Methane and CO_2 Emissions from Covered and Exposed Peat Stockpiles in Drained Peatlands undergoing Harvesting

by

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Abstract

Industrial peat extraction involves removal of surface vegetation and lowering of water table that is known to shift the system from a carbon sink to a source of atmospheric carbon. Peat stockpiles are an important yet understudied component of the landscape of harvested peatlands. In particular, the effect of management styles (e.g., covered vs. exposed) on stockpile greenhouse gas emissions are poorly understood. The goals of this study are to 1) compare the carbon dioxide (CO_2) and methane (CH_4) emitted from tarp-covered peat stockpiles and exposed ones; 2) examine how physical factors of stockpile (height; aspect; peat quality; temperature and moisture) influence the greenhouse gas emissions of the stockpiles. We collected trace gases fluxes and temperature measurements for stockpiles from two companies that manage their stockpiles differently. For Premier Tech stockpiles, the mean CH_4 flux is 1.33±2.05 mg C m^{-2} d^{-1}, over four times bigger than last year's result, but five times smaller than the fields. The mean CO_2 flux is 2.88±2.22 g C m^{-2} d^{-1}, slightly smaller compared to last year's result but still four times larger than the fields. CO_2 flux is found to increase with higher heights on the stockpile because CO_2 is speculated to mostly diffuse upwards through the peat rather than evenly spread outwards. For Berger stockpiles, the effect of factors like height, aspect and peat grade is overrun by the existence of tarp cover, which effectively hinders gas exchange between the stockpile and the atmosphere. No significant correlation is found between temperature and greenhouse gas flux for stockpiles from both companies. Hot spots in both CO_2 and CH_4 data suggest the existence of hot spots for peat decomposition in the stockpile, possibly constrained by water availability. Future work should collect moisture data alongside the temperature probe across different depths for each measurement location on the stockpiles.

Chapter 1. Introduction

Covering only ~3% of the Earth's land surface, peatlands store one-third of the global soil carbon, 10% of the world's drinking water, and 10% of the world's soil nitrogen (Vitt and Short 2020). Peatlands also act as watershed filters and serve as habitat for a wide array of species. Northern peatlands comprise a carbon pool of 455 Pg that has accumulated during the Holocene at an average net rate of 0.096 Pg yr^{-1} (1 Pg = 10^{15}g) (Gorham 1991). Peat is formed through a slow accumulation of detritus with litter input exceeding decomposition rates in waterlogged environments. In pristine peatlands, a shallow water table or permanently waterlogged condition causes oxygen deficiency, allowing the accumulation of organic matter over millennia. These anaerobic conditions also favour methanogenesis, and peatlands thus act as a global source of methane (CH_4) of around 0.8 Gt CO_2-equivalent yr^{-1}. CH_4 is a greenhouse gas (GHG) with a global warming potential that is 28 times that of carbon dioxide (CO_2) over a 100-year time horizon. Previously, Gheta (2020) studied CO_2 emissions from peat stockpiles in an extracted peatland in eastern Quebec in August 2020. I used the same field site for data collection in August 2021 with more attention on the release of CH_4 from peat stockpiles. Other data were collected on a nearby harvested peatland with different styles of management. This study is of great interest to the Canadian Sphagnum Peat Moss Association (CSPMA) since they want to quantify the greenhouse gas emissions during peat extraction and the fate of the peat carbon when peat is used in horticulture (Clark, 2021).

1.1 Study Background

Peatlands represent 90% of all wetlands in Canada (CSPMA, 2022). Peatlands span 113.6 million hectares across Canada, or roughly 13% of the country's surface area, and can be found in all provinces (CSPMA, 2022). With its flat topography and abundant moisture, the Hudson's Bay lowlands of Ontario and Manitoba have the highest concentration of peatland (Tarnocai 2006). The province of Quebec has 11.6 million hectares of peatlands, accounting for around 8% of its total land area, with nearly 85% of it located north of the 51st parallel (Garneau et al 2014).

Peat has long been utilised as a soil amendment and growth medium, and the harvesting of peat moss is a small, but important industry where peatlands are abundant (Vitt and Short 2020). Canada is a prominent producer of commercial peat moss, and the Canadian peat industry has made a consistent effort to restore peatlands to their pre-harvest state through appropriate environmental management. In 2016, 30900 hectares of peatlands in Canada have been or are currently harvested, which represents 0.03% of the natural capital.

1.2 Objective and Research Questions

This research investigates the role that field management plays in the release of greenhouse gases from stockpiles on drained peat fields. This study is an integral part of the NSERC-CRD research project on Carbon Exchange in Drained Peatlands undergoing Harvesting. This NSERC-CRD project aims to describe the controls on GHG production and emission during the period when peat producers are actively harvesting peat from drained fields. This will allow us to estimate the lifetime and magnitude of carbon footprint of the Canadian peat industry, as well as advise the industry on how to use peatlands sustainably.

The main goal of this research is to investigate the factors that influence greenhouse gas (GHG) flux, particularly the release of methane into the atmosphere from peat stockpiles in extracted peatlands in Quebec, and how management styles can be improved to reduce carbon footprint. The key questions that I seek the address in this study are: 1) What is the effect of tarp cover on stockpiles in terms of greenhouse gases emissions? 2) What is the relationship of position and aspect on the peat stockpiles with respect to greenhouse gases emissions? 3) What is the effect of harvested peat quality on stockpile greenhouse gases emissions?

1.3 Thesis Format

This Undergraduate honors thesis is divided into six chapters, the first of which is this introductory chapter that contains background information and the overall structure of this thesis. Chapter 2 provides an overview of the research that has been done on anthropogenically disturbed northern peatlands, with a particular focus on GHG emissions from harvested and restored peatlands. Chapter 3 contains methodologies of data collection, fieldwork sites and sampling strategies, as well as approaches of sorting and analyzing data. Chapter 4 presents the results of atmospheric carbon flux of peat stockpiles and its relationship with environmental parameters. Chapter 5 discusses how physical variables as well as different management styles impact the greenhouse gas emissions of peat stockpiles. Chapter 6 of the thesis presents a summary of the research findings and conclusions, while also give suggestions for future fieldwork and area to focus on.

Chapter 2 Literature Review

The literature review is divided into three parts: the first part is an overview of human's footprints and usage of peatland from antiquity to modern times; the second discusses the GHG exchange in northern peatland system in a general context; the third part examines the current study of stockpile's GHG emissions from actively harvested peatland.

2.1 Peatlands under Anthropogenic Disturbance

In their natural state, ombrotrophic bogs function as a carbon sink, and have had an overall cooling effect on the planet since the postglacial period (Leifeld and Menichetti 2018). The amount of carbon stored in peatlands is about equal to the total CO_2 in the Earth's atmosphere. On the other hand, natural peatlands represent one of the highest terrestrial sources of CH_4 to the atmosphere (Whalen 2005). The transition from a natural peatland to a disturbed peatland will significantly alter its role in ecosystem functions, biogeochemical signatures and global carbon cycle. For instance, a peatland's function as a natural carbon sink is disrupted by land-use change, often resulting in a reversed state of GHG source. This change from sink to source has major implications for the global carbon cycle and future climate change.

Europe has a long tradition of extracting peat blocks from bogs to burn as fuel. The original method of extracting fuel peat was either by hand from trenches in bog margins or by block-cut peat extraction utilising machinery. Given that these actions impacted relatively small areas and included only surface (if any) drainage, the consequences on bog ecosystems were limited and localised, and these peatlands have since re-established themselves through revegetation. The situation changed dramatically in the mid-20^{th} twentieth century with the introduction of peat milling and the vacuum harvesting technique. This relatively new industrial process necessitated massive drainage and the removal of all living plants, as well as the top peat layer from vast areas of peatland. Removal of the surface vegetation cover and artificially lowering of its water table led to an increase in respiration in peatlands (Erkens et al 2016), releasing huge amounts of carbon that peatlands had accumulated over millennia. Extracted peatlands are deprived of carbon-fixing vegetation, which enables intense oxidative decomposition to take over (Waddington et al 2009).

In general, peat bogs 50 ha wide with a minimum peat thickness of 2 m are considered to be of value for horticultural peat production (Canadian Sphagnum Peat Moss Association, 2021).

