Years of extraction determines CO_2 and CH_4 emissions from an extracted peatland in eastern Quebéc, Canada

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ABSTRACT

Draining and extraction of peatlands fundamentally alters the controls of CO_2 and CH_4 emissions. Carbon emissions from peatlands undergoing extraction is not well constrained due to a lack of measurements from extraction sites. We determine the effect that production duration (years of extraction) has on the CO_2 and CH_4 emissions from an actively extracted peatland over three years (2018-2020) of measurements. We studied five sectors identified by the year when extraction began (1987, 2007, 2010, 2013, 2016). Higher average CO_2 and CH_4 emissions were measured from the drainage ditches (CO_2: 2.05 (± 0.12) g C m^{-2} d^{-1}; CH_4: 72.0 (± 18.0) mg C m^{-2} d^{-1}) compared to the field surface (CO_2: 0.9 (± 0.06) g C m^{-2} d^{-1}; CH_4: 9.2 (± 4.0) mg C m^{-2} d^{-1}) regardless of sector. For peat fields, CO_2 fluxes were highest from the youngest sector, opened in 2016 (1.5 (± 0.2) g C m^{-2} d^{-1}). The four older sectors all had similar mean CO_2 fluxes (~0.65 g C m^{-2} d^{-1}) that were statistically different from the mean 2016 CO_2 flux. A spatial effect on CO_2 fluxes was observed solely within the 2016 sector, where CO_2 emissions were highest from the centre of the peat field and declined towards the drainage ditches. These observations occur as a result of the surface contouring that operators create to facilitate drainage. The domed shape and subsequent peat removal resulted in a difference in surface peat age, hence different humification and lability. ^{14}C dating confirmed that the remaining peat contained within the 2016 sector was younger than peat within the 2007 sector and that peat age is younger toward the centre of the field in both sectors. Fourier Transform Infrared Spectrometry (FTIR) (1630/1090 cm^{-1}) values indicated that peat humification increases with increasing years of extraction. Laboratory incubation experiments showed that CO_2 production potentials of surface peat samples from the 2016 sector increased toward the center of the field and were higher than samples taken from the 1987 and 2007 sectors. In contrast to pristine and restored peatlands, peatlands under extraction

are a net source. Our results indicate that C emissions are high in the first few years after a sector is opened for extraction and then decline to half its original value and remain at this level for the next several decades.

RESUMÉ

Le drainage et l'extraction des tourbières modifient fondamentalement le contrôle des émissions de CO_2 et de CH_4. Les émissions de carbone des tourbières en cours d'extraction ne sont pas bien documentées en raison d'un manque de mesures sur les sites d'extraction. Nous déterminons l'effet que la durée de production (années d'extraction) a sur les émissions de CO_2 et de CH_4 d'une tourbière activement extraite sur trois ans (2018-2020) de mesures. Nous avons étudié cinq secteurs identifiés par l'année de début de l'extraction (1987, 2007, 2010, 2013, 2016). Des émissions moyennes plus élevées de CO_2 et de CH_4 ont été mesurées à partir des fossés de drainage (CO_2 : 2.05 (± 0.12) g C m^{-2} j^{-1}; CH_4: 72.0 (± 18.0) mg C m^{-2} j^{-1}) par rapport à la surface du champ (CO_2: 0.9 (± 0.06) g C m^{-2} j^{-1}; CH_4: 9.2 (± 4.0) mg C m^{-2} j^{-1}) quel que soit le secteur. Pour les champs de tourbe, les flux de CO_2 étaient les plus élevés à partir du secteur le plus jeune, ouvert en 2016 (1.5 (± 0.2) g C m^{-2} j^{-1}). Les quatre secteurs les plus anciens avaient tous des flux de CO_2 moyens similaires (~0.65 g C m^{-2} j^{-1}) qui étaient statistiquement différents du flux de CO_2 moyen de 2016. Un effet spatial sur les flux de CO_2 a été observe uniquement dans le secteur 2016, où les émissions de CO_2 étaient les plus élevées à partir du centre de la tourbière et diminuaient vers les fossés de drainage. Ces observations se produisent en raison du contour de surface que les opérateurs créent pour faciliter le drainage. La forme en dôme et l'élimination subséquente de la tourbe ont entraîné une difference dans l'âge de la tourbe de surface, d'où une humification et une labilité différentes. La datation au ^{14}C a confirmé que la tourbe restante contenue dans le secteur 2016 était plus jeune que la tourbe dans le secteur 2007 et que l'âge de la tourbe est plus jeune vers le centre du champ dans les deux secteurs. Les valeurs de la spectrométrie infrarouge à transformée de Fourier (1630/1090 cm^{-1}) ont indiqué que l'humification de la tourbe augmente avec l'augmentation des années d'extraction. Des

experiences d'incubation en laboratoire ont montré que les potentiels de production de CO_2 des échantillons de tourbe de surface du secteur 2016 augmentaient vers le centre du champ et étaient supérieurs à ceux des échantillons prélevés dans les secteurs 1987 et 2007. Contrairement aux tourbières vierges et restaurées, les tourbières enc ours d'extraction sont une source nette de C. Nos résultats indiquent que les émissions de C sont élevées au cours des premières années après l'ouverture d'un secteur à l'extraction, puis diminuent jusqu'à la moitié de leur valeur initiale et restent à ce niveau pendant les prochaines décennies.

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PREFACE

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Contribution of Authors

This thesis is written in manuscript style, with the main results in Chapter 3 formatted for submission to a journal for publication:

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I was responsible for all original writing in the thesis, the data collection, and data analysis. My primary supervisor, Dr. Ian B. Strachan, was responsible for contributing to the development of the research design, reviewing and providing detailed comments and edits on all chapters of this thesis, and helping me in the development of my research questions. My co-supervisor, Dr. Maria Strack, and committee member, Dr. Nigel T. Roulet, contributed to the development of the research design and reviewed and provided detailed comments on Chapter 3 of this thesis. Dr.

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CHAPTER ONE

INTRODUCTION

Peatlands are important global stores of soil carbon (C), containing ~ 644 Gt C (Yu et al., 2012) despite covering only approximately 3% of the Earth's surface (Gorham, 1991). Peatlands take up C from the atmosphere in the form of carbon dioxide (CO_2) via photosynthesis and release methane (CH_4) produced by anaerobic archaebacteria (Lafleur, 2009). Peatland disturbance in the form of land-use change, particularly for agriculture and energy, has been occurring since the Roman times in Europe, the 17th century in North America and southern Africa, and for at least 2000 years in China (Davidson, 2014). In Canada, peat extraction for horticulture to enhance the porosity and drainage of growing media, has been increasing over the past century (CSPMA, 2021; Davidson, 2014). Traditional methods of peat harvest are vacuum and block-cut harvesting, the most popular today being vacuum extraction (CSPMA, 2021).

To convert an undisturbed peatland into an active harvest site, the area is drained and all vegetation is removed. Primary drainage ditches are cut around the entire area and secondary drainage ditches are cut to section the area into individual fields 30 m in width and 500 m in length. Individual fields are grouped into "sectors", classified by the year in which production begins. When the surface peat is sufficiently dry, harrowers turn up the top layer of peat and the top few cm are extracted with vacuum harvesters (CSPMA, 2021). The Canadian peat industry is committed to the responsible management of peatlands. Canadian peat producers under the Canadian Sphagnum Peat Moss Association (CSPMA) adhere to the guidelines outlined in the Responsibly Managed Peatland Certification program and restore extracted peatlands using the moss-layer transfer technique to revert the disturbed area back to its original ecosystem function (CSPMA, 2021).

Peatland draining will drastically alter C cycling through the ecosystem. Unrestored peatland extraction sites are net C sources to the atmosphere as a result of peat decomposition and CH_4 oxidation with an absence of surface vegetation to offset these processes (Rankin et al., 2018). Unblocked drainage ditches act as localized anaerobic zones that emit CH_4 to the atmosphere (e.g., Rankin et al., 2018; Sundh et al., 2000; Waddington et al., 2009). Peatland restoration following extraction aims to return the ecosystem to its natural function in terms of hydrology, plant communities, and C exchange (Quinty & Rochefort, 2003). Research has shown that restoration can successfully revert harvested peatland sites back into net sinks of C due to increased vegetative uptake of CO_2 (Nugent et al., 2018).

In the life cycle of a harvested peatland – from natural C sequestering environments, to drained and extracted areas, to restored ecosystems – a large gap in knowledge exists regarding the C emissions from peatlands undergoing active extraction. Past research has been performed at vacuum extraction sites where harvest has temporarily been halted (Waddington & Price, 2000) but C fluxes have never been examined from vacuum harvest sites while extraction is underway. Lowered water tables, lack of vegetation and nutrient input, continuous exposure of deeper peat to the surface, and compaction of upper peat layers from machinery and mineralization will impact the emissions of CO_2 and CH_4 from the peat surface. In order to gain a full understanding of C emissions over the entire period of peatland extraction, it is necessary to study the C emissions from peatlands undergoing active extraction. This study aims to measure and quantify the CO_2 and CH_4 emissions from a peatland undergoing active vacuum extraction and determine if years of active extraction impacts C emissions from the peat surface.

The specific research objectives of this study are to:

1) Measure CO_2 and CH_4 flux from the surface of peat fields and drainage ditches at a peatland site undergoing active extraction
2) Determine spatial variability in CO_2 and CH_4 fluxes within fields and across varying sector ages at a peatland site undergoing active extraction
3) Test the effect of peat quality on CO_2 and CH_4 production potential of peat samples taken from an active extraction site

The corresponding hypotheses are as follows:

1) CO_2 and CH_4 emissions will be higher from the drainage ditches than the field surfaces
2) CO_2 flux will increase and CH_4 will decrease with increasing distance from the ditch within individual fields
3) CO_2 emissions will be higher from more recently opened, or "younger", sectors
4) Production potential of CO_2 will be higher from the more recently opened sectors

This work is a manuscript-based thesis comprised of four chapters, including this introductory chapter. Chapter 2 is a literature review summarising the distribution, structure, and C cycling from natural peatlands, and reviews the peat extraction process from start to finish, the impact of peat extraction on C cycling, and existing literature on C fluxes from natural, post-extraction, unrestored, and restored peatlands. Chapter 3 outlines and examines both field and laboratory measurements of CO_2 and CH_4 production from an active peatland production site. The first portion of Chapter 3 describes the *in situ* CO_2 and CH_4 fluxes, using chamber measurements, from surface peat at an extracted peatland from the drainage ditches and field surfaces across all available sector ages (Objective 1). Surface fluxes of CO_2 and CH_4 were

measured from five different sectors in which production began at varying points in time across a 30-year period (1987, 2007, 2010, 2013, 2016) and from different positions across the length and width of fields within each of the five sector ages (Objective 2). The second portion of Chapter 3 investigates the effect of peat quality on CO_2 and CH_4 production potential of peat samples from the harvest site (Objective 3). Controlling moisture and temperature conditions allows us to eliminate the impact of changing environmental variables and determine the effect of peat quality on CO_2 and CH_4 production. This study hopes to provide insight into the magnitude and variation in C emissions at an actively extracted peatland site that can lend knowledge towards the mitigation of unnecessary or preventable C emissions from surface peat to the atmosphere during the extraction process. The thesis culminates in a summary Chapter (4) that also discusses limitations and outlines scope for future research.

CHAPTER TWO

LITERATURE REVIEW

2.1 Natural Peatlands

2.1.1 Peatland Formation and Distribution

Peatlands are wetland ecosystems that have accumulated at least 40 cm of partially decomposed organic material, forming in areas of high precipitation or low topography with an underlying impermeable substrate (Gorham, 1991). Containing one third of global soil carbon (C) stores despite covering only ~3% of the Earth's surface, peatlands are important C sequestering ecosystems (Gorham, 1991). Production of biomass exceeds decomposition, causing an accumulation of organic matter from plant debris, leading to the formation of peat. Although peatlands represent large global C reservoirs, peat accumulates at an annual rate of approximately 0.5 – 1 mm (Quinty and Rochefort, 2003).

Most peatlands are located in the boreal and temperate regions of the northern hemisphere. Canadian peatlands are most heavily concentrated in the Hudson Bay Lowlands in Ontario and Manitoba. Peatlands can also be found in significant numbers in the Northwest Territories, Quebec, and Alberta (CSPMA, 2021). Due to their long accumulation period, sparse global distribution, and C sequestration capacity, it is important to understand peatland dynamics and the impacts of disturbance.

2.1.2 Peatland Classification

Peatlands are classified as either swamp, fen, or bog, depending on water and nutrient source. Swamps are found in forested or wooded areas dominated by trees or small shrubs. Swamps are influenced by minerotropic groundwater and the water table is found below the

ground's surface. Fens, or minerotrophic peatlands, have a fluctuating water table fed by groundwater and surface runoff (NWWG, 1997). As water moves over the fen surface, it is exposed to mineral soil and becomes enriched in base cations (Quinty and Rochefort, 2003), causing these environments to have high concentrations of basic substances such as calcium and magnesium (Holden et al., 2004). As peat accumulates in a fen, the peatland surface rises until the system is no longer able to be fed by groundwater or runoff and the available minerals begin to decline. The system becomes acidic and *Sphagnum* moss begins to form, leading to the development of a bog (Quinty and Rochefort, 2003).

