 3.9). Since there was no vegetation present at these plots, the role of aerenchyma is no longer present. A study by Waddington et al. (2001) suggests that the optimal range of soil moisture for respiration was between 70% and 83%, while Husen et al. (2014) determined that around 60% was optimal for respiration. Hunter et al. (2024) also experienced high respiration with high soil moisture values. Although there is a negative relationship between ecosystem respiration and volumetric water content at the depression bare organic collars, it seems that there was an optimal soil moisture through the study period to allow respiration values similar to those experienced at the elevation plots of the same treatment with lower soil moisture values. There were no significant relationships at the full vegetation or bare organic elevations between volumetric water content and ecosystem respiration, and there is large variation at a range of volumetric water contents (Figure 3.7). This suggests that at the elevations, soil temperature may play a larger role due to the large temperature range experienced during the season (Table 3.2).

Ecosystem respiration was also affected by soil temperature. There was a significant positive relationship between ecosystem respiration and soil temperature at the full vegetation depression collars and the bare organic elevation and depression collars (Figure 3.7, Table 3.7, Table 3.9). This relationship is well established in the literature. As soil temperature increases, there is an increase in microbial stimulation, which enhances the decomposition process. Other studies, such as Moore and Dalva (1993) or Swails et al. (2022), also experienced an increase in ecosystem respiration with an increase in soil temperature. Since the elevations experienced a larger range in soil temperature than they did in volumetric water content, this was likely the determining factor in increased ecosystem respiration at these locations.

3.4.2.2 CH_4 dynamics for in-field fluxes

CH_4 was affected by the different vegetation communities (Figure 3.4). The average CH_4 flux recorded at the depression locations was significantly higher than at the elevation locations. This occurred due to a consistently higher soil moisture content, with an above-surface water table for the start of the field season (Figure 3.2), and the extensive presence of sedges with labile litter deposition. As previously stated, a shallow water table and subsequently high soil moisture result in anoxic conditions, which provide adequate conditions for CH_4 production and transport to the atmosphere (Bubier et al., 1993; Lai, 2009). If conditions were dry at the depressions like at the elevations, the majority of CH_4 produced in the anoxic layers of the stockpile would become oxidized during transport and expelled as CO_2 (Lai, 2009; Bridgham et al., 2013). Sedges present at the depression locations also play a large role in the increased CH_4 fluxes at these locations. Due to their ability to allow CH_4 to bypass oxidation in the oxic zone of the stockpile, increased CH_4 emissions can occur (Vasander et al., 2006; Strack et al., 2006). In fact, CH_4 emissions were higher from intact plots than from clipped and trenched plots (Figure A-1). Sedges likely played a larger role later in the field season when the water table was no longer above the surface, and the anaerobic zone was deeper in the peat profile. It is important to note that CH_4 emissions did not play a large role in overall carbon emissions from the stockpile. CH_4 only accounted for approximately 0,04% of overall emissions, with CO_2 making up the rest. This could be due to the extensive drying of the depression locations mid-to-late field season, where an above-surface water table was no longer present, and therefore, the release of CH_4 was minimized. If the above surface water table was retained throughout the entire field season, the proportion of CH_4 emissions from overall carbon emissions could have been increased.

At both the full vegetation and bare organic collars, the relationships between volumetric water content and CH_4 flux and soil temperature at CH_4 flux are similar (Figure 3.7). The difference in these relationships can be seen when comparing the elevations and depressions. There is a significant positive relationship between volumetric water content and CH_4 flux at the full vegetation elevation plots and the bare organic depressions and elevations (Table 3.7, Table 3.10). As volumetric water content increases, the CH_4 increases in response. This follows the well-established pattern in literature (Bubier et al., 1993; Lai, 2009). There is a significant negative relationship at full vegetation elevation plots between soil temperature and CH_4 flux; a similar relationship is seen at the bare organic elevation, but this relationship is not significant (Figure 3.7). All depressions had a large variation in the relationship between CH_4 flux and soil temperature. At the depressions, volumetric water content seems to be the dominating factor in increasing CH_4 flux. At the elevations, because volumetric water content is consistently lower and has a smaller range, when soil temperature increases, this initiates CH_4 oxidation and smaller fluxes. Although this is the general pattern experienced in the data, the three-way interaction between soil temperature, volumetric water content, and CH_4 flux was only significant at the full vegetation plots. At the bare organic plots, only volumetric water content had a significant relationship with CH_4 flux.