Peat harvesting sites in Canada are mainly composed of (i) the peat extraction field, (ii) drainage ditches, and (iii) stockpiles. The vacuum-method of peat harvest is the most common peat harvesting method in Canada (Waddington et al 2009). This method requires harrowing – stirring up the top few centimeters of peat - allowing it to desiccate quickly under wind and sunlight (Clark, 2022). The top layer of peat is then vacuum harvested when it becomes sufficiently dry, with the harvested peat then dumped at the end of the field adjacent to an access road. These stockpiles sit on the field for about 5 to 6 months on average, before being transported and processed for market sale (Cleary, 2003).

2.2 GHG Exchange in Northern Peatlands

Spanning across the subarctic and Boreal regions, northern (latitude 40° to 70°N) peatlands are a major regulator of atmospheric GHG, which has implications for global climate (Abdalla et al 2016). In general, northern peatlands are CO_2 sinks and CH_4 sources, although this can vary year to year and is dependent on environmental and biogeochemical conditions (Gorham 1991). Over the last 10,000 years, atmospheric carbon sequestration by peatlands is thought to have decreased global temperatures by 1.5–2 °C (Leifeld and Menichetti 2018).

It is estimated that northern peatlands can accumulate between 20 to 100 g carbon m^{-2} yr^{-1} (Abdalla et al 2016) and store ~500 Gt carbon in total (Scharlemann et al 2014). Peatlands absorb carbon from the atmosphere in the form of CO_2 via photosynthesis by surface vegetation, which is subsequently stored as undecomposed organic matter. At the same time, peatlands release CO_2 through autotrophic respiration (AR; respiration by plant parts) and heterotrophic respiration (HR; respiration by microbial bacteria in the soil, fungi, etc.), these losses of carbon are referred to as ecosystem respiration (ER) (Rankin et al 2021). Autotrophic and heterotrophic respiration are thought to occur at similar rates, although this is still debated as it is hard to differentiate between the two within the soil (Pelletier et al 2015). The net ecosystem exchange (NEE) of carbon is the difference of ER and photosynthesis, and it represents the quantity of carbon gained or lost by the peatland. ER is controlled by soil temperature, vegetation type, water table depth, peat biogeochemistry and microbial activities (Perkins et al 2016).

Generally, a lesser water table in peatlands is associated with higher respiration rates due to greater oxic environments (Strack et al 2008). Organic matter decomposition in peatland is a result of interactions between soil fauna, bacteria, fungi and actinomycetes (Pelletier et al 2015).

The quantity and quality of peat, as well as environmental factors such as peat moisture, temperature, oxygen, acidity, and redox potential, influence the rate of decomposition. Complex molecules in the soil are broken down by organisms into compounds of low molecular weight, which are then oxidized into CO_2 (Gorham 1991). Following degradation of new litter, the leftover material becomes increasingly recalcitrant and difficult for microbes to break down, suppressing decomposition rates (Strack et al 2008). The rate of soil respiration is thought to be a good indicator of peat quality and general biological activity (Ahlholm and Silvola 1990). Higher rates of respiration indicate a higher labile carbon content, whereas recalcitrant soils decompose more slowly and produce less CO_2. As a result, decomposition rates are highest in youngest peat and have been found to decrease with peat age (Hogg et al 1992).

Despite the fact that CH_4 emissions are lower than CO_2, on a 100-year timescale, CH_4 has a radiative forcing that is almost 28 times greater than CO_2. (Masson-Delmotte et al 2021). Soil–atmosphere exchanges of CH_4 in peatland can be highly spatially and temporally variable because of inter-site as well as micro-scale, seasonal and topographical variations (Strack and Waddington 2008). Two primary mechanisms exist for CH_4 generation in peatlands: hydrogenotrophic and acetoclastic methanogenesis. Hydrogenotrophic methanogenesis uses H_2 to reduce CO_2 into CH_4, whereas acetoclastic methanogenesis creates CH_4 though acetate fermentation. The CH_4 produced in the anoxic catotelm can be consumed in the oxic peat layers through methanotrophic processes, typically occurring within 25 cm of the oxic-anoxic boundary.

CH_4 is oxidized to CO_2 during methanotropy, which lowers CH_4 and enhances CO_2 emissions from peatland, and larger oxic volume means greater opportunity for CH_4 oxidation. The saturated conditions in the bottom layers of peat provide an anoxic environment, allowing methanogenic archaebacteria to produce CH_4 through a process known as methanogenesis (Lafleur 2009). CH_4 produced in the peat is released through diffusion and ebullition due to its low solubility in water, or transport in plant tissues via roots (Abdalla et al 2016). Vascular plants are able to bypass the oxidation zone in the peatland and transport CH_4 from the rhizosphere directly to the atmosphere. Therefore, the release of CH_4 can be facilitated by vascular plant that functions a conduit of CH_4 to the atmosphere and providing methanogenic substrates (Whalen 2005).

There is still uncertainty in the literature regarding the primary control over carbon exchange in northern peatlands. The production of CO_2 is predominantly aerobic while CH_4 is an entirely generated by anaerobic process. It is commonly accepted that the water table exerts a significant control over carbon cycling in peatlands (Limpens et al 2008), whilst some research report no direct correlation between carbon emissions and water table depth (Lafleur et al 2005). Lowering of the water table has been found to increase CO_2 emissions and decrease CH_4 emissions as a result of enhanced aeration and bigger area for CH_4 oxidation to occur (Whalen 2005). Substrate quality and temperature also have significant impacts on microbial CH_4 production in peat (Moore and Roulet 1993). Several studies have found that with more labile C present, more active methanogenesis is observed within wetlands (Lai 2009; Abdalla et al 2016). Meanwhile, anthropogenic disturbance of peatlands, such as draining and extraction of peat, will alter the exchange of CH_4 with the atmosphere. Drainage of the peatlands is thought reduce the amount of methane that is released into the atmosphere because the peat is subject to more aerobic conditions.

2.3 Greenhouse Gas Flux in Peat Stockpiles

Although peat stockpiles are a spatially smaller feature than extraction fields or extensive drainage ditch networks on the production sites, they are important sources of greenhouse gas (Cleary, 2003; Couwenberg, 2011). Peat stored in stockpiles continues to decompose at rates depending on the temperature, oxygen availability of and moisture status (Waddington et al 2009). Vacuum harvested peat in stockpiles is dry and porous, and such aerobic conditions allow increasing decomposition due to enhanced microbial and enzymatic activity, which in turn leads to self-heating. Due to the low conductivity of peat, the increased heat of the stockpile is not dissipated efficiently to the ambient atmosphere and thus further accelerates decomposition of the peat (Cleary, 2003). If internal temperatures of the stockpile exceed 50 °C, chemical reactions lead to further heating in the stockpile, sometimes forming self-igniting compounds which may ultimately lead to peat fires (Kauppi, 1990; Cleary, 2003). Large emissions of greenhouse gases can be observed due to the phenomenon of self-heating in peat stockpiles (Cleary, 2003).

According to a report by the Association of Finnish Peat Industries, the main reason for initiation of self-heating process in peat stockpiles is microbial activity (Ahlholm and Silvola 1990). Microbial metabolism takes place when the temperature is below 70 °C and stops when it rises higher than 70 °C (Mikola and Komppula 1981). Processes of aerobic and anaerobic decomposition by micro-organisms would mineralize the peat in the stockpiles, releasing heat and greenhouse gases at the same time.

In general, stockpiles experience rapid self-heating and higher emission of CO_2 can be attributed to the physical properties of poorly decomposed peat (Mikola and Komppula 1981). There is abundant supply of oxygen due to the low density and porous nature of the *Sphagnum* peat. As the amount of self-heating and CO_2 emission reach a peak level, the oxygen content in the stockpile will gradually drop. This will lead to a subsequent reduction in aerobic activity and CO_2 emission, and possibly a rise in anaerobic activity and CH_4 release.

Despite the potential for large greenhouse gas emissions from peat stockpiles, only two known empirical studies has been conducted, one in Finland and one in Canada. The latest study in the Canadian context by collected stockpile greenhouse gas emissions by removing peat from an extraction site and simulating expected stockpile conditions by imposing different temperature and humidity conditions in a laboratory setting (Waddington et al., 2009). Waddington et al. (2009) reported an estimated total carbon flux of 0.195 g C m^{-2} day^{-1} based on CO_2 emissions from peat stockpiles. However, very little is documented with regards to CH_4 emissions. As peat stockpiles are composed of very dry peat, and CH_4 production is important in anaerobic conditions (Cleary et al 2005a), we expect minimal CH_4 emissions from the stockpiles. Results from Gheta (2020) show that the total carbon flux based on CH_4 emission from peat stockpiles is 0.003 g C m^{-2} day^{-1}, which is a very small number that is consistent with many model predictions.