Bogs rely solely on precipitation, fog, and snowmelt as sources of water and nutrients. Ombrotrophic bogs are acidic (pH 4 - 4.8), as precipitation does not contain dissolved minerals, enhanced by the decomposition of organic matter. The water table (WT) is typically located at or below the ground surface and is raised in elevation relative to the WT of the surrounding area (NWWG, 1997).

2.1.3 Peat Stratification

Bogs have two main soil layers: the acrotelm and the catotelm. The acrotelm is the surface layer, typically extending one m below the surface, composed of dead and poorly decomposed organic matter and the living components of mosses (Strack et al., 2008). Water table fluctuations cause the acrotelm to vary between oxic and anoxic conditions. Microbial activity and other living activities, such as rooting, occur at higher rates within the surface peat layer. The acrotelm is characterized by high hydraulic conductivity (Holden, 2005) and large pore spaces that allow for substantial amounts of water to be contained within this layer (NWWG, 1997). Clymo and Bryant (2008) suggested that the acrotelm be further subdivided

into a mesotelm which is transient but is where C is transferred from the acrotelm to the catotelm (Nykänen et al., 2020).

The catotelm is the deeper peat layer, three to five metres thick, composed of moderately decomposed and compacted organic material (Quinty and Rochefort, 2003). Under poorly oxygenated or anoxic conditions, peat decomposition and microbial activity are significantly slower within this layer. The catotelm is able to retain large amounts of water due to its depth, although the pore spaces are much smaller than those of the acrotelm. As a result, water flows at a slower rate and the amount of water available to plants from the deeper peat is much less than from the surface (NWWG, 1997).

2.2 Carbon Exchange in Natural Peatlands

2.2.1 Carbon Dioxide Emissions and Controls

Generally, ombrotrophic bogs are sinks for carbon dioxide (CO_2) and sources of methane (CH_4), although this can change interannually and is dependent on environmental conditions (Strachan et al., 2016). It is estimated that atmospheric C sequestration by peatlands over the past 10 000 years has reduced global temperatures by approximately 1.5 – 2 °C (Holden, 2005).

Peatlands remove C from the atmosphere in the form of CO_2 via photosynthesis by surface vegetation, which is then stored in the form of incompletely decomposed organic matter, otherwise known as gross ecosystem productivity (GEP) (Strack et al., 2008). Northern peatlands are estimated to store ~500 Gt C (Scharlemann et al., 2014; Yu, 2012) and can accumulate between 20 to 100 g C m^{-2} yr^{-1} (Moore and Knowles, 1989). Peatlands release CO_2 as a result of photosynthesis (autotrophic) and soil (heterotrophic) respiration; these losses of C are referred to as ecosystem respiration (ER) (Lafleur, 2009). Heterotrophic and autotrophic respiration are

estimated to occur at similar rates (Moore et al., 1998), although this is still debated as it is difficult to differentiate between the two within the soil. The sum of photosynthesis and ER form the net ecosystem exchange (NEE) of C, representing the amount of C lost or gained by the peatland (Lafleur, 2009). ER is dependent on WT depth, microbial activity, soil temperature, vegetation type, and peat biogeochemistry (Bubier et al., 2003; Johnson and Damman, 1991; Moore and Dalva, 1993; Strack et al., 2008; Updegraff et al., 1995; Yavitt et al., 1997).

Respiration occurs at higher rates under oxic conditions. Generally, a lower water table is associated with increased respiration rates (Strack et al., 2008), although there is debate in the literature regarding the impact of WT depth on CO_2 emissions (Lafleur et al., 2005; Pelletier et al., 2011). Decomposition of organic matter is a result of interactions between soil fauna, fungi, actinomycetes, and bacteria. Organisms in the soil break down complex molecules into low-molecular weight substances, which are then oxidized into CO_2 (Killham, 1994). Decomposition rates decrease as new litter is decomposed because the remaining material becomes increasingly recalcitrant and difficult for microbes to break down (Strack et al., 2008). The decomposition rate is influenced by the quantity and quality of peat and environmental conditions including peat moisture, temperature, oxygen, acidity, and redox potential (Killham, 1994). Soil respiration rate is considered to be an indication of peat quality and general biological activity (Doran and Parkin, 1994). Higher rates of respiration indicate a higher labile C content, while recalcitrant soils exhibit lower decomposition rates and emit less CO_2 (Killham, 1994). Thus, decomposition rates are largest in newest peat and have been found to decrease with peat age (Hogg, 1992).

2.2.2 Methane Emissions and Controls

Natural peatlands represent one of the highest terrestrial sources of CH_4 to the atmosphere (Whalen, 2005). While CH_4 emissions are lower than those of CO_2, CH_4 has a radiative forcing over 25 times stronger than CO_2 over a 100-year timescale (IPCC, 2013). CH_4 fluxes from peatlands are highly spatially and temporally variable (Moore et al., 1990; 1994; 1998; Roulet et al., 1997). The saturated conditions in the lower layers of peat create an anoxic environment, promoting the production of CH_4 through a process known as methanogenesis (Lafleur, 2009), performed by methanogenic archaebacteria (Whalen, 2005). CH_4 production occurs through two primary pathways in peatlands: acetoclastic and hydrogenotrophic methanogenesis. Acetoclastic methanogenesis produces CH_4 via acetate fermentation into CO_2 and CH_4 and hydrogenotrophic methanogenesis uses H_2 for the reduction of CO_2 into CH_4 (Fenchel et al., 2012). The CH_4 produced in the anoxic catotelm can be consumed in the oxic peat layers through a process known as methanotropy (Turetsky et al., 2014), typically occurring within 25 cm of the oxic-anoxic boundary (Segers, 1998). During this process, CH_4 is oxidized to CO_2, reducing CH_4 and increasing CO_2 emissions. The larger the oxic volume, the greater the opportunity for CH_4 oxidation. CH_4 produced in the peat is released through diffusion and ebullition, as a result of its low solubility in water (Abdalla et al., 2016), or transport by plants via root tissue (Holden, 2005; Rosenberry et al., 2003). Vascular plants transport CH_4 from the rhizosphere directly to the atmosphere, bypassing the oxidation zone. As a result, vascular plants may increase CH_4 emissions by acting as a conduit of CH_4 to the atmosphere and providing methanogenic substrates (Whalen, 2005).

The primary control over C exchange in peatlands is still debated in the literature. The production of CH_4 is an entirely anaerobic process, while CO_2 production is primarily aerobic. It

is commonly accepted that the WT presents a significant control over C cycling in peatlands (eg. Armentano and Menges, 1986; Aslan-Sungur et al., 2016; Rankin et al., 2018; Waddington and Price, 2000), although some studies have not found a direct correlation between WT depth and C emissions (Lafleur et al., 2005; Pelletier et al., 2011). Lowering of the WT has been found to increase CO_2 emissions and decrease CH_4 emissions as a result of increased aeration and area for CH_4 oxidation to occur (Moore and Dalva, 1993; Moore and Knowles, 1989; Whalen, 2005). Peat temperature and substrate quality also have significant impacts on microbial CH_4 production (Moore and Dalva, 1993; Moore and Roulet, 1993; Whalen, 2005). Whalen (2005) argues that substrate quality acts as a primary control on methanogenesis within wetlands and several studies have found that with more labile C present, higher CH_4 production is observed (Valentine et al., 1994; Yavitt and Lang, 1990).

2.3 Closed Chamber Measurements

The standard technique for ecosystem-level NEE measurements is eddy covariance. Eddy covariance through flux towers allow for multi-year analysis of a wide range of environmental variables. However, these systems are costly and do not allow for focused measurements from specific locations within an ecosystem (Rochette and Hutchinson, 2005). Closed chamber measurements have been used to reliably determine soil respiration rates for nearly 100 years (Lundegardh, 1927) and are widely used in modern research to measure small-scale CO_2 and CH_4 exchange from undisturbed, restored, and post-extracted peatlands (e.g., Bubier et al., 1995; 2003; 2005; Moore and Knowles, 1989; Moore et al., 2002; Nugent et al., 2018; Pelletier et al., 2007; Rankin et al., 2018; Riutta et al., 2007; Strack et al., 2016; Sundh et al., 2000). Modern analyzers now allow for simultaneous detection of CO_2, CH_4, and H_2O concentrations. Chambers

measure small fluxes of CO_2 and CH_4, are inexpensive, and are easily modified to address a specific research design or objective. Small-scale variation in trace gas fluxes within an environment require a precise measurement technique to capture spatial and temporal variability, which closed chambers provide.

2.4 Peat Extraction

2.4.1 Harvest Operations

Disturbances, such as peat extraction, drastically alter the C exchange dynamics within peatlands. As the peat harvest industry continues to grow, more peatlands are drained and harvested annually, primarily for horticulture to increase the porosity and drainage of the growing media used in greenhouses (CSPMA, 2019). According to the Canadian Sphagnum Peat Moss Association (CSPMA), the Canadian peat industry "produces", or sells, 1.34 million tonnes of peat annually. Within Canada, 25 % of peat extraction occurs in Quebec (CSPMA, 2021).

Generally, bogs 50 ha wide with a minimum peat thickness of 2 m are considered to be of value for horticultural peat production (CSPMA, 2021). The two traditional methods of peat extraction are 'vacuum' harvesting and 'block cut' harvesting. Block cut harvesting involves the removal of a large block of peat, usually 200 m long and 10 m wide, that are then left in piles to dry. The most common method of peat extraction in Canada today is vacuum harvesting (Waddington et al., 2009).

In order to convert an undisturbed peatland into an active extraction site, the area must first be drained. This is done by cutting drainage ditches to lower the WT in order to dry the peat and support the heavy machinery needed for extraction (Berger Peat Moss Ltd., personal comm., 2018; CSPMA, 2021; Premier Tech Horticultural, personal comm., 2018). A primary ditch is

dug surrounding the entire future extraction area, or sector. Once the peat has dried enough to allow machinery onto the field, the surface vegetation is completely removed and mulched and the top peat layers are harrowed to increase drying to reduce the moisture content (Berger Peat Moss Ltd., personal comm., 2018; CSPMA, 2021; Premier Tech Horticultural, personal comm., 2018). Secondary ditches are then cut approximately 30 m apart, forming many separate fields within each sector (Waddington and Price, 2000). Each field is crowned to allow for better drainage throughout the harvest season. Vacuum harvesters can begin to extract a thin layer of peat from the field surface when the moisture content has reached 50 % (Berger Peat Moss Ltd., personal comm., 2018; CSPMA, 2021; Premier Tech Horticultural, personal comm., 2018).

During the harvest process, the peat fields are constantly harrowed. Harrowing churns the top few cm of peat, helping the peat dry to a point that extraction can be conducted. Generally, fields are harrowed before and after extraction. Different companies employ different harrowing and extraction techniques. Some companies will harrow the fields constantly to allow for the opportunity to extract the peat as soon as weather conditions allow. Other companies choose to harrow exclusively before and after extraction occurs. Independent of the general harrowing and extraction strategy, most companies will harrow immediately after extraction to break up the newly exposed peat layer. Over time, continuous extraction reduces the peat depth significantly. The extracted peat is left in large piles for approximately five to six months, separated on the basis of their quality (Berger Peat Moss Ltd., personal comm., 2018; Premier Tech Horticultural, personal comm., 2018). Peat in these piles will decompose, depending on temperature, moisture content, and oxygen availability (Waddington et al., 2009). Over the course of the harvest season, the ditches will be re-dug and the fields will be re-crowned, depending on the wind conditions of the summer. The density of the peat is consistently checked over the harvest season

to compare to each company's desired quality. On a daily to weekly basis, depending on weather conditions, the internal temperatures of the peat piles are checked. If a "critical temperature" has been reached, the pile will be broken up to avoid overheating and risk of fire (Berger Peat Moss Ltd., personal comm., 2018; Premier Tech Horticultural, personal comm., 2018).

The extracted peat is considered to have different industry-specified "grades", or quality, ranging on a scale from one to five, based on the mechanical properties of the peat. Lightly decomposed peat is considered higher quality, while heavily decomposed, dark brown peat is considered lower quality (CSPMA, 2021). Grade one is considered to be the highest quality peat, with quality decreasing as the grade numbers increase. Grade one peat is high quality with good water retention. This peat is the youngest, coming from freshly opened sectors. Grade one peat is generally mixed with lower quality peat (usually three to five) for sale. Grade two peat comes from sectors opened one to two years before the current harvest year. This peat is considered to be good quality and is sold on its own. Grade two peat is extracted continuously over the season. Grade five peat is considered to be the lowest quality and is extracted from older fields. This peat is either mixed with higher quality peat or sold retail to home gardeners. Unlike the continuous extraction of grade two peat, a summer quota for grade five peat is set and once this has been reached, the fields are shut down for the season. Companies produce different "mixes" of peat with different combinations of each grade, to create particular properties for different buyers and end uses of the product. These mixes are then transported to the processing site where they are packaged and shipped (Berger Peat Moss Ltd., personal comm., 2018; Premier Tech Horticultural, personal comm., 2018).