3.4.2.3 Root-, Plant-, and Soil Organic Matter-derived Respiration

At the depressions, plant-derived respiration was the highest, with some variation over the field season. These locations had large amounts of vascular vegetation, which likely deposited labile litter available for decomposition, increasing respiration from this part of the ecosystem. Roots experienced higher respiration at the depressions versus the elevations, mainly due to the increased root presence in these areas, confirmed through the belowground biomass analysis (Figure 3.8). As previously mentioned, the dominant sedge vegetation located in the depressions had increased root presence and depth, which increased autotrophic respiration among roots here (Figure 3.8). In contrast, soil organic matter-derived respiration was similar across both locations. This is consistent with the limited effect of the plant community on peat respiration measured in an incubation experiment under controlled moisture and temperature conditions (Chapter 2). The soil organic matter-derived respiration was slightly higher at the elevation locations, likely due to the large variability in soil moisture over the field season. The lower soil organic matter-derived respiration values at the depressions may be due to the water-saturated periods of the field season, not allowing for an optimal environment for respiration.

By partitioning the different aspects of respiration, root-derived, plant-derived, and soil organic matter-derived, we can see exactly what each part is contributing to overall ecosystem respiration. This shows that not only is a good portion of respiration occurring from the peat itself, but also from the plants on the stockpile. When comparing the plant-derived respiration to the GEP values, plant-derived respiration from the depressions is very similar to GEP at the depressions (Figure 3.4, 3.5). This means that GEP offsets most of the plant-derived respiration from these locations. At the elevations, GEP looks to be greater than the plant-derived respiration, meaning it is offsetting more than is being produced (Figure 3.4, 3.5).

3.4.2.4 Stockpile Elevation and GHG Emissions

It was hypothesized that the top of the stockpile would have the highest average flux due to its higher elevation and a greater amount of peat below these collars. With more peat beneath the collars on the top of the stockpile, there was more aerated peat material available for decomposition and therefore an increase in heterotrophic respiration, increasing CO_2 emissions. But the findings did not reveal this hypothesis to be true. CO_2 fluxes were not affected by stockpile elevation (Figure 3.6). The highest average CO_2 flux occurred at the middle slope locations, with the next highest average flux occurring on top of the stockpile, but there were no significant differences between CO_2 fluxes at the bottom slope, middle slope, or on top of the stockpile.

Similarly, CH_4 fluxes were not affected by stockpile location (Figure 3.6). The highest average CH_4 fluxes were experienced on top of the stockpile, which was expected. The two slope locations saw very minimal CH_4 fluxes, with very little flux range over the entire field season. Although there were no significant differences among elevations, the top of the stockpile collars saw a large range in CH_4 fluxes over the field season and experienced some of the highest flux values. This is likely due to the higher soil moisture average and the presence of a water table for the majority of the season among the collars on the top of the stockpile, particularly in depression locations. The increased soil moisture and presence of the water table likely created favourable conditions for the production and transport of CH_4 (Bubier et al., 1993; Lai, 2009). There was likely too much variation in the top of stockpile CH_4 fluxes over the season, due local variation in elevation and hence moisture content, for there to be statistically significant differences among the three elevations.

3.4.3 Stockpile Net Carbon Balance

The net carbon balance of the stockpile is high at 539.6 g C m^{-2} yr^{-1}. This value indicates that the stockpile doesn’t have carbon exchange values as expected from natural peatlands. On the stockpile, plants are not offsetting the large amount of peat decomposition occurring. There was no difference in NEE between the fully vegetated collars and the bare peat collars. The vegetated collars had a slightly lower NEE value, but no evidence for a significant difference from the bare organic locations. Depression locations stored more carbon in their aboveground biomass than elevations, and they stored significantly more carbon in their belowground biomass (Figure 3.8). These relationships translated into the depressions having a higher overall NPP, versus a lower NPP at the elevation locations. However, neither NPP was large enough to offset peat respiration at any locations on the stockpile, likely due to enhanced decomposition.