Based on the previous laboratory study (Waddington et al, 2009), and on data from Gheta (2020) and Clark (2022), we expect CO_2 emission from stockpiles to be much higher than fields. Decomposition rates in peat is known the increase with temperatures (Cleary, 2003); thus, we expect stockpiles to produce more CO_2 at higher temperatures. The tops of the stockpiles receive more solar radiation and become warmer than the lower levels; we expect height on the stockpile will be an important factor in greenhouse gas emissions. Preliminary results on peat fields have found that GHG emissions from peat fields were higher from newly opened peatlands (Clark, 2022).

Chapter 3. Material and Methods

3.1 Study Sites

The study area lies between the municipalities of Rivière-du-Loup and Saint-Antonin in the Bas-Saint-Laurent region, southeastern Québec, Canada (Figure 1). It is an agricultural plain bordered on the northwest by the St. Lawrence River and on the southeast by the Rivière Verte. The region was deglaciated about 12 000 years BP following the retreat of the Laurentide Icesheet but was then submerged by the Goldthwait Sea (Dionne 1977). Therefore, its surficial geology is composed of glacial till overlaid by marine deposits. The geomorphology of the study area is largely shaped by glaciation, which scoured depressions in the landscape that were later filled by water and suitable for peatland development.

Figure 1: Location of Rivière-du-Loup city in the province of Québec

The vegetation cover was established about 9500 years BP, shortly after marine regression, and the modern vegetation developed after 8000 years BP (Richard *et al*. 1992). On mesic and xeric sites, modern vegetation is characterized by sugar maple (*Acer saccharum* Marsh.), yellow birch (*Betula alleghaniensis* Britt.) and balsam fir (*Abies balsamea* (L.) Mill.) forests (Grondin 1996). Jack pine typically occurs as isolated clumps on open rocky sites (Blouin 1970; Garneau 1984). Large ombrotrophic peatlands are common in wet depressions and are dominated by black spruce (*Picea mariana* (Mill.) B.S.P.), ericaceous shrubs and *Sphagnum* species (Gauthier and Grandtner, 1975).

During the nineteenth century, the study area's original forest cover was nearly completely cleared. Peatlands were one of the last ecosystems left unaffected by human activity until recently. Nonetheless, between 1930 and 2000, 62% of the total area covered by bogs (4829 ha) has been disturbed by anthropogenic activities in this region (Fortin 1993). Peat extraction for horticultural practice (84% of the disturbed area), wood logging (9%) and farming (4%) are the main human activities disturbing the peatlands (Pellerin 2003).

The climate in Rivière-du-Loup is cold and temperate, and it is classified as Dfb by the Köppen-Geiger climate classification system. Data from the meteorological station of Rivière-du-Loup indicate that the mean annual temperature is 4.2°C. January is the coldest month with an average low of -14 °C and high of -7 °C; and July is the warmest month with an average high of 21 °C and low of 13 °C. The mean annual precipitation is 743 mm, roughly 37% of which falls as snow (Environment Canada 2021). This cool and wet climate of Rivière-du-Loup is favourable for paludification and growth of high-quality peat for commercial usage.

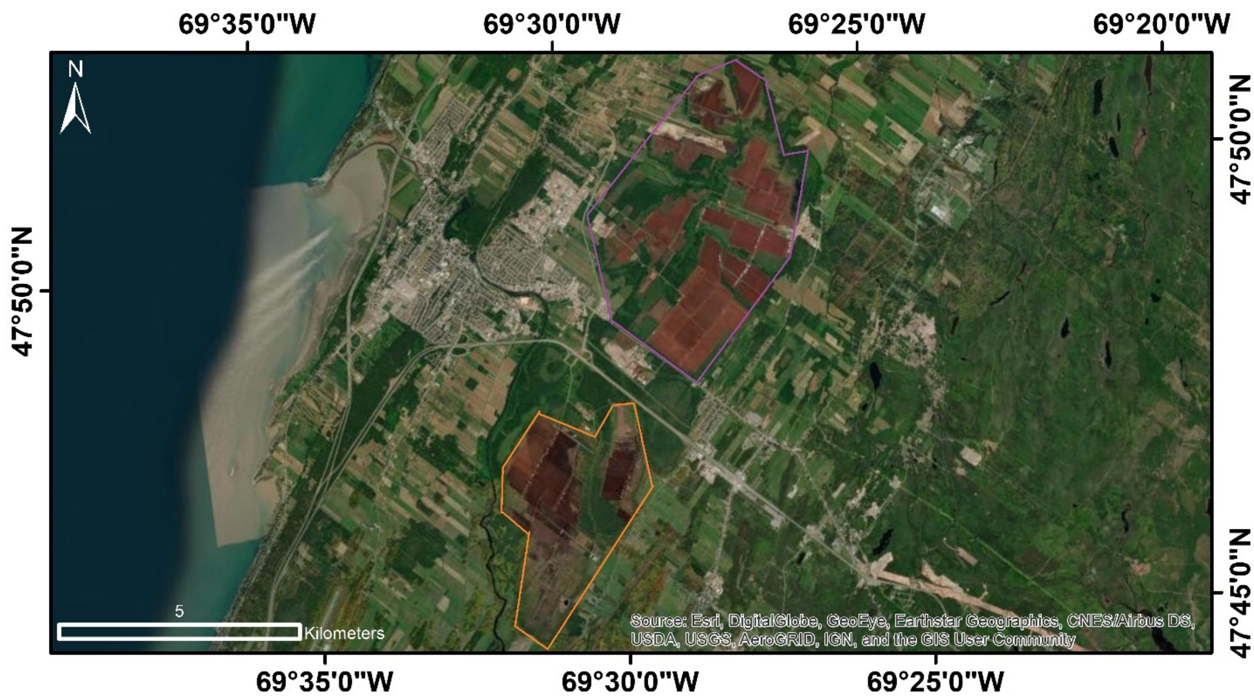

Figure 2: Satellite imagery of fieldwork Sites. Premier Tech Horticulture peatland is delineated by purple lines, Berger Peat Moss Ltd peatland is in the smaller orange boundaries.

The scientific study was conducted on two former Sphagnum-dominated ombrotrophic bogs. The bogs were undergoing active harvesting operated by two different companies (Figure

2). The now-drained peatlands have each been actively harvested for decades, and contained sectors of different lengths of time under extraction.

3.2 Data Collection

The fieldwork took place in late summer of 2021, during active extraction operation. It was arguably the busiest time of the year, with vacuum harvesters extracting peat, harrowing the fields and creating and removing stockpiles on a daily basis. The weather was mostly sunny and hot, with occasional rainy and cooler days. All data used in this study were collected during a 14-day campaign in late August, with on-average two stockpiles sampled per day. In the first week, we measured ten stockpiles from the Berger field that were covered with plastic tarps. In the second week, we moved to the Premier Tech field and measured nine stockpiles that were exposed (uncovered). The companies had different operational management of the stockpiles with Berger stockpiles being quickly covered with white (occasionally black) plastic tarps and given a specific identification code once created (Figure 3), while the Premier stockpiles were more actively manipulated through addition and removal and were left uncovered (Figure 4).

Figure 3: Harvested Peat Stockpiles by Berger

At each site, the peatland was operationally divided into sectors which were subdivided into 30-m wide fields. Each sector represents a year when that area of the peatland was drained and prepared for active harvesting operations. Even though each sector usually has one peat stockpile dumped on the end that is close to the driveway, but this does not mean that each stockpile contains peat that originated exclusively from a single sector. Based on information from previous studies and our own observations, peat from multiple fields and perhaps multiple sectors can be dumped into a single stockpile. The companies are usually only concerned about the grade (quality) of the peat harvested, not the year which sectors were opened. These stockpiles were placed at the end of each sector for the sole purpose of facilitating operation, in which the trucks can easily access these peat stockpiles and take them away for further processing. Unfortunately, we also cannot determine when these stockpiles were created or how long they have been sitting there beside the driveway.