2.4.2 Peat Production Impacts

In comparison to other methods, peatlands disturbed by the vacuum harvest technique are not able to naturally revegetate, as the viable seed bank is removed during extraction (Waddington et al., 2009). If left unrestored, drained peatlands can act as large sources of C to the atmosphere (McNeil and Waddington, 2003; Rankin et al., 2018; Waddington et al., 2002). Draining peatlands causes a loss of buoyancy within the upper peat layers due to the loss of water. This causes the normally saturated, deeper peat layers to subside via mechanical compression (Arementano and Menges, 1986; Oleszczuk et al., 2008). The degree of subsidence depends on a range of factors, including peat density and drainage depth. Continued subsidence usually occurs as a result of the decomposition of organic matter (Oleszczuk et al., 2008).

Drainage improves aeration of the peat and as a result, increases the area for CH_4 oxidation and organic matter decomposition to occur (Abdalla et al., 2016; Holden, 2005; Sundh et al., 2000; Waddington et al., 2009). Drainage also decreases the input of C to the anoxic methanogenic layer (Basiliko et al., 2003; Bergman et al., 1998). Due to the lower water table and deeper oxic layer, drainage of peatlands decreases CH_4 emissions by an average of 84% (Abdalla et al., 2016). Unfilled drainage ditches at abandoned extraction sites can become new anoxic zones and act as significant emitters of CH_4 due to the saturated conditions, warm temperatures, and large amounts of labile C normally found in these areas (Rankin et al., 2018; Schrier-Uijil et al., 2010; Sundh et al., 2000; Waddington et al., 2009). The removal of biomass decreases the water content of the soil and lowers the GEP to zero. Both fields and ditches emit CO_2 to the atmosphere from respiration and the sparse vegetation does not uptake enough C through photosynthesis to counteract these emissions (Rankin et al., 2018). Thus, draining and removing the vegetation from peatlands turns them from a net C sink to a net C source.

2.5 Prior Research

Sundh et al. (2000) studied CO_2 and CH_4 fluxes at drained peatland mining sites in Sweden. The authors measured C fluxes from both the mining strips and drainage ditches at six mining sites in the northern and southern regions of Sweden. They found that CH_4 emissions were much higher from the drainage ditches than the mining strips and that the rate of emissions was heavily dependent on WT depth and vegetation cover. The average CO_2 flux from the Swedish mining sites were found to be 0.6 kg CO_2 m^{-2} yr^{-1}, representing a loss of ~6% of the total C content of the peat (Sundh et al., 2000).

Rankin et al. (2018) performed one of the first long term ecosystem-level studies at an abandoned peatland site. They found that an abandoned peatland 16 years post-extraction acted as a persistent net source of C to the atmosphere. The site had 92 % bare peat cover with little natural revegetation. The sparse vegetation present did not take up enough C to compensate for the CO_2 emissions coming from the bare peat and unblocked ditches (Rankin et al., 2018).

The plant species that tend to naturally revegetate abandoned sites include ericaceous shrubs and invasive species such as birch trees, which decrease the productivity of *Sphagnum* in these ecosystems (Waddington and Price, 2000). The history of wetting plays an important role in CO_2 emissions in abandoned sites; short rewetting events produce large spikes in soil respiration without being long enough to allow *Sphagnum* to re-establish and perform photosynthesis (McNeil and Waddington, 2003).

Peatland restoration efforts following extraction aim to return the ecosystem to its natural functioning in terms of hydrology, plant communities, and C exchange (Quinty and Rochefort, 2003). Research has shown that restoration can successfully revert harvested peatland sites back into net sinks of C due to increased vegetative uptake of CO_2 (Nugent et al., 2018). According to

Schouwenaars (1993), it is essential to start the restoration process as soon as possible to prevent degradation of the soil by decomposition and compaction of surface peat. Tuittila (2000) and McNeil and Waddington (2003) found that in restored sites with *Sphagnum* growth, more respiration occurred but CO_2 emissions remained lower than those from bare fields. McNeil and Waddington (2003) found that sites revegetated with *Sphagnum* emitted 1.5 times less CO_2 than abandoned sites.

At a peatland site 10 years post-restoration, Strack and Zuback (2013) found that the ecosystem took up more CO_2 than a nearby natural site when photon flux density was greater than 1000 $\mu mol\ m^{-2}\ s^{-1}$. At a peatland site restored using the moss transfer technique, 14 years post-restoration, Nugent et al. (2018) found that the area was also able to successfully act as a sink of C. Nugent et al. (2018) determined that maintaining the WT depth below the peat surface was essential to maintain CO_2 uptake and minimize C emission to the atmosphere. CH_4 emissions have been found to be lower in restored sites, as a result of reduced WT extremes compared to drained and abandoned sites (Nugent et al., 2018; Strack and Zuback, 2013).

Waddington et al. (2009) conducted a C emissions analysis to compare vacuum harvest and block cut harvesting techniques. They found that drainage ditches represented the largest source of C to the atmosphere for both vacuum harvest and block cut extraction. Vacuum harvesting garnered the highest total emissions as a result of the peat extraction process itself due to the extensive use of large machinery to remove the peat (Waddington et al., 2009).

Several incubation studies of peat from extracted peatlands examining CO_2 and CH_4 production potentials exist in the literature. Waddington et al. (2001) performed aerobic and anaerobic incubations of peat from a natural peatland and a 2- and 7-year post-cutover peatland. They examined the different factors affecting CO_2 production, including temperature, soil

moisture, and peat depth, from natural and cutover peatlands. Waddington et al. (2001) found that the cutover sites had lower CO_2 production rates than the natural peatland and that production rates increased with soil temperature and moisture. Higher CO_2 production rates were observed in the surface peat layers than those at depth (Waddington et al., 2001).

Glatzel et al. (2004) performed incubations of peat samples from the surface and just below the WT from natural, actively-vacuum extracted, restored, and abandoned peatland sites. The authors found that CO_2 production potential rates were smallest in the lower parts of the profiles and from the recently restored sites where deep peat was exposed at the surface (Glatzel et al., 2004). Basiliko et al. (2007) incubated peat samples of peat profiles from natural, mined, mined-abandoned, and restored northern peatlands. They found that mined and abandoned sites had lower nutrient and substrate availability and lower CO_2 and CH_4 production, likely as a result of drier conditions (Basiliko et al., 2007). Croft et al. (2001) compared microbial communities across paired neighboring natural and post-vacuum extracted peatlands in eastern Québec. Lower total bacterial populations were found in the post-vacuum extracted sites than the natural and restored peatlands (Croft et al., 2001).

Currently in the literature, to the best of our knowledge, Waddington and Price (2000) have performed the only published research at an active peat production site. Waddington and Price (2000) studied a natural peatland, two rewetted block cut sites, an actively vacuum harvested site, a partly restored site, and an abandoned site. However, the "active harvest site" was taken out of production during the year of study and only heat flux measurements were taken. Waddington and Price (2000) found that the pore spaces in the block cut sites were smaller, allowing for greater capillary action, causing the surface of the peat to feel damp following a precipitation event. After a precipitation or melting event, water drains into the

drainage ditches and is carried away from the site, allowing for WT drawdown (Waddington and Price, 2000). The peat remains saturated until enough evaporation occurs. If the peat is moist, harrowing turns the top layer of peat over, helping to increase evaporation. Once the top layer becomes dry, the evaporation rate is then lowered due to decreased capillary contact (Waddington and Price, 2000). This study provides valuable insight into the evaporative dynamics of peatlands following a disturbance and a good starting point from which to move forward. More research is still needed to understand the consequences of active extraction on CO_2 and CH_4 emissions.

The C emissions and controls on C exchange from natural peatlands have been well documented and researched. Undisturbed peatlands sequester CO_2 and release CH_4. Water table depth, soil temperature, vegetation type, and peat biogeochemistry represent the largest controls over CO_2 and CH_4 production in natural ombrotrophic bogs. It has been determined that without restoration, post-extraction and unrestored sites act as net sources of C to the atmosphere. Restoration can successfully revert post-extraction sites from net C sources to net C sinks. However, a gap still exists in the literature pertaining to how C emissions are altered during the active extraction process.

CHAPTER 3

YEARS OF EXTRACTION DETERMINES CO_2 AND CH_4 EMISSIONS FROM AN ACTIVELY EXTRACTED PEATLAND IN EASTERN QUÉBEC, CANADA

Bridging Statement to Chapter 3

Undisturbed peatlands sequester C from the atmosphere, which is stored over millennia. The extraction of peat for commercial use requires the draining of peatlands and this industry continues to grow, particularly within Canada. While measurements of post-extraction GHG exchange have been made from both unrestored and restored peatlands, to date, GHG emissions from active extraction sites have not been made, thus leaving a gap in scientific knowledge of trace gas exchange over the life cycle of an extracted peatland. In Chapter 3, I quantify the CO_2 and CH_4 emissions from a peatland undergoing active extraction and examine the effect that years of extraction has on measured C fluxes.

3.1 Background and Context

3.1.1 CO_2 and CH_4 Production in Natural Peatlands

Containing one third of global soil carbon (C) stores, peatlands are important C sequestering ecosystems (Limpens et al., 2008; Yu, 2012). Generally, peatlands are sinks of carbon dioxide (CO_2) and sources of methane (CH_4), although this can vary interannually and is dependent on environmental conditions (Bubier et al., 1993; 2003; 2005; Lafleur et al., 2003; Moore et al., 1990). Carbon is removed from the atmosphere in the form of CO_2 by surface vegetation via photosynthesis, which is then stored in peat soils as incompletely decomposed organic matter (Strack et al., 2008). Carbon is released from peatlands as a by-product of plant (autotrophic) and soil (heterotrophic) respiration, otherwise known as ecosystem respiration

(ER). Respiration is dependent on labile C, soil temperature and moisture content (Strack et al., 2008).

Organisms in the soil break down complex molecules into low-molecular weight substances, which are then oxidized into CO_2 (Killham, 1994). Decomposition rates decrease as new litter is decomposed because the remaining material becomes increasingly recalcitrant and difficult for microbes to break down (Strack et al., 2008). The decomposition rate is influenced by the quantity and quality of peat and environmental conditions including peat moisture, temperature, oxygen availability, acidity, and redox potential (Killham, 1994). Carbon dioxide production rates can be used as an indication of peat quality because they describe the rate at which microorganisms decompose organic matter. High quality peat contains large amounts of labile C available to decompose (eg. carbohydrates, proteins, amino acids), leading to higher rates of CO_2 production (Schlesinger & Andrews, 2000; Wardle et al., 2004). Decomposition rates are largest in youngest peat and have been found to decrease with peat age (Hogg, 1992).

Controlled by peat water saturation and microbial activity, CH_4 emissions from peatlands are spatially and temporally variable (Moore et al., 1990; 1994; Roulet et al., 1997). Methane is produced in the anoxic regions of natural peatlands via methanogenesis (Lafleur, 2009) and can be consumed in the oxic peat layers through a process known as methanotrophy (Turetsky et al., 2014). The greater the oxic layer thickness, the greater the opportunity for CH_4 oxidation, which typically occurs within 25 cm of the oxic-anoxic boundary (Segers, 1998). Methane produced in the peat is released to the atmosphere through diffusion, ebullition, or plant mediated transport via root tissue (Holden, 2005; Rosenberry et al., 2003; Whalen, 2005).

3.1.2 Peatland Disturbance

Peat extraction intrinsically alters the C exchange dynamics of a peatland. To convert a natural peatland into an active extraction site, briefly, the area is drained by cutting drainage ditches to lower the water table (WT) and all vegetation is removed. When the surface peat is sufficiently dry, vacuum harvesters begin to extract a thin layer of surface peat. Following the end of extraction activities, peatlands that have been disturbed by vacuum harvesting in this manner are often not able to naturally revegetate and regain their original ecosystem function because the viable seedbank is removed during extraction (Waddington et al., 2009).