Most of the vegetation analyzed during the plant surveys was vascular, and most survey locations had no moss at all. Vascular plants produce labile, easily decomposable litter, which increases microbial activity and therefore GHG emissions (Bombonato et al., 2010; Wilson et al., 2021). Sedges, a type of vascular plant, can also aid CH_4 to bypass oxidation and be transported directly to the atmosphere, increasing emissions, but have significant amounts of belowground biomass, which add labile materials (Vasander et al., 2006; Strack et al., 2006). This is especially experienced in the depression locations of the stockpile, which encompass around 55% of the top area, and see significant amounts of CH_4 being emitted when compared to the elevation locations. However, there is still a relatively small amount of CH_4 emitted compared to CO_2; therefore, the significance of CH_4 to the overall carbon balance of the stockpile is minimal. If the stockpile was dominated by moss, rather than vascular vegetation, ecosystem respiration could be much lower, and there would be increasing CO_2 uptake, due to how recalcitrant moss litter is (Pinsonneault et al., 2016). Although peat stockpile conditions are vastly different from those of a natural peatland, introducing *Sphagnum spp.* onto the stockpile could enhance overall carbon storage and create an environment for new peat production, reducing the overall net carbon balance (Bragazza et al., 2006). The addition of mosses to the stockpile could also help to create a suitable substrate for future moss growth when the stockpiled peat is used as reclamation soil (Alberta Environment and Water, 2012).

Since the stockpiled peat was moved from its natural, water-saturated conditions to a large, aerated stockpile, organic matter decomposition has increased, resulting in a positive net carbon balance. The peat in the stockpile is from the catotelm, meaning it originates from deep underground, where it was likely water-saturated, with lower temperatures. Putting this peat into the stockpile has altered the soil moisture conditions and the temperature regime. The higher temperatures on the stockpile, compared to those experienced deep in the peat profile, are likely affecting soil moisture and are one of the causes of increased decomposition of the peat (Moore and Dalva, 1993; Wilson et al., 2021). These processes have enhanced the availability of oxygen in the peat, which has affected the microbial processes and increased the production of GHG (Moore and Dalva, 1993). Though this study only analyzed the surface layer of the stockpile, an above-surface water table for part of the season at depressions indicates that the middle of the stockpile could be experiencing colder, water-saturated conditions, unlike the surface. These conditions would help to minimize organic matter decomposition compared to well-aerated conditions.

With the increased decomposition, there is likely also an increase in dissolved organic carbon (DOC) leaving the stockpile. Although DOC was not directly measured in this study, Dieleman et al. (2016) discovered that under future climate warming, there will be elevated peat decomposition and DOC quantities in porewater will also be impacted. This information could apply to the stockpile since there was increased sun exposure and resulting temperatures, therefore also increased DOC export. If DOC were included in the net carbon balance, it could increase the value, meaning more carbon loss from the stockpile. Erosion also plays a role in the net carbon balance of the stockpile. A separate study conducted on this stockpile indicates that the summer after wetland vegetation was planted on the stockpile, summer 2023, all locations, including the slopes and the top of the stockpile, were sources of erosion. This means that there was extra carbon loss through erosion that was not initially accounted for in the net carbon balance, resulting in an underestimated value (Northern Alberta Institute of Technology, 2025). Summer 2024, after the vegetation was better established, all locations on the stockpile eroded less than the year before, with some locations even having peat deposition (Northern Alberta Institute of Technology, 2025). This trend suggests that as vegetation on the stockpile increases in size each year, carbon lost to erosion will diminish. Overall, the large net carbon balance of the stockpile indicates that autotrophic and heterotrophic respiration, as well as decomposition processes, and their end products (CO_2, CH_4, DOC), and erosion are greater than the amount of CO_2 being taken up during photosynthesis and the carbon stored within plant biomass on the stockpile.

The net carbon balance from the stockpile can be compared to those of other studies. Roulet et al. (2007) did a multi-year analysis at a bog in Quebec, Canada, to determine its annual carbon balance. They have reported that the bog has an estimated net carbon balance between 50 and -105 g C m^{-2} yr^{-1} (Roulet et al., 2007). There were large interannual and interseasonal variations throughout the study, which resulted in a range of carbon release to uptake (Roulet et al., 2007). This net carbon balance is much lower than that of the stockpile. Even when this bog experienced hotter or drier years, the amount of carbon lost is not as significant as what is experienced in the stockpile. This could be due to the vegetation types present at the bog, such as sparse cover by sedges and increased cover by *Sphagnum spp.* (Roulet et al., 2007). However, a study by Strack and Zuback (2013) determined that the annual carbon balance of an unrestored peat harvesting site was 546.6 g C m^{-2}. This value is much closer to what was calculated for the stockpile. This location was characterized by patches of high and low-density plant cover, minimal moss presence, and a deep water table (Strack and Zuback, 2013), similar to conditions on the stockpile. In contrast, the restored site in the Strack and Zuback (2013) study saw an increase in steady vascular plant and moss cover due to the rewetting of the site during the restoration process (Strack and Zuback, 2013). This site had a similar moss, sedge, and shrub cover as the adjacent natural peatland, with an annual net carbon balance of 148 g C m^{-2} (Strack and Zuback, 2013). This net carbon balance is much lower than that of the stockpile, suggesting that rewetting and the introduction of certain plant types play a large role in carbon sequestration in peatlands.