Figure 4: Harvested Peat Stockpiles by Premier Tech

3.3 Trace Gas Measurements

Measurements of CO_2, CH_4 and water vapor were made from ten stockpiles using an infrared gas analyzer (LI-7810, LI-COR Biosciences, Lincoln, NE, USA). Stockpiles were chosen based on their peat grade and accessibility. All sampled stockpiles remained intact throughout the period of data collection. Gas measurements were taken at three different heights (0.3-0.5 m; 2 m; 4 m) on the four sides of each stockpile corresponding to the cardinal directions for a total of twelve measurements for each visit to that stockpile.

At each measurement location, a square opaque steel chamber was manually placed into the surface of the peat stockpile, and there is a mechanical fan to properly mix the air inside the chamber for accurate trace gas measurements. The chamber itself is 64 cm long for both width and length with a height of 20 cm, so it has a surface area of 0.4096 m^2 and a bulk volume of 0.08192 m^3. The actual heights of the chamber at its four corners above the peat surface were recorded and used to calculate the headspace volume. A battery powered fan mixed the air inside the chamber during measurements. Air was cycled between the closed chamber and the portable Infrared Gas Analyzer (IRGA) using two plastic tubes. CO_2 and CH_4 concentrations were recorded over a four-minute period and the data was stored by the IRGA. At the end of each day of sampling, data were transferred from the IRGA to a laptop and backed up on USB storage.

At each location, the ambient air temperature at the surface of the stockpile, as well as the peat temperature at varying depths in the stockpile were taken using a one-meter-long temperature probe. The temperature probe was inserted into the peat at proximity to the place where the Trace Gas Fluxes were taken. The temperature probe was pushed in at a 10 cm increment between the 10 cm and 100 cm depth, so a total of ten peat temperatures were measured for each location. Moisture measurements were unable to be taken because of a malfunctioning device.

Table 1: Summary Table of data collection during fieldwork

Sampling and Measurement Strategies		
Company	Berger Peatlands Ltd.	Premier Tech Inc
Stockpile Type	Covered with white plastic tarps	Exposed under open air
Factors	Aspect, Peat Quality, Status of Hole	Aspect, Peat Quality, Position
Data Collected	Trace Gases Flux, Temperature	Trace Gases Flux, Temperature
Number of data collected	10 Stockpiles 112 measurements	9 Stockpiles 120 measurements

3.4 Data Analysis and Chamber Flux Calculations

The rate of change in gas concentration (ppm/min) was determined from the raw CO_2 and CH_4 data measurements. All resulting slopes with r^2 values less than 0.8 were discarded. The gas flux was then determined in g CO_2 $m^{-2}day^{-1}$ for CO_2 and in mg CH_4 $m^{-2}day^{-1}$ for CH_4 using

$$F1 = \frac{f_x \cdot \left(\frac{V_c}{R(273 + T_a)}\right) \cdot n \cdot t}{S}$$

where f_x is the slope in the gas concentration (ppm 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 the 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).

The resulting flux was converted to mass of C m^{-2} day^{-1} using

$$F2 = \frac{F1}{1000} * c$$

where c is the ratio of molecular weight of C to the gas (CO_2 = 0.273 and CH_4 = 0.75). CO_2 fluxes are in g C m^{-2} day^{-1} and CH_4 fluxes in mg C m^{-2} day^{-1}.

All statistical analyses and figures were done using the SPSS software package (Raynald's SPSS Tools, 2021). A one-way ANOVA of CO_2 and CH_4 fluxes between different physical parameters was performed for the exposed stockpiles from Premier Tech. The correlation between different types of trace gas flux was also explored using T-test. Linear regressions and interaction test were performed between temperature measurements and the weight of carbon that was released through CO_2 and CH_4 fluxes. To determine how trace gas emissions are affected by aspect, peat quality, temperature, and height on the stockpile on the gas emissions, they are tested against each other for significance.

Chapter 4. Results

4.1 Flux of trace gases from covered stockpiles

There are in total of 112 measurements made on stockpiles in Berger Peat Moss Ltd., which are all covered with white plastic tarps. However, two measurements were inherently flawed due to equipment malfunctioning or battery issues, thereby got excluded. Meanwhile, there are 5 data points collected on one stockpile that does not have marked grade; hence they got taken out. Afterwards, I calculated the mean values for all three trace gases measured by Li-COR for the remaining 105 measurements, which are CO_2, CH_4 and H_2O (Table 2). Due to the lack of direct measurement of volumetric soil moisture content, I explored the avenue of using water vapor flux as a proxy of moisture conditions in the peat stockpiles.

Table 2: Summary of result for Premier Tech stockpiles, standard deviation is reported in brackets.

Number of measurements	mean of CO_2 flux in g C m^{-2} d^{-1}	mean of CH_4 flux in mg C m^{-2} d^{-1}	mean of H_2O flux in mg H_2O m^{-2} d^{-1}
105	35.26 (±8.90)	59.29 (±13.24)	45.51 (±6.69)

The following section reports values according to each category of variables for all the measurements on Berger peat stockpiles, which are covered with tarps. The peat grade of N/A has too little data (n=5) to be meaningful, therefore this category is discarded during analysis that involves quality of the peat as a variable.

Table 3: Mean trace gas fluxes per status of holes

Status of Hole	Number of measurements	mean of CO_2 flux in g C m^{-2} d^{-1}	mean of CH_4 flux in mg C m^{-2} d^{-1}	mean of H_2O flux in mg H_2O m^{-2} d^{-1}
No Hole	45	0.27 (±0.30)	-0.05 (±1.00)	19.49 (±51.23)
Covered Hole	18	17.64 (±22.32)	32.46 (±39.01)	15.71 (±31.85)
Open Hole	42	80.29 (±131.59)	134.37 (±189.95)	86.15 (±76.59)

In the category of "Status of Hole", there are two kinds of "Open Hole" when we took the measurement on the stockpile. There are newly opened holes that we created by puncturing the tarp with a wooden stick to collect data on trace gas fluxes and temperature. There are also existing holes that were sealed with duct tape, and we remove the tapes to take measurements. The class of

"Covered Hole" are the already existing holes on the plastic tarp that are sealed with duct tapes prior to our investigation. However, these duct tapes do not provide a perfect zeal from time to time, as can be seen by higher CO_2 and CH_4 fluxes than measurements with no hole on the tarp.

Table 4: Mean trace gas fluxes per status of holes, open holes can be old or new

Status	**Number of measurements**	**mean of CO_2 flux in g C m^{-2} d^{-1}**	**mean of CH_4 flux in mg C m^{-2} d^{-1}**	**mean of H_2O flux in mg H_2O m^{-2} d^{-1}**
No Hole	45	0.27 (±0.45)	-0.46 (±0.15)	19.49 (±7.64)
Covered Hole	18	17.64 (±5.26)	32.46 (±9.20)	15.71 (±7.51)
Open Old Hole	19	113.54 (±40.98)	153.86 (±35.87)	64.43 (±7.83)
Open New Hole	23	52.82 (±13.86)	118.27 (±45.03)	104.08 (±20.04)

To further explore the relationship between trace gas measurements made on wide open holes, an Independent T-test is conducted between the means for CO_2, CH_4 and water vapor for Hole status of Open Hole. The result reveal that, for all measurements taken on open holes, whether an open hole is new or old does not have a significant statistical difference for flux of CH_4 ($p = 0.446$), CO_2 ($p = 0.136$) and water vapor ($p = 0.113$). The trace gas fluxes measurements of "No Hole" is not significantly different from the ones with "Covered Hole" ($p = 0.098$).

Table 5: Mean trace gas fluxes per peat grade

Peat Grade	**Number of measurements**	**mean of CO_2 flux in g C m^{-2} d^{-1}**	**mean of CH_4 flux in mg C m^{-2} d^{-1}**	**mean of H_2O flux in mg H_2O m^{-2} d^{-1}**
C5	66	23.53 (±7.43)	77.06 (±19.82)	36.40 (±6.66)
C6	39	55.10 (±20.17)	29.22 (±10.79)	60.91 (±13.85)

The result reveals that peat grade of C5 has significantly higher methane flux than C6, while C6 commonly emits more carbon dioxide than C5 (Table 5). One can also see that C6 stockpiles are a lot wetter than C5 stockpiles. I did an Independent T-test between the means of peat grade (C5 and C6) for trace gases flux from Berger stockpiles. The result show that the peat grade has no significant impact on fluxes of CO_2 flux ($p=0.135$) and H_2O ($p=0.402$) but makes a difference for CH_4 emission ($p=0.043$).