If left unrestored, drained peatlands act as large sources of C to the atmosphere (Hirashi et al., 2014; Joosten et al., 2002; McNeil & Waddington, 2003; Rankin et al., 2018; Smith et al., 2014; Waddington et al., 2002). Drainage lowers the WT, creating a thicker oxic layer of peat (Abdalla et al., 2016; Waddington et al., 2009). This results in higher rates of respiration and increases the volume within which CH_4 oxidation can occur (Abdalla et al., 2016; Holden, 2005; Sundh et al., 2000; Turetsky et al., 2014). Therefore, while CO_2 emissions to the atmosphere rise, CH_4 emissions are decreased by an average of 84% (Abdalla et al., 2016). Methane emissions become localized in the former drainage ditches that can become new anoxic zones due to the saturated conditions, warm temperatures, and large amounts of labile C normally found in these areas (Rankin et al., 2018; Schrier-Uijil et al., 2010; Sundh et al., 2000; Waddington & Day, 2007; Waddington et al., 2009).

Carbon emissions and controls on C exchange from undisturbed peatlands have been well-documented and researched (e.g. Bubier et al., 1993; 2003; 2005; Lafleur et al., 2003; Moore et al., 1990; Pelletier et al., 2007; 2011; Roulet et al., 2007; Strachan et al., 2016; Updegraff et al., 1995; Valentine et al., 1994). Post-extracted, unrestored peatlands have been

shown to be persistent sources of C to the atmosphere (Rankin et al., 2018); however, restoration can successfully revert disturbed peatlands from net C sources to net C sinks as a result of increased vegetative uptake of CO_2 (Nugent et al., 2018; Strack & Zuback, 2013). Until recently, research has focused on understanding the impacts of disturbance on gas exchange after the disturbance has ended or sites where extraction has been halted (Ahlholm and Silvola, 1990; Aslan-Sungur et al., 2016; Bergman et al., 1998; Nykanen et al., 1995; Oleszczuk et al., 2008; Sundh et al., 2000; Waddington and Price , 2000; Waddington et al., 2002; Wilson et al., 2015) To the best of our knowledge, this is the first study conducted in a drained peatland undergoing active vacuum extraction. Thus, little is currently known about how C emissions from vacuum-harvested peatlands are altered during the active extraction process. This study aims to quantify the CO_2 and CH_4 emissions from a peatland undergoing active extraction to gain a better understanding of how this process affects C exchange.

3.2 Materials and Methods

3.2.1 Site Description

In situ fluxes of CO_2 and CH_4 were measured at an active horticultural peat production site approximately five km southeast of Rivière-du-Loup, QC (47.47°N, 69.31°W; Figure 3.1). Originally a treed ombrotrophic bog system, this location was prepared for peat extraction, beginning in 1985, using standard industry methods resulting in drained peat devoid of vegetation. The bare peat is sectioned into individual "fields" 500 m in length and 30 m in width via drainage ditches. These individual fields are combined into "sectors" classified by the year in which peat extraction began. In eastern Canadian peat production sites, each field is domed; the elevation of the middle of the field is highest and slopes down toward the drainage ditches to

assist in precipitation drainage. A gravel service road approximately 1 km in length runs down the middle of the site, separating the peatland into two halves. Large piles of loose peat and wood debris removed from the surface of the fields are stored on either side of this main road, between the gravel and the beginning of the individual fields. The storage piles are continuously moved and resized, either to transport the peat to a handling facility or to form new peat piles to prevent overheating and combustion. The site has been in operation for 36 years and was undergoing active extraction at the time of this study. Large machinery such as tractors and vacuum-harvesters frequently drove over the surface of the fields during the measurement period. Measurements were taken from fifteen fields, each with an area of 0.015 km^2. Measurements were taken over a period spanning three years in August 2018, June through August 2019, and July through September 2020.

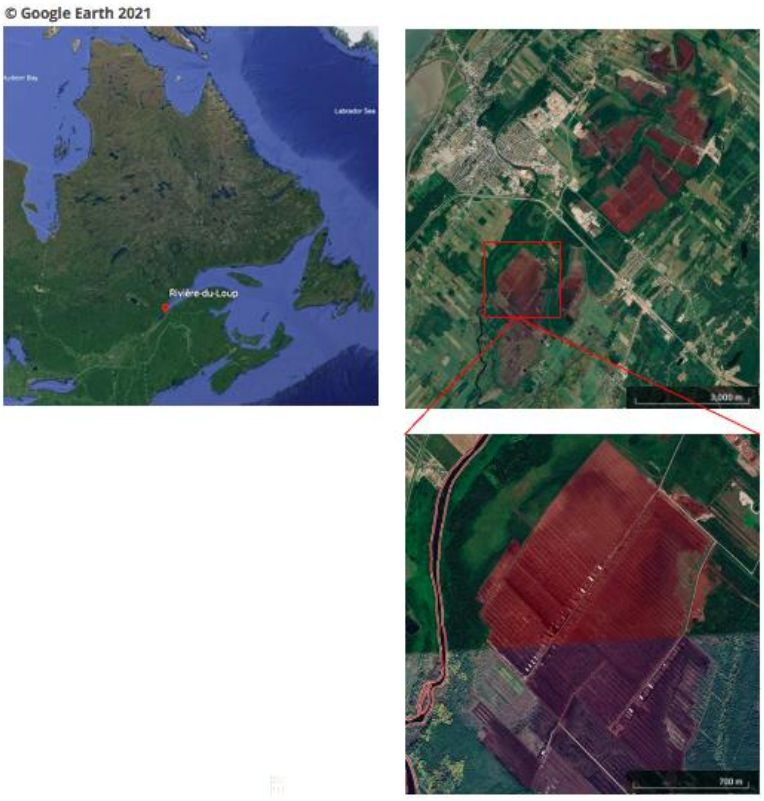

Figure 3.1 – The location of the studied peatland near Rivière-du-Loup, Québec, Canada.

The climate of the study area is cool-temperate with a normal mean annual temperature of 3.5 °C and mean precipitation of 963.6 mm (normal period 1981 – 2010; Environment and Climate Change Canada, 2021). The normal mean temperatures for June, July, and August, are 14.9, 17.6, and 16.7 °C, respectively (Environment and Climate Change Canada, 2021). The corresponding mean precipitation values are 92.6, 95.0, and 94.2 mm, respectively (Environment and Climate Change Canada, 2021).

3.2.2 Chamber Measurements

The closed chamber method (discussed in detail in Rankin et al. 2018) was used to measure fluxes of CO_2 and CH_4 from the peat surface. Chamber measurements have been used to reliably measure trace gas fluxes for nearly 100 years (Lundegardh, 1927) and are accessible, inexpensive, and easily modified to fit a specific research design. Chambers allowed the comparison of *in situ* CO_2 and CH_4 fluxes from specific points within fields and between sectors.

Collars could not be left in place between measurements because we were measuring from active peat extraction fields that had harvest machinery driving on them. Therefore, at each measurement location on the peat field, at the time of measurement, a metal collar was inserted approximately 5 cm into the surface of the field. An opaque aluminum chamber (64 cm x 64 cm) was then placed on top of the collar. Air was cycled between the chamber and a trace gas analyzer. In 2018, a PP Systems EGM-4 IRGA was used, in the first two weeks of measurements in 2019 a Los Gatos Research Ultraportable Greenhouse Gas Analyzer was used, and in the remainder of 2019 and in 2020, a LI-COR Biosciences LI-7810 Trace Gas Analyzer was used. A one-way ANOVA ($\alpha = 0.05$) was conducted between the fluxes from the different analyzers for the 2016 sector 2 m position and 2007 sector 15 m position. There was no statistical significance

between the means of the fluxes measured with the three analyzers from the 2016 ($p = 0.552$, $F_{2,85} = 0.599$) or 2007 ($p = 0.06$, $F_{2,87} = 2.848$) sectors. A measurement lasted four minutes, after which the chamber was lifted for a minimum of 30 seconds to allow the CO_2 and CH_4 to return to ambient concentrations. The measurements taken in the drainage ditches required a different chamber because the ditches were too narrow to accommodate the field chamber. The ditch chamber was cylindrical (35 cm height, 27 cm diameter) and was composed of translucent plastic covered in opaque reflective tape. The same measurement procedure was followed as for the ditch measurements. A battery-powered fan was installed on the interior of each of the field and ditch chambers to ensure adequate air mixing during measurements. The chamber and collar were removed from the field after each measurement was completed and moved between measurement locations.

3.2.3 Ancillary Measurements

The interior height of the field chamber above the peat surface, including the collar, was measured at all four corners at each sample measurement. The height of the ditch chamber, including the collar, was measured at three different points around the perimeter. Volumetric water content (%VWC) was measured at three separate locations at each measurement site where a time domain reflectrometry (TDR) probe was inserted from the surface to give an integrated 0 - 10 cm measurement. Peat temperature was taken at depths of 2, 5, 10, 15, and 20 cm below the surface to attain a temperature profile at each measurement location.

3.2.4 Chamber Flux Locations

Fluxes of CO_2 and CH_4 were measured from five different sectors at this site, representing production beginning in 1987, 2007, 2010, 2013, and 2016 (Figure 3.2). Within each of these sectors, measurements were taken from five transects 50 m apart perpendicular to the lateral drainage ditches, alternating across three consecutive fields (Figure 3.3a). Each transect contained four measurement locations: 0 (representing in the ditch itself), and 2, 5, and 15 m away from the drainage ditch, which was the centre of a field, thus capturing spatial variability in the fluxes across the field (Figure 3.3b). The 1987 sector age was under-sampled relative to the other four sectors in 2020 because previous measurements indicated that this sector had CO_2 and CH_4 flux values similar to younger fields and limited variability between measurements.

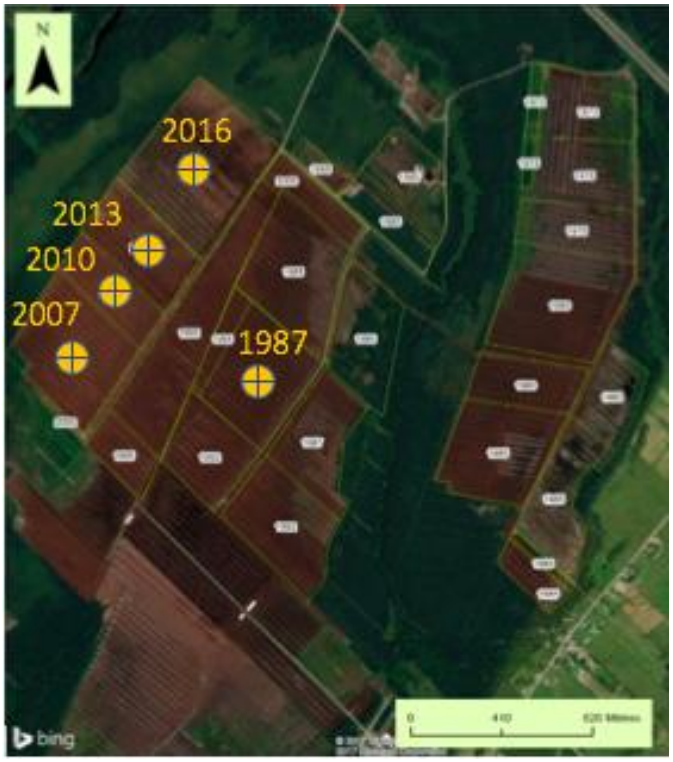

Figure 3.2 – Location of measured sectors within the study site

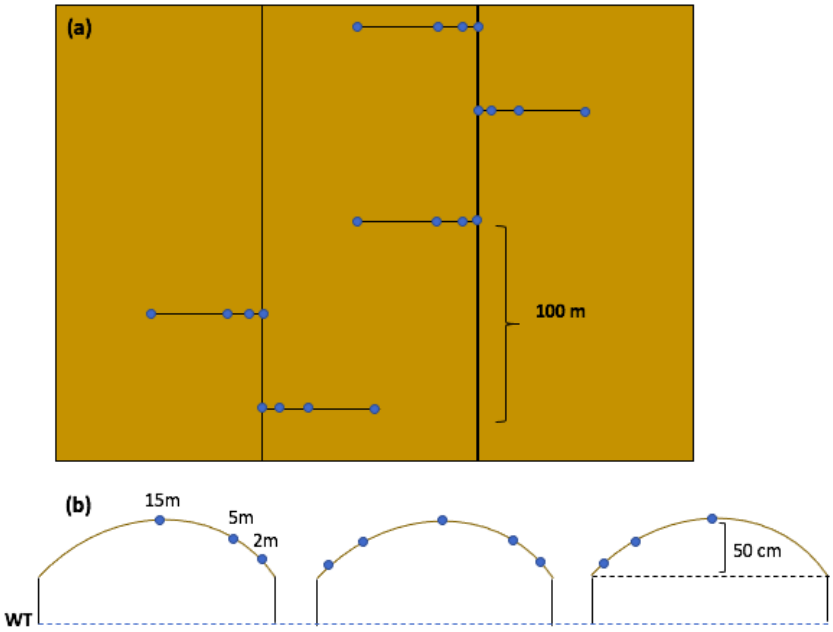

Figure 3.3 – (a) Sampling transects and (b) measurement locations within transects with estimated elevation increase at field centre.