3.5 Conclusion

The peat stockpile is a net source of carbon to the atmosphere at a rate of approximately 539.6 g C m^{-2} yr^{-1}. Although vegetation was present on the stockpile, it was only able to offset about 20% of emissions from the decomposing peat. The vegetation also added labile litter, which contributed to the already rapid decomposition of the peat in the stockpile. CH_4 did not contribute a lot to overall carbon emissions, approximately 0.04% of overall emissions measured. CH_4 emissions were highest at the depression communities on the stockpile due to increased soil moisture and the presence of sedges.

This study was limited in the fact that it only analyzed one subsurface peat stockpile. Inherent conditions and processes acting within surface peat are different from those of subsurface peat and should be analyzed in a stockpile setting. This would allow for a better understanding of how the stockpiling process affects organic matter decomposition and respiration processes from multiple depths in the peat profile.

Variables such as stockpile size and age should also be analyzed.

Chapter 4

Conclusion

4.1 Summary of Main Findings

GHG emission dynamics from peat stockpiles that are set to stand for decades in the Alberta OSR have not been thoroughly studied. This study began to analyze carbon dynamics on a subsurface peat stockpile in this region by focusing on carbon fluxes among different established vegetation communities on the stockpile. These fluxes were paired with measurements of environmental variables, including soil temperature and volumetric water content, as well as an end-of-season tree survey and biomass collection, used alongside stockpile age to estimate carbon inputs as net primary production (NPP). One of the end goals was to estimate a stockpile-wide net carbon balance to determine how much carbon is being emitted per unit area on the stockpile, to determine whether the stockpiled peat has lost its function as a carbon sink and has become a carbon source, though the extent is unknown.

To investigate whether plant establishment on the stockpile altered rates of organic matter decomposition in peat samples from the stockpile, an incubation study was conducted. Although none of the relationships between moisture content and root presence were significant, the Fen with roots sample did respire more than the other samples. These samples likely had more roots in them from the start due to the presence of sedges at their sampling location, and it was these labile roots that resulted in higher CO_2 emissions. Limited differences in peat respiration between peat collected under different plant cover types once roots were removed suggested that vegetation establishment had little effect on the lability of the peat substrate. For CH_4, all wet samples (60% volumetric water content (VWC)) produced more than their dry counterparts (40% VWC), due to the increase in soil moisture leading to more ideal conditions for CH_4 production and likely less CH_4 oxidation.

In-field flux measurements (NEE, GEP, ER) indicated that depression locations had a lower GEP (i.e., greater productivity), and a higher ER, with a large range in NEE, whereas the opposite was seen at the elevations. However, these differences were not statistically significant. The dense cover of sedges at the depressions respired more and added more labile material for decomposition, but also took in more carbon through photosynthesis. The elevations were sparsely vegetated, with lots of bare peat at the stockpile surface, leading to higher GEP and lower ecosystem respiration, with a smaller range in NEE. Environmental variables affected the fully vegetated collars differently from the bare organic collars. At full vegetation, the interaction between soil temperature and volumetric water content significantly affected depression ecosystem respiration, and elevation and depression CH_4. Whereas those variables individually only affected depression ecosystem respiration and elevation CH_4. At the bare organic collars, soil temperature was the only variable to significantly affect elevation respiration. While at the depressions, respiration was significantly affected by soil temperature and volumetric water content, as well as their interaction. Soil temperature had no significant effect on CH_4 flux at any vegetation community, but volumetric water content significantly affected CH_4 flux at both elevations and depressions.