Table 6: Mean trace gas fluxes per aspect for all measurements

Aspect	Number of measurements	mean of CO_2 flux in g C m^{-2} d^{-1}	mean of CH_4 flux in mg C m^{-2} d^{-1}	mean of H_2O flux in mg H_2O m^{-2} d^{-1}
East	10	0.75 (±0.32)	25.94 (±7.43)	28.12 (±6.28)
North	53	54.49 (±16.35)	58.72 (±15.66)	42.55 (±8.86)
South	32	24.83 (±9.05)	73.79 (±33.45)	44.70 (±12.73)
West	10	1.19 (±0.91)	49.25 (±33.90)	81.16 (±32.02)

The value of trace gas fluxes by individual aspect for covered stockpiles is presented in Table 6. However, this analysis is done using all measurements and there is not a balance of status of holes in the aspect sample. There also exists a significant imbalance of sample sizes across different aspects.

To investigate how physical variables effect trace gas fluxes, a *Compare Means* function was run in SPSS for factors of peat quality, aspect and status of hole. The result show that the grade of the peat stockpile, whether it is classified as C5 or C6, makes no significant difference on quantity of trace gas emission ($p=0.231$). The aspect of measurement has no significant effect on trace gas flux neither ($p=0.092$). The status of holes, that is, whether there is no hole on the tarp, a hole covered by duct tape or a hole that is exchanging gas with the atmosphere, is making a difference ($p=0.020$). Data of trace gas fluxes collected on class "no hole" is effectively zero because of the tarp does not allow any gas to diffuse through it. The trace gas fluxes on class "covered hole" are very small, primarily due to the gas seeping through the duct taped holes on tarp as they are not perfectly sealed. The measurement of trace gas fluxes through the class "open hole" shows huge variations, but their mean values are a magnitude higher than the data collected on exposed stockpiles at Premier Tech.

A bivariate correlation test was performed in SPSS to investigate the relationship between the fluxes of the two main GHG: CO_2 and CH_4. The same analysis is also run to explore the relationships between CO_2 and water vapor, as well as between CH_4 and water vapor (Table 7).

Table 7: Correlations between trace gas flux measurements in Berger stockpiles

Trace Gases	Person correlation coefficient (r)	Level of significance (p)
CH_4 and CO_2	0.448	< 0.001
CO_2 and H_2O	0.119	0.228

CH_4 and H_2O	0.269	0.006

The Pearson's Correlation Coefficient indicates a positive correlation (r = 0.448) between fluxes of CO_2 and CH_4, and this correlation is very significant ($p < 0.001$). There is no significant correlation (p = 0.228) between the fluxes of CO_2 and water vapor. There exists a week positive correlation (r = 0.269) between fluxes of CO_2 and water vapor and this correlation is highly significant (p = 0.006).

To investigate whether trace gas fluxes would be different for measurements made on pre-existing open holes and newly created open holes, an independent T-test is run in SPSS. The result reveal that for an open hole measurement on tarped stockpiles, whether that hole is old or new has no significant impact on the fluxes of CO_2 (p=0.136), CH_4 (p=0.446) and H_2O (p=0.113).

Besides the ambient air temperature, the temperature inside the peat stockpiles was also taken 10 times at every measurement location between the 10 cm and 100 cm, with a depth increment of 10 cm each time. I calculated the average temperature across 100 cm of peat for each location. Afterwards, a regression analysis was performed between this average temperature and trace gas fluxes for measurement made on open holes. For every measurement location on the stockpile, there are trace gas fluxes measurement based on 'no hole', 'covered hole' and 'open hole' status. Nonetheless, we are only interested in 'open hole' measurements (n=44) since the other two class yield minimal numbers. The result show that there is no significant correlation between average temperature and CO_2 flux (p=0.65) and H_2O water vapor flux (p=0.77), whereas CH_4 flux decreased (r=-0.415) with average temperature of stockpiles (p=0.005).

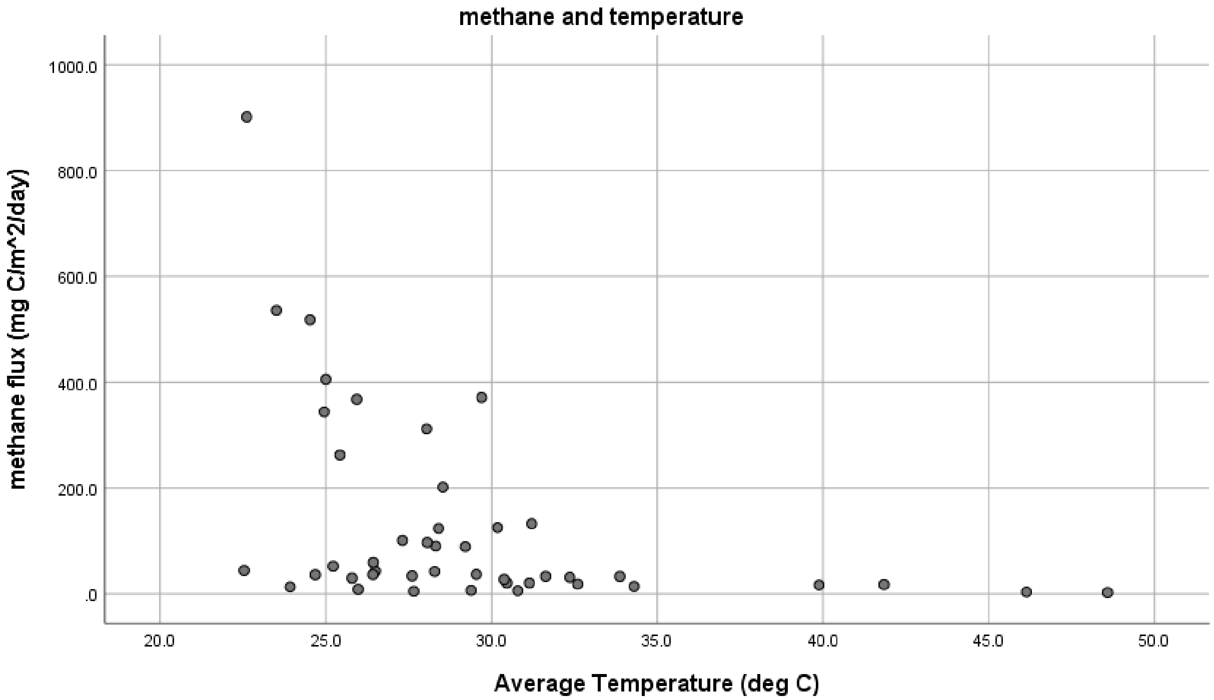

Figure 5: Temperature versus CH_4 flux of data points from open holes in Berger peat stockpiles.

Unfortunately, due to the small sample size, no clear correlation can be drawn between GHGs fluxes and these physical variables. It is recommended to collect more data to investigate the difference between peat grade on the Berger stockpiles in the future.

4.2 Flux of trace gases from exposed stockpiles

Table 8: Summary of Result for Premier Tech stockpiles

Number of measurements	mean CO_2 flux and standard deviation in g C m^{-2} d^{-1}	mean CH_4 flux and standard deviation in mg C m^{-2} d^{-1}	mean H_2O flux and standard deviation in mg H_2O m^{-2} d^{-1}
120	3.00 (± 3.4)	1.87 (±6.31)	0.11 (±0.08)

Firstly, I utilize raw, unfiltered data collected from exposed stockpiles in Premier Tech harvested peatland, with 120 measurements in total (Table 8). By plotting them on the graph, I realized that the mean values of these trace gas fluxes are largely dominated by a few data points with big measurements. Afterwards, I selected data based on R^2 bigger than 0.8 and both their CO_2 and CH_4 fluxes are within 2 standard deviations away from their mean values. This filtering process effectively got rid of all the data outliers and left us with 88 measurements as a cleaned dataset (Table 9). After preliminary analysis, I realized the water vapor flux from LiCOR is not a reliable proxy and have decided to abandon it in future analysis, detailed reasons will be found in the discussion section.