3.2.5 Data Analysis and Chamber Flux Calculation

The measured concentrations of CO_2 and CH_4 were stored in the internal memory of the gas analyzer and downloaded to a computer at the end of each day of sampling. Trace gas flux was determined as change in concentration over time using the equation

$$F = \frac{f_x \cdot \left(\frac{V_c}{R(273 + T_a)}\right) \cdot n \cdot t}{S}$$

where f_x is the rate (ppmv min^{-1}), V_c is the chamber volume (m^3), R is the ideal gas constant (0.0821 L atm K^{-1} mol^{-1}), T_a is the air temperature (°C), n is the molecular mass of each gas (CO_2 = 0.044 kg mol^{-1}; CH_4 = 0.016 kg mol^{-1}), S is the surface area of the collar (m^2), and t is the number of minutes in a day (1440 minutes). Change in concentration over time for both CO_2 and CH_4 were plotted for each measurement location and the flux was kept if a linear increase or decrease was observed to ensure that low values were not disproportionately discarded. In 2018, 49% of CO_2 and 55% of CH_4 measurements were rejected, in 2019 21.8% of CO_2 and 26% of CH_4 measurements were rejected and in 2020, 11.6% of CO_2 and 37.6% of CH_4 measurements were rejected.

All statistical analysis was performed in the R software package (R Core Team, 2021) and figures were produced using the R package ggplot2 (Wickham, 2016). A one-way ANOVA of CO_2 and CH_4 fluxes between the field surface and drainage ditches was performed and a two-way ANOVA between sector age and measurement position was performed, excluding drainage ditch measurements, with $\alpha = 0.05$. An interaction test was conducted to determine the relationship between sector age and measurement position and a Tukey post-hoc test was conducted to show the specific interactions. Linear regressions were performed between surface VWC and temperature measurements and CO_2/CH_4 flux.

3.3 Peat Incubation

3.3.1 Field Sampling

In order to investigate differences in peat substrate quality among sectors and field positions, incubations were performed with peat samples taken from the 1987, 2007, and 2016 sectors, spanning the largest number of production ages available at the research site. Samples were taken at the second chamber measurement transect from each of the three sector ages (Figure 3.3a). Within each transect, approximately 1 kg of peat was obtained at 2, 5, and 15 m away from the drainage ditches both from the surface and from a depth of 10 cm. Additional samples were taken from a depth of 50 cm, at a distance of 2 m from the ditch and from a depth of 80 cm, 15 m away from the ditch (Figure 3.4). The 50 and 80 cm positions were estimated to be parallel at depth, based on an elevation difference of approximately 50 cm resulting from the field doming. Samples were kept in sealed plastic bags during transport from the field and frozen upon arrival to the lab. Four samples were taken from both the 2007 and 2016 sectors for ^{14}C dating, performed by the AEL AMS Laboratory at the University of Ottawa. (Figure 3.4)

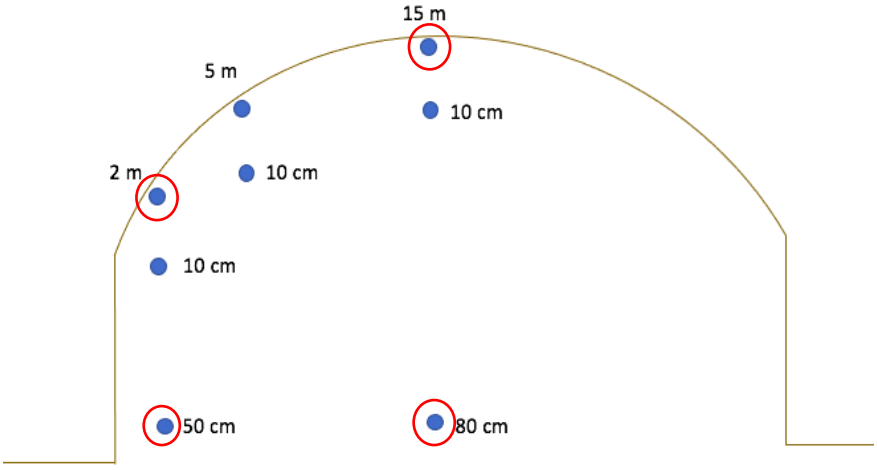

Figure 3.4 – Peat sampling locations and depths from the 1987, 2007, and 2016 sectors. Those with red circles were also sampled for ^{14}C dating at the 2007 and 2016 sectors.

3.3.2 Incubation Experiment Methodology and Analysis

Incubations were performed in 250 mL mason jars fit with air-tight lids and a short plastic tube fixed with a stopcock valve, sealed with epoxy. Nine replicates and an additional blank were used for each sampling position. 30 g of peat was weighed and placed into each jar after removing woody debris. To keep moisture conditions between the samples similar, 30 mL of distilled water was added to the jars and mixed with the peat to create a slurry. This is not meant to represent field conditions. The estimated VWC of the slurries was 80 – 90%. The height and diameter of peat in the jar was recorded to calculate the headspace volume for each sample. Jars were kept at a constant temperature of 23 °C.

5 mL of air from the jars were sampled at 0, 6, 12, 24, 48, and 72 hours. After the initial 72-hour samples were taken, the lids were removed, the jars were left open for 12 hours, resealed and sampling was repeated for an additional 72 hours. This was done to account for increased respiration rates that may have occurred during the first sampling period from cellular rupture after the samples were thawed. 5 mL of ambient air was backfilled into each jar after each sample was taken.

The concentrations of the gas samples were analyzed using two gas chromatographs (GC) (Shimadzu 2014 GHG GC & SRI 8610 C GHG GC). The carrier gas was N_2 and the column temperature was 400 °C for both GCs. Three standards of 5000 ppm CO_2 and 5 ppm CH_4 were run through the GC before injecting the 5 mL gas samples at each sampling interval. Gas samples were analyzed within six hours of withdrawal from the jars. Samples were consistently run on the same GC throughout the course of the experiment. Gas concentrations from fifteen samples of ambient air were run on both GCs and were compared every 72 hours throughout the course of the experiment to cross calibrate between the readings of the two machines. The

Shimadzu 2014 GHG GC had an average (± SD) ambient CO_2 reading of 609.2 ppm (± 152.0) and the SRI 8610 C GHG GC had an average ambient CO_2 reading of 589.5 (± 132.6) ppm. CO_2 and CH_4 concentrations were corrected for dilution from back-filling of ambient air and for variation in ambient concentrations of CO_2 and CH_4 using the blank measurements. CO_2 and CH_4 production were calculated as change in concentration over time. 10% of data was discarded after quality control, where values with $r^2 < 0.8$ were rejected. A three-way ANOVA was used to determine the variance of means between sector age, position, and depth.

3.3.3 Quality Analysis

Samples were prepared for Fourier transform infrared (FTIR) spectrometry corresponding to the sampling locations used in the peat incubations. All samples were oven-dried at 60 °C for 48 hours and ground into a fine powder using a mortar and pestle, after which they were run through a 50 µm mesh sieve. Once prepared, the samples were shipped to the Institute for Landscape Ecology, University of Muenster, Germany, for FTIR analysis performed by Dr. Henning Teickner and Dr. Klaus-Holger Knorr and analyzed in the R package irpeat (Teickner & Hodgkins, 2021). Humification indices (HI) were computed between the wavelengths ~1090 cm^{-1} (polysaccharides representing the labile fraction) and ~1650 cm^{-1} (lignins and other aromatics), as described in detail in Broder et al. (2012). Larger ratios (1650/1090 cm^{-1}) indicate a greater degree of humification.

3.4 Results

3.4.1 CO_2 Fluxes Between Field Surface and Drainage Ditches

The average (± SE) CO_2 flux from all sectors, field locations and ditches is 1.2 (± 0.06) gC m^{-2} d^{-1}. The mean CO_2 flux from all fields combining all sector ages and excluding the drainage ditch measurements, is 0.9 (± 0.06) gC m^{-2} d^{-1}. The mean CO_2 flux from the drainage ditches across all sectors is 2.05 (± 0.12) gC m^{-2} d^{-1}. A significant difference is present ($F_{1,1272}$ = 79.47, $p < 2 \times 10^{-16}$) between the CO_2 emissions from the drainage ditches and the field surface.

The base of the drainage ditches is closer to the WT than the surface of the fields and as a result, are frequently saturated and often completely water filled. The C cycling dynamics within the ditches are different than those at the surface of the field and thus, the results from the drainage ditches will not be directly compared to those from the field surface.

3.4.2 CO_2 Fluxes Between Sectors

The average CO_2 flux from all locations within the 1987, 2007, 2010, 2013, and 2016 sectors, excluding the drainage ditch measurements, are 0.6 (± 0.05), 0.7 (± 0.03), 0.6 (± 0.04), 0.7 (± 0.04), and 1.5 (± 0.2) gC m^{-2} d^{-1}, respectively (Figure 3.5). The highest measured flux was 37.1 gC m^{-2} d^{-1} and the lowest measured flux was -0.3 gC m^{-2} d^{-1}. A single value of -36.5 gC m^{-2} d^{-1} was deemed to be an outlier and removed from the 1987 sector flux data. A two-way ANOVA between sector age and measurement position was performed and the outcomes for sector age and measurement position, as well as any interactions, will be discussed separately in the following sections. Sector age (years of active harvest) appears to have an influence on CO_2 flux only for the initial four years after the commencement of harvest operations. The two-way ANOVA shows that the 2016 sector has significantly higher CO_2 emissions than all other sector

ages ($F_{4,942} = 12.80$, $p < 0.05$). The 1987, 2007, 2010, and 2013 sectors exhibit similar fluxes over time, with no significance between their means, although the 2010 and 2013 sectors were only measured in 2020.

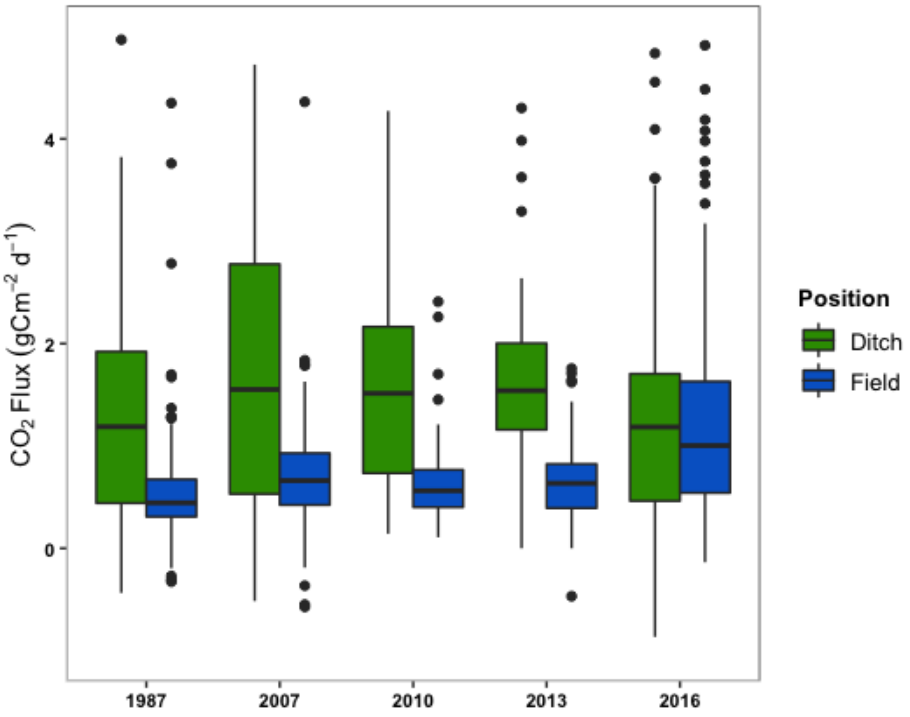

Figure 3.5 – CO_2 fluxes from drainage ditch and field surface by sector, measurement positions combined

3.4.3 CO_2 Fluxes Between Measurement Positions

When measurements are averaged by field position (2, 5, and 15 m away from the drainage ditches) across all five sector ages, the mean CO_2 fluxes (± SE) are 0.7 (± 0.04), 0.7 (± 0.1), and 1.4 (± 0.1) gC m^{-2} d^{-1}, respectively (Figure 3.6). A statistically significantly different mean CO_2 flux from the 15 m position compared to both the 2 m and the 5 m positions ($F_{2,942} = 6.90$, $p < 0.05$) is found.