Aboveground biomass had no significant differences between vegetation communities, but depressions did have more biomass carbon stored than at elevations. Although elevations had larger vegetation, such as shrubs, the depressions had more vegetation overall, leading to enhanced carbon storage. There was a significant difference in belowground biomass among locations. The depressions stored significantly more carbon in belowground biomass than the elevations did. Due to the increased depth of sedge roots (Strack et al., 2006), more root material was likely captured in the biomass samples.

All of the flux data and biomass data were combined to create a net carbon balance for the stockpile. It was determined that the stockpile is a net source for carbon of 539.6 g C m^{-2} yr^{-1}. When compared to other studies, the stockpile has a similar net carbon balance to an unrestored peat harvesting site. The addition of vegetation to the stockpile had a minimal impact on the carbon balance of the stockpile. The addition of vascular plants has led to some carbon uptake but also increased autotrophic respiration and decomposition from labile litter.

4.2 Insights

The oil and gas industry is set to increase its presence and disturb significantly more peatlands in the coming years, as thousands more square kilometres of land have already been leased for these purposes (ABMI, 2018). With this comes the need for expanding infrastructure construction for processing facilities, access roads, or well pads, among many others. As these natural peatlands become impacted, the peat that was stripped from these areas will be increasingly stockpiled, where the GHG emissions can be impacted by many of the variables analyzed in this study, such as soil temperature, soil moisture, and vegetation communities. Because the study of peat stockpiles, particularly in the OSR, is so limited, the GHG emissions from the increasing presence of stockpiles will be relatively unknown. This study took into account the actively introduced vegetation to the stockpile by industry partners and analyzed how the vegetation may play a role in GHG emission reduction. Results show that the stockpile was a large net source for carbon and has lost the carbon sequestration function that it once had in its natural environment. By removing peat soils from the landscape for oil and gas-related activities, we are ultimately decreasing the peatland area available for taking up carbon from the atmosphere.

By increasing the number of peat stockpiles in the Alberta OSR, and possibly other areas with heavy oil and gas presence, there will be increasing GHG emissions that go unaccounted for in national emissions reporting. This has large implications for carbon accounting, accurate emissions reporting, and the overall issue of excess GHG emissions and climate change. Inclusion of these emissions in decision-making helps provide an incentive for avoiding peatland disturbance. The results of this study suggest that peat stockpiles in the Alberta OSR should be heavily studied, as not all emissions occur at the first stripping of peat processes and final use as reclamation soil, as some studies previously suggested (Rooney et al., 2012). The stockpile has resulted in a large GHG source, even during its current standing duration, which is set to continue for decades to come.

4.3 Future Research

This study was the first to quantify GHG emissions and analyze several environmental variables and vegetation communities on a peat stockpile in the Alberta OSR; therefore, further study on peat stockpiles is required. Future research priorities should include quantifying GHG emissions across peat stockpiles of all sizes, and ones with and without vegetation presence. Factors such as stockpile age, orientation, and construction methods should all be considered, as these aspects were not thoroughly analyzed in this study. This study focused on measuring GHG emissions on a subsurface stockpile, but surface stockpiles should also be analyzed to determine similarities and differences in GHG dynamics and how the surface peat reacts to changing environmental conditions. Other mining settings that have stockpiles on the landscape should also be studied and compared to those in the OSR due to their potential difference in material, construction practices, and standing duration, among other variables. Though this study inferred there were areas of differing microbial activity on the peat stockpile due to the different emissions in certain areas, no direct microbial analysis was conducted. To fully understand how the input of labile materials and the addition of plants to the stockpile impact GHG emissions, microbial analysis should be completed in future studies. A common method to test decomposition rates is by using litter bags filled with plant material from the study site (Blume-Werry et al., 2021). But this method makes it difficult to compare results between study sites due to the use of site-specific plants for each litter bag (Blume-Werry et al., 2021). A better method for comparison between sites, or between stockpiles in this case, could be the use of a standard litter, such as the Tea Bag Index (Keuskamp et al., 2013). This approach uses a standard method and commercially available tea bags (Keuskamp et al., 2013). This analysis would provide valuable information about microbial activity in individual stockpiles and could explain their GHG emission dynamics. Also, if the introduction of *Sphagnum* spp. to peat stockpiles is a possibility, it should be considered as it could have significant implications for carbon storage and decomposition reduction (Bragazza et al., 2006; Moore et al., 2008; Pinsonneault et al., 2016; Dieleman et al.,

2017) and could serve as plant propagules if the stockpiled peat is used in peatland restoration (Lehan et al., 2022).