Table 9: Summary table of GHG fluxes using filtered data

Number of measurements	mean of CO_2 flux in g C m^{-2} d^{-1}	mean of CH_4 flux in mg C m^{-2} d^{-1}
88	2.88 (±2.22)	1.33 (±2.05)

The maximum and minimum values of GHG fluxes we got from using cleaned data (n=88) show much smaller variations than the original result that we got from raw dataset (n=120). These mean values decreased because a few data points with unusual large measurements were filtered out, and their standard deviations also got smaller as a result. Then I am interested to know how each individual variable plays a role in influencing GHG emission from peat stockpiles. These physical variable for Premier Tech Horticulture stockpiles includes position, aspect and peat grade (Table 10, 11, 12).

Table 10: Mean of CO_2 and CH_4 fluxes per height level for filtered data

Position	Number of measurements	mean of CO_2 flux in g C m^{-2} d^{-1}	mean of CH_4 flux in mg C m^{-2} d^{-1}
Bottom	27	1.78 (±1.10)	0.77 (±1.15)
Middle	33	3.05 (±1.98)	1.72 (±2.64)

Top	28	3.76 (±2.83)	1.42 (±1.87)

For exposed peat stockpiles managed by Premier Tech Horticulture, the position of measurements has a significant effect on CO_2 flux ($p = 0.003$), but not on CH_4 flux ($p = 0.199$). It is observed that elevated height correlates with increasing level of CO_2 emission (Table 10), this trend is consistent with the result of previous summer (Gheta, 2020). Emissions of CO_2 at the top of the stockpile is significantly different from that bottom ($p = 0.0001$) and middle ($p = 0.0001$) positions. The relationship between CO_2 flux at the top of the stockpile is stronger than at the bottom ($p < 0.001$) and at the mid levels ($p < 0.001$). On the other hand, CH_4 flux is highest at the Middle position.

Table 11: Mean of CO_2 and CH_4 fluxes per Aspect for filtered data

Aspect	**Number of measurements**	**mean of CO_2 flux in g C m^{-2} d^{-1}**	**mean of CH_4 flux in mg C m^{-2} d^{-1}**
East	22	4.10 (±2.67)	2.12 (±2.73)
North	19	3.11 (±2.30)	1.88 (±2.59)
South	27	2.50 (±1.86)	0.89 (±1.19)
West	20	1.85 (±1.36)	0.55 (±0.85)

The aspect of measurements significantly influences the flux of CO_2 ($p = 0.048$) and CH_4 ($p = 0.0029$) from exposed stockpiles. The east-facing side of stockpiles has the biggest GHG fluxes but also highest level of standard deviations, whereas the western side emitted the least amount of GHG and has the lowest level of standard deviations (Table 11).

Table 12: Mean CO_2 and CH_4 fluxes per grade for filtered data, within brackets are standard deviations

Peat Grade	**Number of measurements**	**mean of CO_2 flux in g C m^{-2} d^{-1}**	**mean of CH_4 flux in mg C m^{-2} d^{-1}**
2	22	3.68 (±2.28)	0.70 (±1.06)
3	20	3.35 (±2.36)	0.74 (±0.74)
5	20	2.66 (±2.18)	2.94 (±2.73)
EcoFlow	26	2.03 (±1.84)	1.08 (±2.20)

The peat grade plays a significant role in determining how much CO_2 ($p = 0.048$) and CH_4 ($p=0.001$) are released from the stockpile. One can observe that grade 2 peat stockpiles have the biggest CO_2 flux and smallest CH_4 flux (Table 12). The "Ecoflow" grade has the smallest CO2 emission and smallest standard deviation.

A summary of bar charts illustrating the relationship between all the aforementioned physical variables and GHG fluxes for exposed stockpiles in shown below (Figure 2).

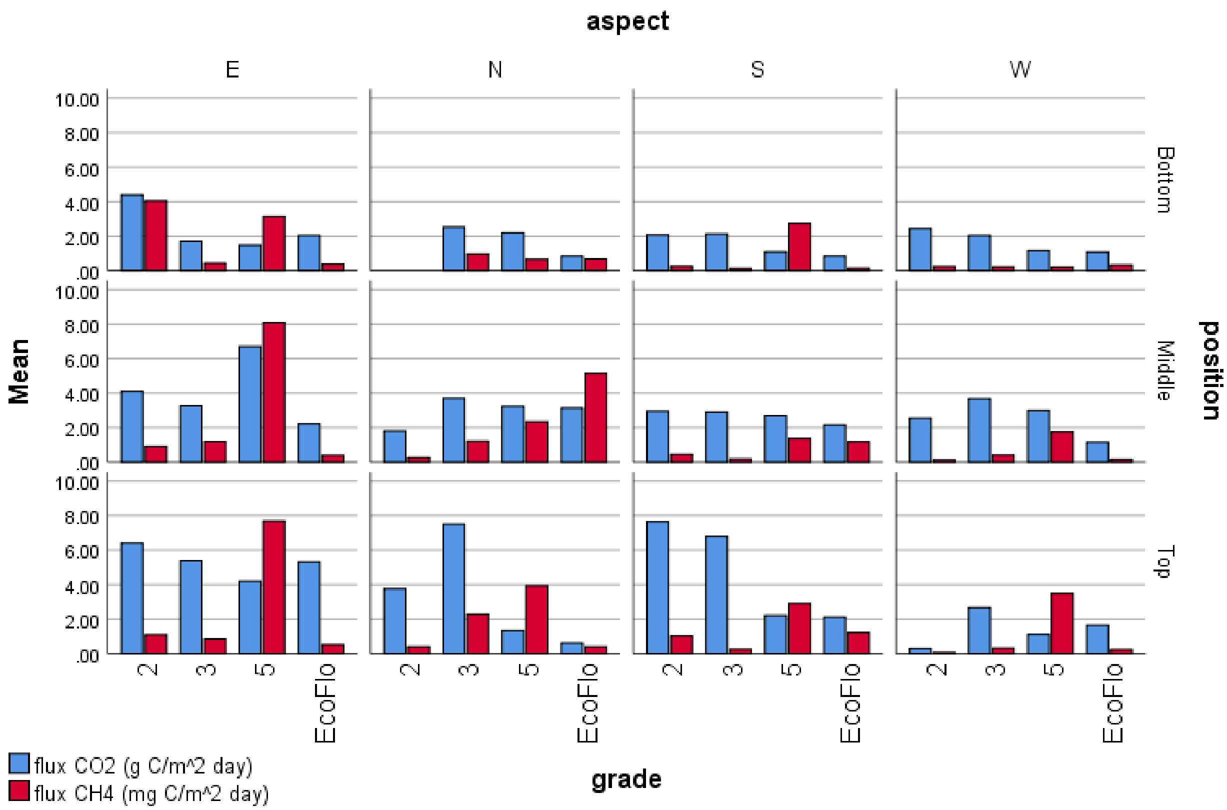

Figure 6: Bar charts for all factors on Greenhouse Gas emissions

A linear regression analysis was performed between the average temperature at each measurement location and its GHG fluxes. The results show that average temperature across 100 cm in the peat stockpile has no significant relationship with CO_2 ($p = 0.191$) and CH_4 ($p = 0.347$). In fact, I performed linear regression analysis for all peat temperature at different depths against CH_4 and CO_2, but no significant correlations was established. There seem to be no significant relationships between temperature and GHGs emissions on exposed stockpiles.

Multi-factor ANOVA is extremely useful and has been used repeatedly throughout the process of data analysis. A three-way ANOVA was performed using SPSS to determine if there is an interaction effect between three independent variables (Aspect, Position and Grade) on a continuous dependent variable (CO_2: g C m^{-2} day^{-1}). The highest measurement position and the North and East directional faces were significantly different, while the peat grade of *EcoFlo* always had the largest standard deviations.

An interaction test was conducted to determine the relationship between Position, Grade and Aspect, and a Tukey post-hoc test was also conducted to show the specific interactions. The results show that the CO_2 emissions from the East and West aspects are significantly different from each other, while other combinations are not. In addition, the Pearson's Correlation Coefficient indicates that there is no significant correlation ($p = 0.516$) between the fluxes of CO_2 and CH_4.

Table 13: Linear model and analysis of variance of linear model outputs of CH_4 and physical variables. Colons (*) denote significant interactions.