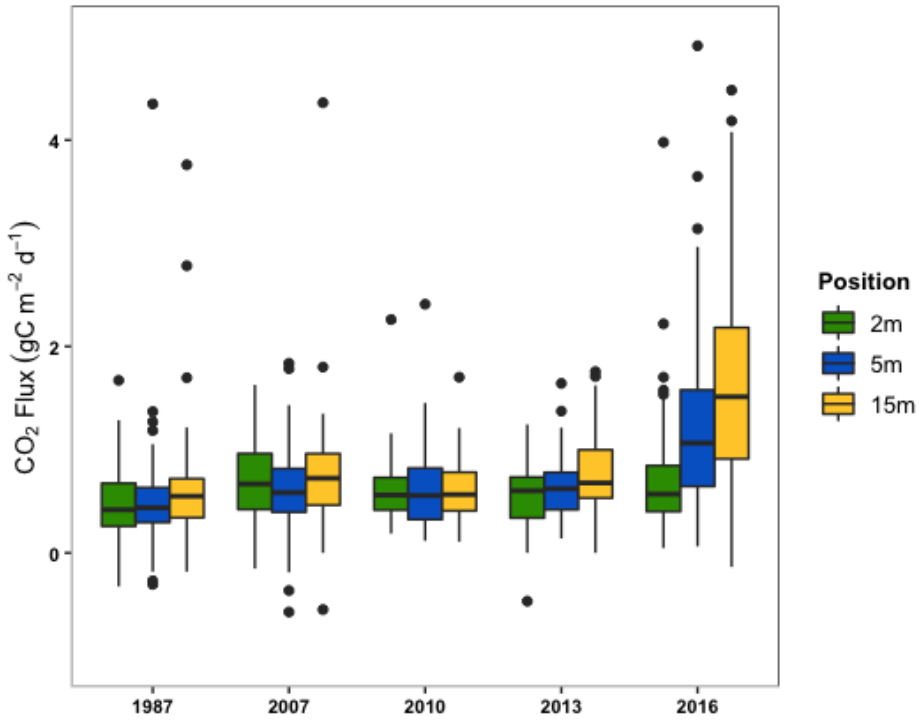

Figure 3.6 – CO_2 flux by sector and measurement position

3.4.4 Spatial Variation in CO_2 Flux Within Fields and Between Sectors

Sector age and measurement position have combined effects on CO_2 emissions (age x position interaction, $F_{8,942} = 3.41$, $p < 0.001$). The mean of the CO_2 emissions from the 15 m position in the 2016 sector are significantly different from every other sampling position and sector age. Within the 2016 sector, the means of the CO_2 emissions from the 15 m position are statistically different from those of the 2 m position ($F_{8,942} = 2.22$, $p < 0.001$). No statistical difference emerges between the means of the 2016 15 m and 2016 5 m positions. Within the 2016 sector, a difference was only found between the middle and edge of the fields. No differences were noted within or between the other four sectors. Across the whole data set, there was no correlation between VWC ($r = -0.2$) or temperature ($r = 0.19$) and CO_2 flux.

3.4.5 CH_4 Fluxes Between Fields and Drainage Ditches

Variation in CH_4 emissions is even greater than that of CO_2 between the field and drainage ditches. The mean CH_4 flux (± SE) from the drainage ditches from all sectors is 72.0 (± 18.0) mgC m^{-2} d^{-1}. The mean CH_4 flux (± SE) from the total field surface is 9.2 (± 4.0) mgC m^{-2} d^{-1}. The maximum CH_4 flux from the fields and ditches are 2518.5 and 2737.8 mgC m^{-2} d^{-1}, respectively, and the minimum fluxes are -74.7 and -5.8 mgC m^{-2} d^{-1}, respectively. A single value of 10822 mgC m^{-2} d^{-1} was deemed an outlier and removed from the 2016 drainage ditch flux data.

Drainage ditches are much larger sources of CH_4 to the atmosphere than the exposed peat at the field surface (Figure 3.7). A high standard error is present in both the field and the drainage ditch measurements, although the drainage ditches show more variation. The mean CH_4 emissions from the drainage ditches is statistically higher than that of the fields ($F_{1,905} = 15.6$, $p < 0.001$).

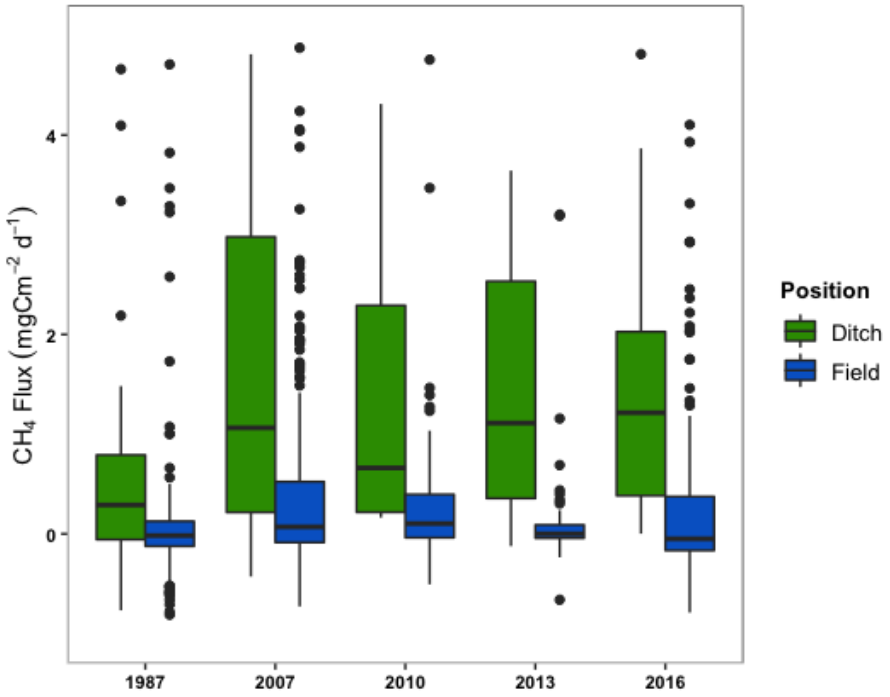

Figure 3.7 – CH_4 fluxes from drainage ditch and field surface by sector, measurement positions combined

3.4.6 CH_4 Fluxes Between Sectors

The average CH_4 flux (± SE) from the drainage ditches from each sector is 32.9 (± 22.6), 113.6 (± 48.0), 46.7 (± 11.04), 14.4 (± 11.7), and 128.4 (± 50.6) mgC m^{-2} d^{-1} from the 1987, 2007, 2010, 2013, and 2016 sectors, respectively. The average CH_4 flux (± SE) from the field surface is 2.4 (± 2.1), 5.0 (± 1.6), 11.7 (± 7.3), 2.0 (± 1.8), and 21.9 (± 14.9) mgC m^{-2} d^{-1} from the 1987, 2007, 2010, 2013, and 2016 sectors respectively. None of the sectors are statistically different from each other.

3.4.7 Spatial Variation in CH_4 Fluxes Within Fields and Between Sectors

Combining the sectors and stratifying data by measurement position, the average (± SE) CH_4 fluxes from the 2, 5, and 15 m positions on the fields are 13.4 (± 11.1), 8.6 (± 3.0), and 5.3

(± 2.4) mgC m^{-2} d^{-1}, respectively. Lower CH_4 emissions are seen mid-field, but there are no statistically significant differences between the means of the three field measurement positions (Figure 3.8). Across the whole data set, no relationship was present between VWC (r = -0.077) or temperature (r = 0.084) and CH_4 flux.

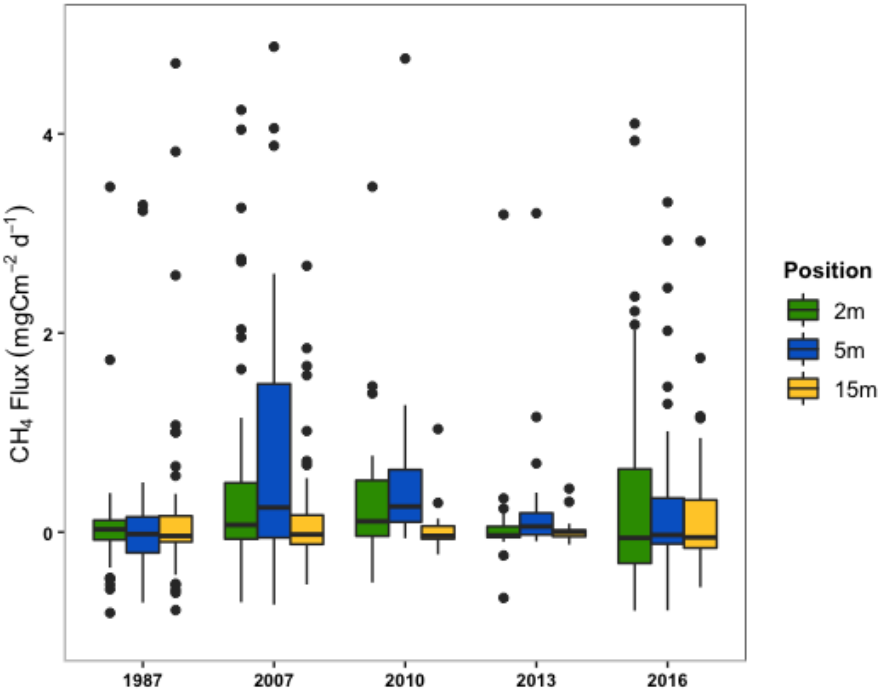

Figure 3.8 – CH_4 flux by sector and measurement position

3.4.8 Peat Age and Quality

The ^{14}C dating results of peat samples from the 2007 and 2016 sectors reveal distinct differences in peat age across and within sectors (Figure 3.9). The elevation difference across the field introduces an age difference between the peat closest to the drainage ditches and peat at the centre. The results indicate that peat age ($\Delta^{14}C$) decreases toward the centre of the field, with elevation, in both the 2007 (-163.46 ± 3.27‰ and -104.10 ± 3.54‰ for 2 and 15 m, respectively)

and 2016 (-94.06 ± 3.56‰ and 30.03 ± 4.00‰ for 2 and 15 m, respectively) sectors. Mid-field, at a depth of 80 cm from the surface, the age difference is also apparent between sectors (-276.62 ± 2.88‰ and -154.39 ± 3.29‰ from the 2007 and 2016 sectors respectively) (Figure 3.9).

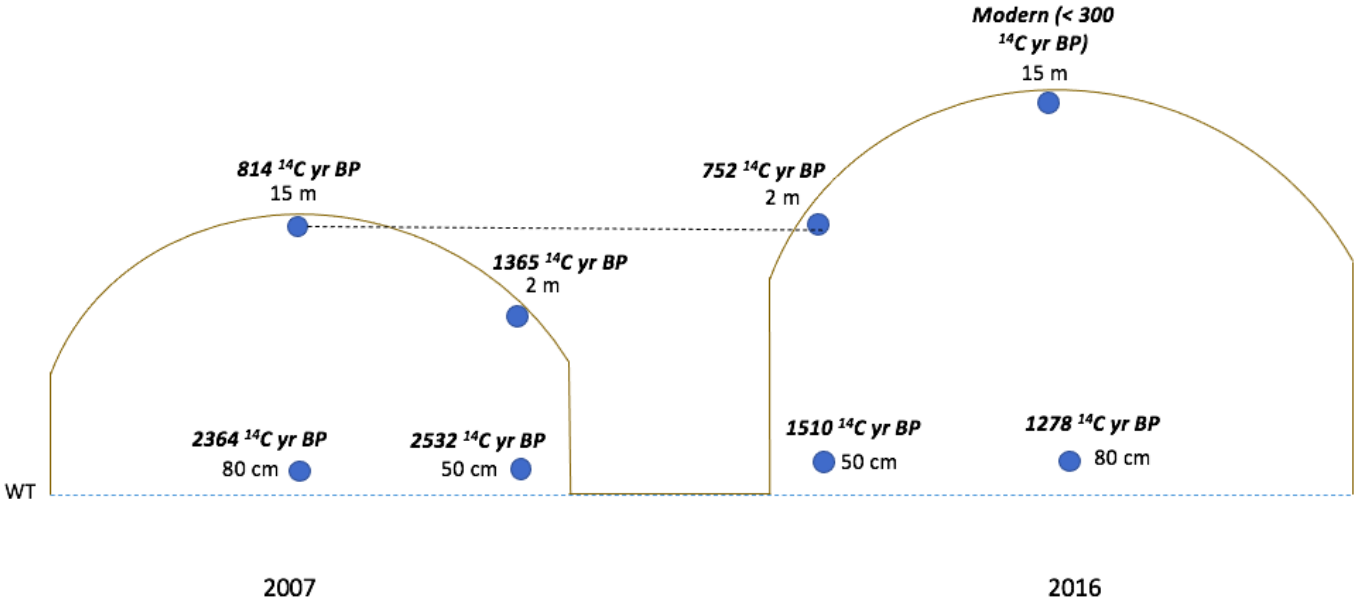

Figure 3.9 – Incubation sampling locations with respective ^{14}C ages, all depths approximate

Results from FTIR analysis indicate that the degree of humification increases with a longer time of extraction. Assessing samples from the surface and 10 cm depths, the sector average HI (± SD) are 1.05 (± 0.08), 0.82 (± 0.08), and 0.70 (± 0.09) from the 1987, 2007, and 2016 sectors, respectively. The 50 and 80 cm samples were excluded from this analysis because the deep samples are older and more humified than the surface peat as a result of their depth in the profile. A one-way ANOVA demonstrated that there is a significant difference between the average HI from the 1987 and 2007 sectors ($p < 0.001$, $F_{(2,21)} = 26.73$) and from the 1987 and 2016 sectors ($p < 0.001$, $F_{(2,21)} = 26.73$).