In conclusion, having widespread knowledge about GHG emission dynamics among peat stockpiles in the Alberta OSR would be valuable for lease-scale and national emissions reporting. This study serves as a first step in quantifying carbon emissions on a peat stockpile and will be used to estimate emissions from other stockpiles in the Alberta OSR. Currently, peat stockpiles are not included in these national reports. Therefore, mining companies are underreporting their emissions, which will have significant implications now and for future climate change scenarios. All steps should be taken to include emissions from this disturbed peat in annual GHG emission estimates to ensure accurate emissions reporting, land-use decisions, and the subsequent management of peat stockpiles.

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Appendices

Appendix A

Table A-1 Incubation Jar Summary.

Site	Field VWC (%)	Dry BD (g cm^{-3})	Wet BD (g cm^{-3})	Amount of Peat Added to Jars		
				Wet Weight (g)	Dry Weight (g)	Volume (mL)
Bare Organic 1	0.31	0.46	0.77	25	15.10	33
Bare Organic 2	0.27	0.50	0.77	25	16.18	33
Bare Organic 3	0.28	0.32	0.59	30	16.09	51
Grass 1 – Root	0.27	0.45	0.72	25	15.59	35
Grass 2 – Root	0.40	0.21	0.61	45	15.46	74
Grass 3 – Root	0.56	0.75	1.31	30	17.18	23
Grass 1 – No Root	0.26	0.38	0.64	30	17.97	47
Grass 2 – No Root	0.42	0.18	0.61	50	15.09	83
Grass 3 – No Root	0.56	0.57	1.12	35	17.67	31
Fen 1 – Root	0.57	0.31	0.88	45	15.85	51
Fen 2 – Root	0.62	0.38	1.00	40	15.29	40
Fen 3 – Root	0.55	0.36	0.91	40	15.92	44
Fen 1 – No Root	0.68	0.31	0.99	50	15.55	50
Fen 2 – No Root	0.51	0.77	1.28	25	15.09	20
Fen 3 – No Root	0.50	0.61	1.12	30	16.58	27
			x 2 (Wet + Dry Treatments) = 30 Jars Total			