CO_2 ~ Grade*Position*Aspect		
Analysis of Variance Output	**F-value**	**P-value**
Grade	2.197	0.089
Position	9.104	0.001*
Aspect	4.576	0.004*
Aspect * Position	4.01	0.001*
Aspect * Grade	2.926	0.003*
Position * Grade	2.532	0.022
Aspect * Position * Grade	2.624	0.001*

Out all of the physical variables, peat grade is the least significant ($p = 0.089$) and position is the most significant ($p = 0.0001$). The overall interaction between aspect, position and grade on CO_2 flux is highly significant ($p = 0.001$).

Table 14: Linear model and analysis of variance of linear model outputs of CO_2 and physical variables. Colons (*) denote significant interactions.

CH_4 ~ Grade*Position*Aspect		
Analysis of Variance Output	**F-value**	**P-value**
Grade	10.391	0.001*
Aspect	4.550	0.008*
Position	1.468	0.242
Grade * Aspect	2.292	0.034*

Grade * Position	1.537	0.191
Aspect * Position	0.313	0.927
Grade * Aspect * Position	0.969	0.508

Grade (p=0.001) and Aspect (p=0.008) are highly significant for methane while Position is not significant, this is in contrast with CO_2 where Position is the most significant factor. The overall interaction between Aspect and Grade on CH_4 flux is significant (p = 0.034), whereas the interaction between any other variables on CH_4 flux are not significant.

Overall, these results compared well with analysis done by Gheta (2020) (Table 15). Therefore, I decided to combine my data of CO_2 measurements from the exposed stockpiles with the available data from Gheta to create a new dataset that contains 258 measurements. In order to combine two datasets of carbon emission of CO_2 together, I re-selected the measurements by discarding the data with R^2 value less than 0.65 in order to be consistent with analytical results from 2020 summer.

Table 15: Carbon emission from Greenhouse Gas fluxes in Premier Tech

Carbon from Greenhouse Gas Emissions in Premier Tech			
Researcher	**Source and year of data collection**	**mean CO_2 flux in g C m^{-2} d^{-1} and number of measurements**	**mean CH_4 flux in mg C m^{-2} d^{-1} and number of measurements**
Maria Gheta	Stockpiles (2020)	3.04 ± 8.54 (n=187)	0.3 ± 0.9 (n=34)
Kaiyuan Wang	Stockpiles (2021)	2.88 ± 2.22 (n=88)	1.33 ± 2.05 (n=88)
Laura Clark	Fields (2019-2020)	0.75 ± 1.77 (n=510)	6.64 ± 39.56 (n=337)

In terms of height for measurements, the Top position is significantly different from the Bottom and the Middle, whereas the Bottom and Middle positions are not significantly different from each other. No significant differences were found between grades of peat. In fact, Top position is coming ahead of other positions regardless of Aspects and Grade, except for EcoFlo. This is probably due to the insufficient data gathered from this specific category of peat, since our dataset only has measurements taken on three Ecoflo stockpiles from 2021 summer. The effect of Aspect (p = 0.004) and Position (p < 0.001) on CO_2 flux is highly significant, but not Grade (p =

0.089). The overall interaction between Aspect, Position and Grade on CO_2 flux is also highly significant ($p = 0.023$).

Chapter 5. Discussion

In Berger Peat Moss Ltd., peat stockpiles that are covered with plastic tarps behave quite differently from the exposed stockpile on Premier Tech field. There is limited number of measurements from Berger peat field (n=112) and quickly becomes insufficient to explore different sub-categories. Physical factors like aspect of stockpiles, quality grade of peat, and old or newly created holes do not seem to affect the emissions of greenhouse gases significantly. The atmospheric GHG exchange of peat stockpiles at Berger is significantly different from that of Premier Tech. Besides the effectiveness of the plastic tarp in blocking GHG exchange between the peat and the air, no definitive or robust conclusion were reached.

Water vapor fluxes data from Berger stockpile does not seem to show any trend. It is concluded that it is not meaningful to further explore this avenue of analysis since it cannot represent the moisture conditions in the deeper peat column, that is, the volumetric water content. Whether it rained or not would not have a direct effect on covered stockpiles, which will be further explored in the discussion section. I strongly recommend abandoning use water vapor measurement since it is not a reliable proxy of moisture conditions in peat stockpiles.

For Premier Tech stockpiles, the most significant physical parameter in determining GHG emissions is height, and the top position yields the highest flux measurements. A measurement in the peat stockpiles mostly reflect GHG fluxes from the underlying peat, so higher position means a greater mass of peat contributing to the gas flux. If we assume the decomposition per unit mass is the same, then the more peat there is (e.g. height) the greater GHG flux. Moreover, east-facing side of stockpiles have much higher CO_2 and CH_4 than any other sides. This might be explained by the translocation of wind effect, in which wind coming from the West enriched the amount of CO_2 measured from the East-facing side on stockpiles. A more plausible cause is that the East-facing side of stockpiles are more soaked with rainwater during the precipitation event that happened on August 23rd because the frontal system would have the rain blowing from the East. Therefore, the higher moisture level brings up the microbial activities in the peat and more decomposition, which subsequently release more CO_2 on the East aspect of stockpiles.

Out of the 24 measurements with particularly high CH_4 emission (higher than 2 mg C/ m^2 day), 16 of them (66.67% of this sub-dataset) were taken on 2 stockpiles on August 27th. It was the last fieldwork day that we took measurements, and it has the lowest temperatures (Max, Min, Mean) for the 5 consecutive days we spent on taking measurements from the Premier Tech stockpiles. Interestingly, the CO_2 emission on August 27th is not significantly different from that from previous dates, which is in contrast with methane. According to the field notebook, August 27th was particularly windy, and several measurements have to be re-taken or discarded due to the fluctuating Trace Gas readings. Data from a nearby weather station (ID = 7056616, Environment Canada) records strong winds and a significant reduction in air temperature on August 27th, which confirms with our observation.

The temperature readings from both study site show that the peat stockpiles mostly reflect ambient air temperature of the day. Temperature is widely documented to be a driver of CO_2 production (Hogg et al 1992; Lafleur et al 2005); however, average temperature exerts little to no influence over our measured CO_2 flux for both covered and exposed stockpiles. It is also worth noting that there may be a lagging effect in temperature, as the surface layer of peat is porous and insulating. The recorded temperature of the peat stockpiles sometimes does not reflect the ambient air temperature, and this effect varies with depth and water content. It is also dependent on the time of the day we took the measurements, such that a morning measurement of gas fluxes and temperature will be much different from an afternoon measurement at the same locality. There were several days that we took the temperature measurement after one rainy day, or it rained in the night before. The air temperature was climbing up as the sun gets higher and higher, but the temperature reading beneath the surface 10-20 cm is much lower than ambient air temperature. This can be explained by the high heat capacity of water, and rainwater tends to mitigate the effect of the low albedo of peat. It is very difficult to separate the confounding affects of soil water content and temperature, particularly for methane as it effects both production and oxidation.

In addition, Maria Gheta's data from 2020 summer could join with 2021 summer's data to form a combined dataset for Premier Tech stockpiles (n=258). This is because the analytical results of both years' datasets were tested to be statistically similar to each other. With the combined dataset, the data analysis yield very similar results and the basically the same conclusion can be reached: the top position on exposed stockpiles emit the largest amount of GHG, and that both CH_4 and CO_2 measurements are dominated by a few large data points, indicating the presence of hotspots for microbial activities and high decomposition in the peat stockpile.

There are major sources of error and uncertainties in this study. One source of error is the disturbance of the surface layer of peat caused by the movement of personnel and instruments during measurement. This stockpile's surface layer is subject to strong wind action and intense evaporation under the sun, which all tend to diminish their original structure and physical properties. Premier Tech and Berger have totally different codes for peat grade in their working sites. The peat grade is subjectively determined with the degree of humification on the von Post scale was determined in the field of both companies (Petrone et al 2008).

Methane production in stockpiles is highly localized, and some of it will get oxidized into CO_2 before making its way up through the peat to reach the surface of stockpiles. Methane is a gas with low diffusivity, therefore certain 'hotspot' sites for methane production can obscure the dataset and seem to reveal two separate populations. Methane is usually produced where there is a wet chunk of peat inside the stockpile. Since stockpiles are composed of harrowed, harvested peat of 35-55% volumetric water content (Cleary, 2003), and is then further dried as it is stockpiled, very little moisture is retained in the stockpiles. Likely any moisture that is present, perhaps deeper in the stockpile, is getting oxidized into CO_2 before ever reaching the surface of the stockpile. As an attempt to resolve the issue of the broken moisture probe sensor, the water vapor flux data from LiCOR were retrieved and compiled for each measurement of trace gas flux. This comes with the intention to explore the potential of using water vapor fluxes collected at the stockpile surface as a proxy for the volumetric soil moisture content of peat deeper inside. Water vapor is a relatively diffusive gas and the LiCOR might be able to capture the moisture signal from the deep column of peat reaching the surface of the stockpile.