3.4.9 CO_2 Production Potential

Carbon dioxide production potentials range from 0.50 – 1.39, 0.28 – 0.88, and 0.40 – 1.36 $\mu gCO_2\ g^{-1}\ h^{-1}$ from the 1987, 2007, and 2016 sectors respectively. The highest CO_2 production potential comes from the 1987 sector at the 2 m position, 50 cm depth (1.39 $\mu gCO_2\ g^{-1}\ h^{-1}$), while the smallest is observed from the 2007 sector at the 5 m position, 10 cm depth (0.28 $\mu gCO_2\ g^{-1}\ h^{-1}$). Carbon dioxide production from the 1987 sector samples do not appear to follow any clear pattern or trend in regard to position on the field or depth (Figure 3.10a), although notable statistically significant differences can be seen among depths of the surface and 10 cm from the 2 and 5 m positions and the 5 and 15 m positions. Carbon dioxide production within the 2007 sector also does not appear to follow a trend or pattern (Figure 3.10b). Notable statistically significant differences within the 2007 sector emerge at a depth of 10 cm between the 5 and 15 m positions. The 2016 sector samples, however, exhibit a clear increase in CO_2 production with increasing distance from the drainage ditches at the surface and 10 cm depths (Figure 3.10c). From these depths, the 2 and 15 m positions and the 5 and 15 m positions are statistically different ($F_{6,366} = 19.5$, $p < 0.001$). From all three sectors, CO_2 production potentials are similar between the 50 and 80 cm depths, although the absolute values vary between the sectors.

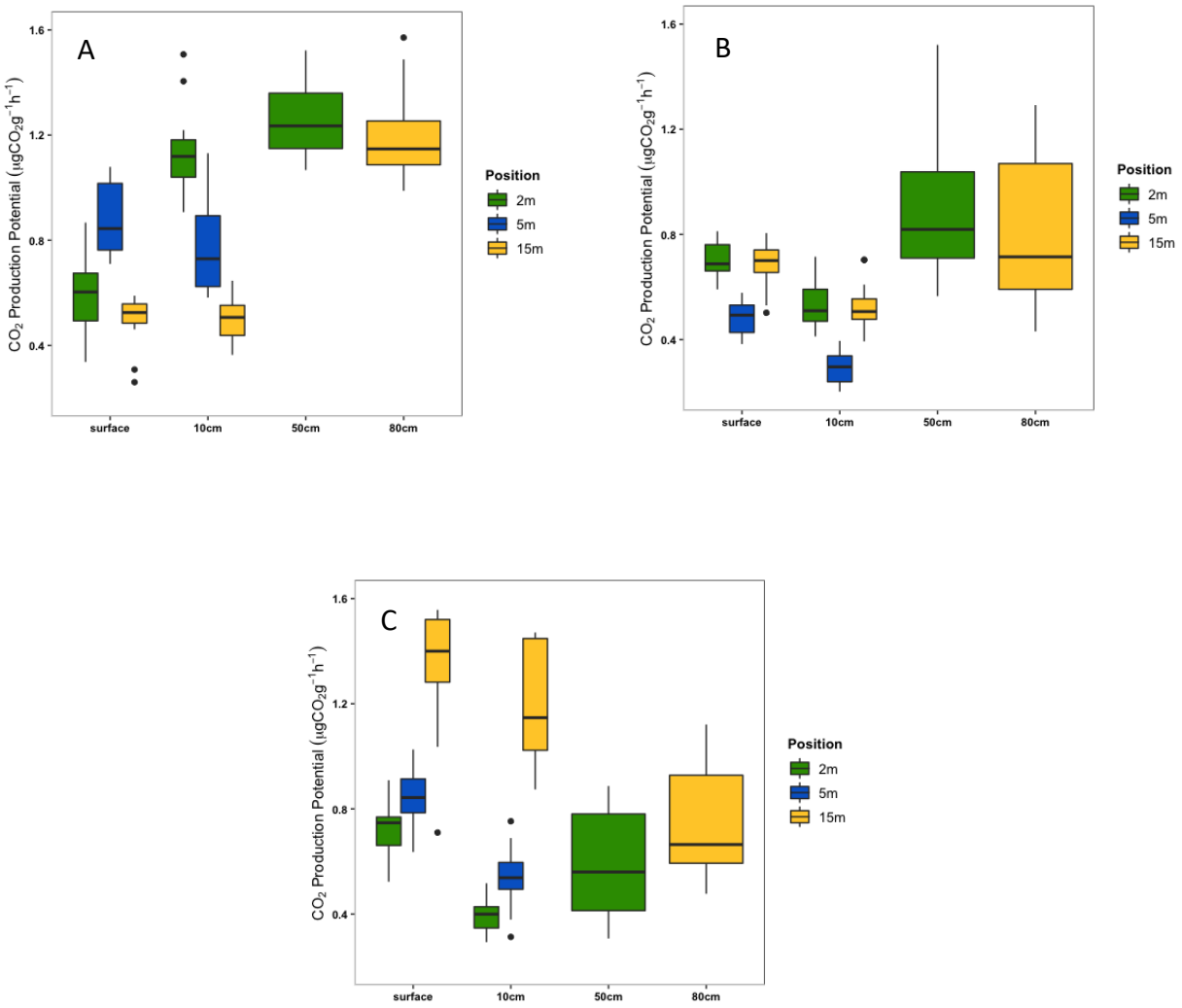

Figure 3.10 – CO_2 production potentials of all samples from the A) 1987, B) 2007, and C) 2016 sectors.

3.4.10 CH_4 Production Potential

There were no incubations that showed a consistent increase in CH_4 concentration over the course of the experiment and all CH_4 r^2 values were < 0.8.

3.5 Discussion

3.5.1 Comparison to Literature

The net ecosystem exchange (NEE) of undisturbed peatlands ranges between -10 to -60 gC m^{-2} yr^{-1} (Koehler et al., 2010; Roulet et al., 2007; Sagerfors et al., 2008), whereas our study site is a net source of C to the atmosphere, similar to values reported from disturbed and post-extraction, unrestored peatlands. Aslan-Sungur et al. (2016) reported CO_2 fluxes of 246, 244, and 663 gC m^{-2} yr^{-1} in 2011, 2012, and 2013 respectively, from a peatland site drained for mining and agricultural use. Rankin et al. (2018) reported annual CO_2 emissions of 173 - 259 gC m^{-2} yr^{-1} from a 20-year post-extracted, unrestored peatland. For our study site, using the mean daily emission of 0.7 gC m^{-2} for six months and ~0.5 gC m^{-2} d^{-1} for the six cold months, would yield an estimate of 200-250 gC m^{-2} yr^{-1} which is in line with previous results (Alm et al., 2007; Aslan-Sungur et al., 2016; Nykanen et al., 1995; Wilson et al., 2015). A higher respiration rate from the drainage ditches is consistent with findings from previous studies at post-extraction (Waddington et al., 2010) and unrestored (Rankin et al., 2018) peatland sites.

Our measured CH_4 fluxes correspond to published values from other drained peatland sites (Manning et al., 2019; Waddington et al., 1996). Korkiakoski et al. (2020) reported that a drained peatland site in Finland became a CH_4 sink over the growing season, measuring emissions to the atmosphere only following precipitation events. Although our site is not a net sink, some uptake of CH_4 by the field surface was measured consistently over all three years of study from all sector ages. We likely have under sampled gas fluxes after rainfall events, and this may influence temporal variation in CH_4 emissions.

3.5.2 Environmental Variables

Peat fiber content, indicated by visual analysis and industry specification, does not appear to have a great deal of influence over respiration rates. According to industry quality classifications, the 1987 sector contains the most fibric peat, while the 2007 through 2016 sectors do not vary greatly in fibre content. Thus, mechanical quality does not predict variation in CO_2 production within fields or between sectors. Temperature is widely documented to be a driver of CO_2 production (Blodau, 2002; Holden, 2005; Moore & Dalva, 1993; Yavitt et al., 1997); however, surface temperature exerts little to no influence over our measured CO_2 flux ($r = 0.19$). It is possible that other drivers, such as substrate quality, may have a larger impact on CO_2 emissions. Surface VWC also does not appear to have an influence on CO_2 flux ($r = -0.2$), possibly due to increased respiration rates in the deeper aerated peat that would offset a decline in CO_2 production from desiccation (Dimitrov et al., 2010; Marwanto & Agus, 2014; Waddington et al., 2002). Average VWC is lower than values documented from other disturbed peatlands (Manning et al., 2019; Waddington et al., 2002), but values from actively extracted peatland sites are difficult to find in the literature.

3.5.3 Chamber Measurement CO_2 Fluxes

The overarching observation that the most recently opened 2016 sector has higher CO_2 emissions than the older sectors was an expected result and can be best explained by the relative age of the surface peat. Since this sector was most recently opened, aerated peat in the upper profile is younger than sites where peat extraction has occurred for many years, exposing older peat present deeper in the profile. Further, the elevation gradient that results from the practice of

doming the field surface exposes older peat deeper in the soil profile to the surface near the ditches, leaving younger peat in the middle of the fields (Figure 3.9).

Nutrients and microbial biomass have been lost over time in the older sectors as peat at depth is continuously exposed to the surface (Croft et al., 2001; Glatzel et al., 2004). The decrease in CO_2 production could also be a result of an accumulation of inhibitory compounds, such as lignins, phenolics, or humic substances, that hinder extracellular enzyme activity (Hogg et al., 1992). This is supported by the FTIR (1650/1090 cm^{-1}) values that show an increase in humification with length of extraction. In an incubation study of peat samples from 2- and 7-year post-extraction peatlands, Waddington et al. (2001) concluded that CO_2 production did not change from peat below a depth of 35 cm. The authors did not find a significant difference in CO_2 production between the young and old cutover sites and argue that peat age is a stronger influence on CO_2 production than gas transport through peat layers (Waddington et al., 2001).

Spatial variation within fields further illustrates the effect of peat age on respiration. The site average CO_2 flux is similar to average values from post-extraction, unrestored sites while the 2016 sector 15 m position emits more CO_2 than is recorded in the literature for post-extraction, unrestored sites (Rankin et al., 2018; Strack & Zuback, 2013). The 2016 sector displays a clear linear increase in CO_2 flux with increasing distance from the ditch, but this effect declines and plateaus in the older sectors. Spatial variation in CO_2 emissions is not apparent in the older extracted sectors because the surface peat is older and the respiration rates are correspondingly lower. The peat at the 2 m position in the 2016 sector has a similar ^{14}C age to the middle of the 2007 sector (Figure 3.9) and also displays a similar mean CO_2 flux to the 2007 15 m position (0.57 and 0.72 gC m^{-2} d^{-1} for 2016 and 2007, respectively).

Previous studies have compared trace gas production from natural and cutover peatlands (Croft et al., 2001; Glatzel et al., 2004; Waddington et al., 2001; Waddington et al., 2002; Waddington & Price, 2000); however, none have compared the spatial variation in respiration rates between peat age based on depth and production year at an extracted peatland. Our results indicate that in the first few years of peat extraction, the residual labile C contained in the surface peat encourages C mineralization and high levels of CO_2 production. This is clearly observed in the high emissions from the center of the youngest field, opened two years prior to our initial measurements. An obvious decline in respiration within the 2016 sector is demonstrated over a distance of 10 m (Figure 3.6), with an estimated 15 cm difference in depth and an age difference of ~ 450 years, driven by the fact that easily available C has been consumed by microbes. Over a period of approximately three to four years, based on measurements from the sector opened in 2013, respiration rates plateau. Peat quality appears to decline with extraction length, as indicated by the FTIR (1650/1090 cm^{-1}) values. Soil moisture and temperature, typical drivers of CO_2 production, do not appear to influence respiration rate, further indicating peat age to be the primary control.

3.5.4 Peat Substrate Age and Decomposability

The CO_2 production potential from the incubation experiments mirror those observed in our field chamber fluxes, suggesting that peat samples taken from the field site behave similarly as under field conditions when controlling for moisture and temperature. In high-latitude peatlands, deeper peat has been shown to be more resistant to decomposition than more recently formed peat (Hogg et al., 1992). Supporting our field measurement results, CO_2 production potential of incubated peat from the 2016 sector increases with distance from the ditch and

decreasing peat age in the top layers of peat (surface and 10 cm depths; Figure 3.10c). Increased CO_2 production potential with younger peat supports the conclusion that the 2016 sector contains C in substrate that is more easily available for decomposition. This is not observed from the older sectors that have undergone extraction for longer durations of time, also in accordance with our field measurements.