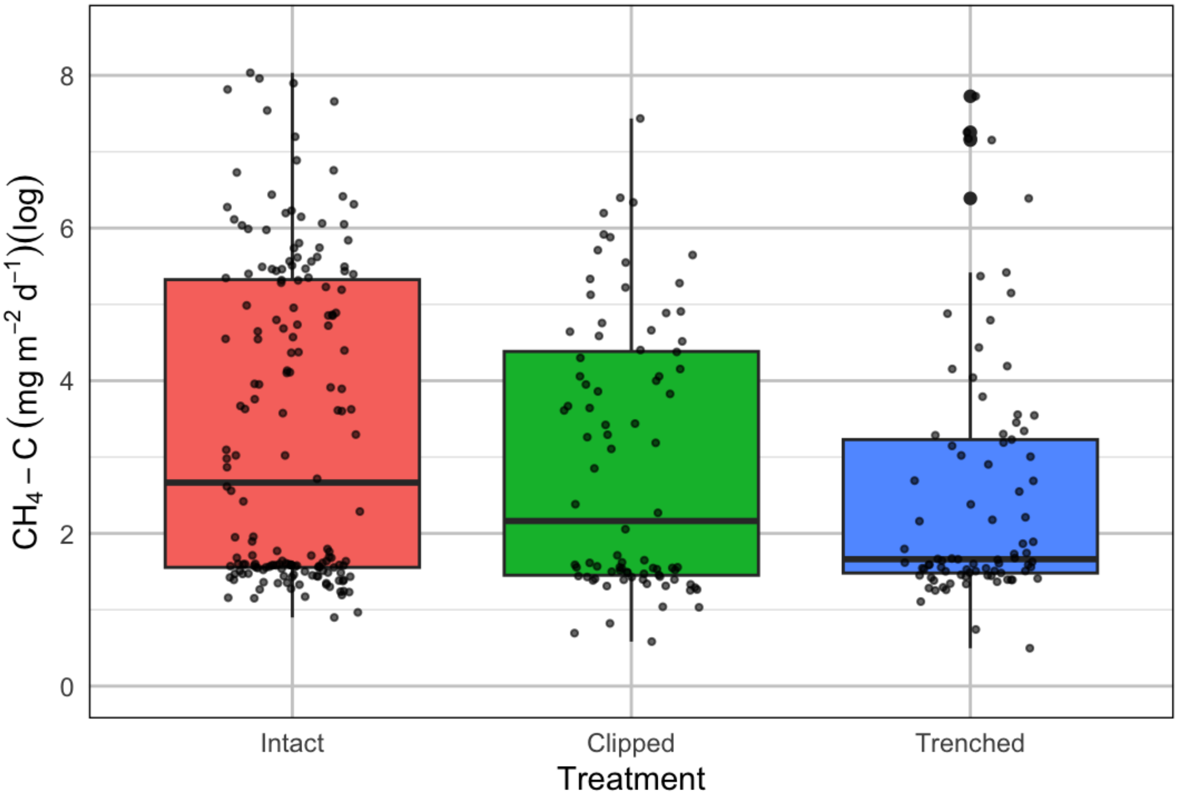

Figure A-1 CH_4 flux across stockpile collar treatments.

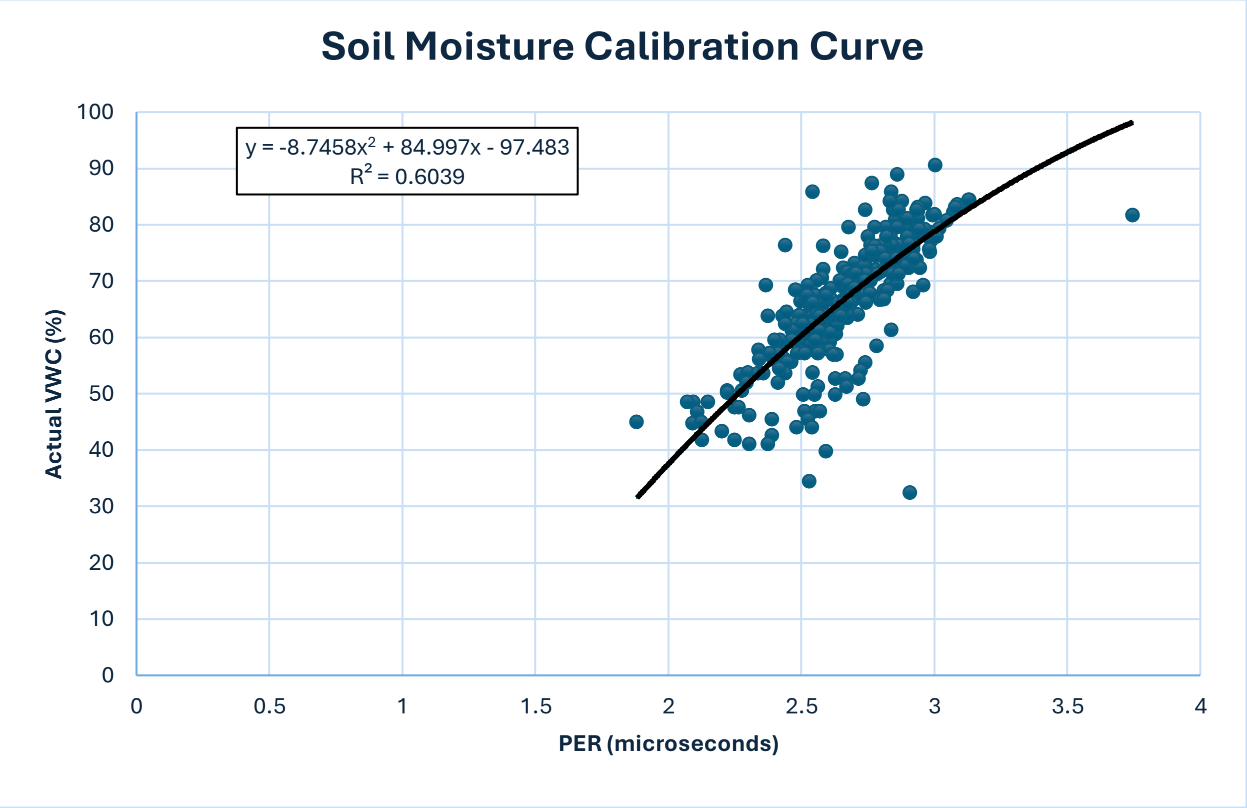

Figure A-2 Soil moisture calibration curve with line equation.