However, preliminary analysis of water vapor flux did not yield significant result, therefore this line of investigation is not pursued since this has proven to be a futile exercise. Water vapor flux density is decoupled from CO_2 and CH_4 fluxes and seems to be independent of any variations in physical parameters. On the other hand, the positive or negative fluxes of water vapor seem to be largely dependent on the ambient air humidity. The mean values of water vapor flux according to each dependent variable were put in the tables for future reference and comparison. However, it would not be meaningful to further explore this dataset in the future since direct measurement of volumetric soil moisture content across different depths in the peat stockpile from moisture probe would be a lot more useful.

There is hypothesized to be a zone of enriched greenhouse gas beneath the plastic tarp and on top of the underlying peat without much chance to diffusing out. Therefore, the action of creating holes on tarped stockpiles would lead to an exodus of trace gases were stored under the non-diffusive tarp. This hypothesis is tested by comparing the mean fluxes of trace gases from open holes on covered Berger stockpiles and exposed Premier tech stockpiles. Unsurprisingly, the open holes on covered stockpiles released a lot more CO_2 and CH_4 than uncovered stockpiles on average (Table 16). In the meantime, it was rather unexpected to see the water vapor flux from opened holes on covered stockpiles to be smaller than that of the exposed stockpiles (Table 16). However, this really does not mean much since water vapor has been proved to not be a flawed proxy for the real moisture conditions deep inside the peat stockpile. It is possible that exposed stockpiles were able to absorb some rainwater from precipitation events, and slowly releasing them into the atmosphere; whereas the covered stockpile could retain water because the tarp effectively hinders evaporation, but the source of moisture is never replenished because rainfall could not penetrate through the plastic tarp.

Table 16: Comparison of trace gas flux between exposed stockpiles and covered stockpiles with open hole

Stockpile Type	**Number of measurements**	**mean of CO_2 flux in g C m^{-2} d^{-1}**	**mean of CH_4 flux in mg C m^{-2} d^{-1}**	**mean of H_2O flux in mg H_2O m^{-2} d^{-1}**
Covered (open hole)	42	80.26 (±128.50)	128.84 (±187.24)	85.18 (±75.5)
Exposed	88	2.88 (±2.22)	1.33 (±2.05)	114.9 (±77.98)

6. Summary and Conclusion

For exposed peat stockpiles managed by Premier Tech Horticulture, GHG exchange is primarily controlled by two physical factors – position and aspect. On the other hand, the quality of harvested peat, noted by grade, has little to new effect on GHG fluxes. Emissions of CO_2 and CH_4 from stockpiles increased with height on the stockpile increased, this effect might be attributed to the mass of peat is lesser at the top, allowing more oxygen for decomposition. CH_4 emissions from these stockpiles were extremely small, likely due to their lack of moisture and the oxidation of deeper generated methane into CO_2. According to Gheta (2020) and my result, the CO_2 flux area-weighted mean was 20 times larger than the only other empirical study on peat stockpiles. The reason for this huge gap in data can be attributed to the fact that our projects were carried out in the field, while the other stockpile study mainly relies on lab conditions.

Berger Peat Moss Ltd cover their peat stockpiles with white, plastic tarps aiming at reducing peat decomposition and avoid mass loss. Physical parameters like position and aspect of measurement have no significant influence on the quantity of CO_2, CH_4 and H_2O fluxes. No robust conclusions can be drawn with regards to GHG emissions between newly created holes or opened existing holes on tarped stockpiles due to small sampling size in our study. No significant relationships were found between temperature measurements and trace gas fluxes, and there seem to be no direct correlation between temperature and decomposition in peat stockpiles

No statistical analysis can be performed to explore the relationship between GHG emissions and moisture regimes of peat stockpiles due to the equipment malfunctioning. Further research should be conducted to draw indisputable conclusions with regards to CH_4 flux from stockpiles. Whether the greenhouse gas emission exhibits a diurnal pattern could not be determined, but worth further exploration in the future.

Our study under-sampled the top level of the peat stockpiles due to material restrictions, which caused large variance in our results for this height level. Since most CO_2 is being diffused through the top of the stockpile, more sampling sites at this level would be beneficial in better understanding CO_2 fluxes of stockpiles. Further research should also be conducted to better understand the prevalence of hot spots in peat stockpiles and what factors determine their occurrence. This study suggests that peat stockpiles are not negligeable in carbon flux budgets of exploited peatlands and must be further studied to better understand their impact on the peat extraction sites' greenhouse gas emissions.

Scope for future work:

We did not test the leakage of gas from the ground around the tarped stockpile, it is recommended to test this in future fieldworks, as CO_2 might diffuse underground and eventually make its way to the atmosphere. Another area for future work is to measure moisture content and test its relationship with CH_4 emissions from the stockpiles. Using water vapor measurement from LiCOR as a proxy of moisture condition in the peat stockpile is insufficient and prone to ambient air humidity. LI-COR instrument can be hyper-sensitive to environmental conditions and physical variables, which makes it susceptible to disturbance during fieldwork. For instance, putting weight or exerting slight pressure on the LiCOR container would mess up the measurements, which can be detected by it showing abnormal level of ambient trace gases. This problem was encountered a couple of times, and we either had to wait for 30 - 40 minutes for it to recover or directly restart the instrument. There is no solution by now except being careful with it.

A moisture probe senor of at least 1 meter in length, such as a long stem compost moisture-meter is required for next field season. The measurement of the volumetric water content of peat in the stockpile would allow further statistical analysis and explore the relationship between moisture condition and greenhouse gas production. It is recommended to have two set of this instrument just in case one is malfunctions or taking multiple measurements of moisture at different locations in the stockpile. It is known that the spatial heterogeneity of the soil moisture content have an impact on surface flux densities and near-surface meteorology (Ronda et al 2002). Making multiple measurements of soil moisture in the peat stockpile will help us find the locations and zones for high volumetric water content, which are potential hotspots for microbial activities and production of greenhouse gases.

Due to difficulties in transporting the equipments to the crest of the peat stockpile, no trace gas flux and temperature measurements were taken on the side that is directly facing upwards. This is an area for further investigation next year, the easiest solution would be to have portable longer tubes that connect the LiCOR box and the steel gas chamber. This report has effectively demonstrated that the top positions of stockpiles emit the highest level of greenhouse gases, as well as having the highest temperature for exposed stockpiles. In addition, it would be ideal to have continuous instead of instantaneous temperature measurements, since it might be able to show a time lapse effect between moisture conditions and changes in temperature.

However, climbing to the top of exposed stockpiles will be physically demanding and tricky because the peat tend to be very porous and loose in texture, especially on top of stockpiles because of dryness. One would easily sink into the peat under one's own body weight while climbing up while facing the risk of contaminating the steel gas chamber and plastic tubes with small peat particles, which has happened before. In the meantime, climbing up the stockpiles, even with the aid of the ladder, tends to cause disturbance of the surface peat and lead to collapse and little avalanche of the top layer of peat.

On the Berger site with covered stockpiles, climbing on top of the tarped surface would press against the underlaying peat, possibly leading to more greenhouse gas emission. In addition, the emplacement of the portable ladder has shown to damage the plastic tarp on covered stockpiles with its metal sharp edges. It is possible to reach the top of covered stockpiles with taller ladder and properly treat the surface of these ladders, wrapping them with a buffer material that could prevent the sharp edges od the ladder to tear the tarp.

Future data collection will greatly benefit from visiting the fields prior to fieldwork season and design a safe and detailed fieldwork protocols and improved methodologies based on this report. The fact that Maria Gheta and Kaiyuan Wang reached the same conclusions in two consecutive years using different equipments regarding greenhouse gas fluxes on Premier Tech stockpiles cross-validates each other's results. It is recommended to build upon our existing observations and conclusions to further confirm our hypothesis and theories in the incoming 2022 field season, whereby enhancing the scientific rigour of our research.

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