Decreased CO_2 production potential from older peat is consistent with what has previously been presented in the literature for temperate peatlands. Research has shown that CO_2 production potential declines with depth (Bridgham & Richardson, 1992; Waddington et al., 2001), helping to explain the consistent behaviour of the deep peat samples from the 2007 and 2016 sectors. This was an expected outcome as these samples were parallel to each other at depth and have similar (within ~100 years) ^{14}C ages (Figure 3.9). Research has shown that intra- and inter-community CO_2 production potential from well-humified peat does not vary significantly (Bridgham & Richardson, 1992). McKenzie et al. (1998) reported that CO_2 and CH_4 production potential declined with depth from different locations at two flooded peatland sites, which they attribute to differences in peat quality as a result of age.

Moreover, previous studies found decreased CO_2 production potential from peat in extracted peatlands compared to natural and restored sites (Croft et al., 2001; Glatzel et al., 2004). Glatzel et al. (2004) observed lower rates of respiration from surface peat at a production site, compared to natural and restored sites, finding the degree of humification to be an important control on CO_2 production. Waddington et al. (2001) also found that CO_2 production was lower in block-cut sites compared to a natural peatland and that the most active CO_2 production was in the surface layers. Croft et al. (2001) found lower microbial biomass in a vacuum-harvested

production site, leading to lower CO_2 production, and found that microbial populations increased following restoration.

3.5.5 Chamber CH_4 Fluxes

A measured difference in CH_4 fluxes between the field surface and drainage ditches was an expected outcome, as this has been demonstrated in many previous studies (Manning et al., 2019; Minkkinen et al., 1997; Minkinnen & Laine, 2006; Rankin et al., 2018; Schrier-Uijl et al., 2010; Strack & Zuback, 2013; Sundh et al., 2000; Waddington & Day, 2007). The drainage ditches act as localized anoxic zones that exhibit ideal moisture and temperature conditions for CH_4 production. Higher CH_4 fluxes, particularly if standing water is present, from the drainage ditches could be partially explained by microbial breakdown of dissolved organic carbon (DOC) or the lateral transport of dissolved CH_4 produced in the anoxic peat field layers (Billett & Moore, 2008; Teh et al., 2011; Cory et al., 2014; Logue et al., 2016).

The lack of correlation between surface soil moisture and CH_4 emissions was a surprising and unanticipated outcome. Drainage has been documented to decrease CH_4 emissions (Abdalla et al., 2016; Basiliko et al., 2007; Korkiakoski et al., 2020; Waddington & Price, 2000), but soil moisture is widely accepted to have a significant influence over CH_4 emissions (eg. Abdalla et al., 2016; Basiliko et al., 2007; Manning et al., 2019; Moore & Dalva, 1993; Moore & Roulet, 1993). VWC measurements likely do not correlate with CH_4 flux as they were taken in the surface peat that is disconnected from the moisture profile as a result of harrowing.

Preliminary WTD measurements taken from June 2019 through August 2020 indicate that during the summer months, the WT decreases toward the edge of the field, measuring approximately 60 cm from the surface at a distance of 1 m from the ditches, due to the drainage

of water into the base of the drainage ditches. Between June and October, at a distance of ~ 13.5 m away from the drainage ditches, the WT remained at a consistent depth of ~ 17 cm from the surface. These measurements indicate that the WTD decreases toward the center of the field, decreasing the depth for CH_4 oxidation, further supporting our assertion that peat age is the primary control over CO_2 production.

Vegetation removal also plays a role in the decline of CH_4 transmission to the atmosphere compared to natural or restored sites. The absence of vegetation removes the input of labile C to the anoxic layer normally facilitated by sedge roots in natural peatlands (Joabsson et al., 1999) and the transport of CH_4 to the surface via vascular plants ceases (Korkiakoski et al., 2020).

Our results clearly indicate that the field surfaces from all sectors are not significant sources of CH_4 to the atmosphere, while the drainage ditches produce almost seven times more CH_4 on average (9.2 and 72.0 mgC m^{-2} d^{-1} for the field and drainage ditches, respectively). Ultimately, no other significant trends or correlating variables were found to explain variation in our measured CH_4 fluxes. Additional measurements, such as flux measurements after precipitation events, may help explain the drivers of CH_4 emissions at this site.

3.6 Summary and Conclusion

We were able to determine that peatlands undergoing active peat extraction are net sources of C to the atmosphere, with average CO_2 and CH_4 flux values similar to those of post-extraction, unrestored peatland sites. The newly opened sectors are significantly higher sources of CO_2 to the atmosphere and fluxes decline over several years to become consistent sources over the remaining period of extraction. The spatial-age effect across the domed fields, where CO_2 emissions increase with increasing distance from the drainage ditches, also declines and

plateaus. CH_4 emissions do not appear to exhibit a clear spatial or temporal pattern between sector ages or measurement positions, although lower CH_4 fluxes are observed from the centre of the peat fields. The drainage ditches are sources of CH_4 to the atmosphere, while the field surfaces do not show large amounts of CH_4 production. Laboratory incubations did not show a significant level of CH_4 production potential from the peat samples, at an estimated 80-90 % moisture content. Under constant moisture and temperature conditions, the CO_2 production potential of peat from the 1987, 2007, and 2016 sector ages displayed the same behaviour as CO_2 emissions under field conditions. CO_2 production potential increased with distance from the ditch from the top peat layers in the youngest 2016 sector, but this pattern was not displayed from the older 1987 or 2007 sectors. CO_2 production potential of peat samples at depths of 50 and 80 cm was similar between all three sector ages, although a significant amount of variation was observed between the years. Peat age across the field width and between sectors was determined to be the primary driver of CO_2 production.

The quantification of C emissions from these sites allows for more accurate estimates of the overall impact peat production has on atmospheric C accumulation. The results of this study provide industry with scalable numbers of CO_2 and CH_4 production to determine potential mitigation tactics and move forward with the continued sustainable and responsible management of this resource.

CHAPTER FOUR

SUMMARY AND CONCLUSIONS

4.1 Research Findings and Context

The results in this thesis represent the first scientific study to measure C emissions from a production peatland undergoing active vacuum extraction. While C emissions from undisturbed (e.g., Bubier et al., 1993; 2003; 2005; Lafleur et al., 2003; Moore et al., 1990; Pelletier et al., 2007; 2011; Roulet et al., 2007; Strachan et al., 2016; Updegraff et al., 1995; Valentine et al., 1994), drained and unrestored (e.g., Aslan-Sungur et al., 2016; Bergman et al., 1998; Oleszczuk et al., 2008; Rankin et al., 2018; Sundh et al., 2000; Waddington & Price, 2000; Waddington et al., 2002), and restored (e.g., Nugent et al., 2018; Strack & Zuback, 2013) peatland sites have been documented in the literature, a gap in knowledge was still present regarding the C emissions from peat during active extraction. Previously, C emissions estimates relied on incubation studies or measurements from areas in which extraction had been halted. Therefore, the objectives of this study were to: (1) measure CO_2 and CH_4 flux from the surface of peat fields and drainage ditches at a peatland site undergoing active extraction; (2) determine spatial variability in CO_2 and CH_4 fluxes within fields and across varying sector ages at a peatland site undergoing active extraction; (3) test the effect of peat quality on CO_2 and CH_4 production potential of peat samples taken from an active extraction site. This research brings novel knowledge to the scientific community and provides quantitative data that allow for C flux estimates from actively extracted peatlands to be made. This thesis also provides biogeochemical and flux data for the development of models to extrapolate the findings and address further questions.

The CSPMA aims to be socially responsible in their management of Canadian peatlands and is committed to restoring extracted peatland sites and assessing the environmental impacts of production peatlands over the entire course of the extraction process (CSPMA, 2021). This study provides data that will assist the industry in assessing the overall impact that their operations have on atmospheric C accumulation.

The research in this thesis represents measurements from sectors opened in five different years (1987, 2007, 2010, 2013, 2016) over a 30-year period at an in-production peatland undergoing active extraction. CO_2 fluxes from chamber measurements were highest from the youngest sector, opened in 2016. In comparison, the four older sectors all had similar mean CO_2 fluxes that were statistically different from the mean 2016 CO_2 fluxes. A spatial effect on CO_2 fluxes was observed solely within the 2016 sector, where CO_2 emissions were highest from the center of the peat field and declined towards the drainage ditches. Draining and extraction of peatlands fundamentally alters the drivers of CO_2 and CH_4 emissions. Carbon emissions from peatlands undergoing extraction have not been well constrained due to a lack of research from sites where extraction is actively occurring. We determine the effect that production duration (years of extraction) has on the CO_2 and CH_4 emissions from an actively extracted peatland over three years (2018-2020) of measurements. We studied five sectors identified by the year in which extraction began (1987, 2007, 2010, 2013, 2016). Higher average CO_2 and CH_4 emissions were measured from the drainage ditches (CO_2: 2.05 (± 0.12) gC m^{-2} d^{-1}; CH_4: 72.0 (± 18.0) mgC m^{-2} d^{-1}) compared to the field surface (CO_2: 0.9 (± 0.06) gC m^{-2} d^{-1}; CH_4: 9.2 (± 4.0) mgC m^{-2} d^{-1}) regardless of sector. For peat fields, CO_2 fluxes were highest from the youngest sector, opened in 2016 (1.5 (± 0.2) gC m^{-2} d^{-1}). The four older sectors all had similar mean CO_2 fluxes (~0.65 gC m^{-2} d^{-1}) that were statistically different from the mean 2016 CO_2 flux. A spatial effect

on CO_2 fluxes was observed solely within the 2016 sector, where CO_2 emissions were highest from the centre of the peat field and declined towards the drainage ditches. These observations occur as a result of the surface contouring that operators create to facilitate drainage. The domed shape and subsequent peat removal resulted in a difference in surface peat age within each sector that corresponded to differences in the labile C available for decomposition within the peat. ^{14}C dating confirmed that the remaining peat contained within the 2016 sector was younger than peat within the 2007 sector and that peat age is younger toward the centre of the field in both sectors. Fourier Transform Infrared Spectrometry (FTIR) (1630/1090 cm^{-1}) values indicated that peat humification increases with increasing years of extraction. Laboratory incubation experiments showed that CO_2 production potentials of surface peat samples from the 2016 sector increased toward the centre of the field and were higher than samples taken from the 1987 and 2007 sectors.

CH_4 fluxes from the drainage ditches were nearly seven times higher than from the field surface, likely as a result of moisture conditions and nutrient concentrations. However, chamber measurements and laboratory incubation results did not allow for concrete conclusions about the drivers of CH_4 emissions to be made.

The quantification of CO_2 and CH_4 emissions from peatland production sites undergoing active extraction provides scalable data to both the scientific community at large and the peat industry to determine the impact of extraction on atmospheric C accumulation and allows for the identification of avenues to mitigate and reduce C emissions as a result of the extraction process.

4.2 Study Limitations and Scope for Future Research

This study provided the first measurements of GHG emissions from an actively harvested drained peatland. However, we did not capture the effect of management on fluxes of CO_2 and CH_4. Preliminary research by Weinberg (2018) indicated that there was an increase in CO_2 flux following disturbance by machinery. Different management practices, such as harrowing and harvesting frequency and rotation, may have an effect on CO_2 and CH_4 emissions. While companies follow similar management practices, variation between companies and the corresponding effects on trace gas fluxes between peat harvesting companies is an additional avenue for research.

We did not measure during months when the site was not undergoing extraction so an estimate (200-250 gC m^{-2} yr^{-1}) using the mean daily emission of the site (0.7 gC m^{-2} d^{-1}) and an estimate (~0.5 gC m^{-2} d^{-1}) for the six cold months was made. Chamber measurements were limited to pre-defined measurement periods and were conducted in non-rain conditions. The measurements were not arranged explicitly to precede or follow rain events and therefore future research could target the effect that environmental conditions (i.e., large precipitation events) have on CO_2 and CH_4 production. A multi-year study using an eddy covariance system would allow for an accurate assessment of trace gas flux in response to changes in environmental variables and determine inter-annual variability in C emissions.

Further research into the C cycling dynamics and CH_4 production in the drainage ditches would be important to provide additional understanding of the spatial variation in C emissions at the extraction site. While their overall areal coverage is small, the drainage ditches nonetheless represent GHG hotspots exhibiting different behaviour from the field surface.

Preliminary measurements show that peat stock piles are additional sources of CO_2 at the study site. Further measurements on storage piles could indicate the magnitude of the C flux from the stock piles and the variation between stock piles of different industry specified "grades", or quality, peat. This data would be helpful when constructing a total C budget for the study site or for vacuum extraction operations generally.

Performing incubations under anaerobic conditions would be fundamental to understanding differences in CH_4 production as a result of peat age. Future research could vary the moisture and temperature conditions to determine the response of CO_2 and CH_4 production to differing environmental variables.

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