2011

Open top chambers and infrared lamps : a comparison of heating efficacy and CO_2/CH_4 dynamics in a Lake Superior coastal peatland

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Recommended Citation

Johnson, Christopher P., "Open top chambers and infrared lamps : a comparison of heating efficacy and CO_2/CH_4 dynamics in a Lake Superior coastal peatland", Master's Thesis, Michigan Technological University, 2011.
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OPEN TOP CHAMBERS AND INFRARED LAMPS: A COMPARISON OF HEATING EFFICACY AND CO_2/CH_4 DYNAMICS IN A LAKE SUPERIOR COASTAL PEATLAND

By
Christopher P. Johnson

A THESIS

Submitted in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

(Forest Ecology and Management)

MICHIGAN TECHNOLOGICAL UNIVERSITY
2011

The thesis, “Open Top Chambers and Infrared Lamps: A Comparison of Heating Efficacy and CO_2/CH_4 Dynamics in a Lake Superior Coastal Peatland,” is hereby approved in partial fulfillment of the requirements for the Degree of MASTER OF SCIENCE IN FOREST ECOLOGY AND MANAGEMENT.

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PREFACE

The journal article which is included as the main body of this manuscript was written by Christopher Johnson. The creation of figures and tables was done by Johnson, as well as the statistics for temperature data. Johnson collected and processed all data.

R.A. Chimner provided the gas flux statistics and editing assistance. Chimner was the PI on the grant which made this research possible.

T.G. Pypker offered valuable insight into micromet theory and instrumentation, and provided editing assistance.

J.A. Hribljan was essential in the construction of the Pequaming research site as well as the development of other infrastructure. Hribljan also provided much of the basic training with gas sampling, methane analysis, and micromet setup.

ACKNOWLEDGEMENTS

I would like to thank my advisors at MTU, Drs. Rod Chimner and Tom Pypker for guiding me through this crazy process and teaching me along the way, as well as for providing steady funding. Your help and friendship will always be remembered.

Thank you to my fellow peatlanders from MTU: Jim Bess, Laura Kangas, Drew Ballantyne, Margus Paesalu, Arvo Aljaste, and most especially John Hribljan. John’s dedication to the project and eye for detail has inspired me.

I would like to thank Dr. Harri Vasander from the University of Helsinki for mentoring me during my time there. I learned a tremendous amount about peatlands and Finland in general from you. You are one of the most inspiring professors I have ever known.

Thank you to Dr. Noel Urban for serving on my committee.

Thank you to Dr. Evan Kane for all of your guidance. You helped a great deal.

I would like to thank the Swedish University of Agricultural Sciences and the Euroforester program for hosting me as a visiting student. I learned a great deal about European forest policy and ecology.

Thank you to the ATLANTIS program students and organizers. Everyone helped to make this happen.

I can say that there was one person who is single-handedly responsible for me being at the place I am now – Dr. Bryant Browne. Dr. Browne (now deceased) inspired me to become a scientist through his teachings of the chemical and physical interactions between water, soil, and wetlands. His demanding, yet rewarding style of teaching hooked me. Working alongside him in the field and lab taught me a lot about what I wanted to do with my life.

I owe this thesis most of all to Tamara Baker and Kessey. You were there for me throughout this 2.5 year process of moving around the world and working long days. Your commitment and perseverance can never be repaid.

ABSTRACT

Experimental warming provides a method to determine how an ecosystem will respond to increased temperatures. Northern peatland ecosystems, sensitive to changing climates, provide an excellent setting for experimental warming. Storing great quantities of carbon, northern peatlands play a critical role in regulating global temperatures. Two of the most common methods of experimental warming include open top chambers (OTCs) and infrared (IR) lamps. These warming systems have been used in many ecosystems throughout the world, yet their efficacy to create a warmer environment is variable and has not been widely studied. To date, there has not been a direct, experimentally controlled comparison of OTCs and IR lamps. As a result, a factorial study was implemented to compare the warming efficacy of OTCs and IR lamps and to examine the resulting carbon dioxide (CO_2) and methane (CH_4) flux rates in a Lake Superior peatland.

IR lamps warmed the ecosystem on average by 1-2 ^{o}C, with the majority of warming occurring during nighttime hours. OTC's did not provide any long-term warming above control plots, which is contrary to similar OTC studies at high latitudes. By investigating diurnal heating patterns and micrometeorological variables, we were able to conclude that OTCs were not achieving strong daytime heating peaks and were often cooler than control plots during nighttime hours. Temperate day-length, cloudy and humid conditions, and latent heat loss were factors that inhibited OTC warming. There were no changes in CO_2 flux between warming treatments in lawn plots. Gross ecosystem production was significantly greater in IR lamp-hummock plots, while ecosystem respiration was not affected. CH_4 flux was not significantly affected by warming treatment. Minimal daytime heating differences, high ambient temperatures, decay resistant substrate, as well as other factors suppressed significant gas flux responses from warming treatments.

THESIS INTRODUCTION

This thesis was written to provide readers with detailed information about my Master’s research work. The contents of this document include a journal article which I have written and will submit for publication soon after this thesis is defended. In addition to the journal article, this document includes all of the sections required by the Michigan Tech Graduate School as well as a “Thesis Introduction” and “Thesis Conclusion”. The Thesis Introduction and Conclusion are aimed to provide readers with the following information: a timeline of the two and a half years that I have been enrolled at Michigan Technological University (MTU), a background into the project, some basic peatland ecology concepts that will aid in comprehending the main body of the thesis, and a conclusion which wraps everything together and provides final thoughts about the study. The journal article, or main body of the document, is written in a traditional peer-reviewed format and includes the following sections: Journal Introduction, Methods, Results, and Discussion.

Timeline

I began my Masters work in March 2009 after leaving the Dissolved Gas Lab at the University of Wisconsin-Stevens Point. After arriving at MTU, I spent most of my time during the first 1.5 months constructing infrastructure for the Seney and Pequaming projects. Gas flux collars, open top chambers (OTCs), carbon dioxide (CO_2) chambers, and methane (CH_4) chambers were all constructed with the help of John Hribljan. In early May 2009 an intensive two-week site-construction campaign was performed at Seney. By June 2009 I was focused mainly on Pequaming, my research site, finishing the installation and programming of an array of micrometeorological equipment and constructing CH_4 chambers. By July 2009 nearly everything was up and running smoothly and I was performing regular field duties that included weekly CO_2 sampling, bi-weekly CH_4 sampling, and data logger management. Lab and office work included CH_4 analysis on a gas chromatograph and data processing. Data collection and analysis were performed, year round, although less often in the winter months, until August 2010.

In August 2010 I moved to Helsinki, Finland on exchange as part of the ATLANTIS program to pursue a trans-Atlantic Masters degree in forest resources. The ATLANTIS exchange agreement is partnered by MTU and North Carolina State University in the US and the University of Helsinki (UH) and the Swedish University of Agricultural Sciences (SLU) in the European Union (EU). US students spend one semester at each EU institution and EU students spend two semesters at one US institution. Students who successfully complete the degree requirements are awarded two MS degrees: one from their US home university and one from an EU university of choice. UH was my chosen degree awarding university in the EU. While there, I worked with my advisor Dr. Harri Vasander in meeting my degree requirements for an MScFB in peatland ecology. I moved to southern Sweden in January 2011 to study in the Euroforester program at SLU. I returned to the US in June 2011. The summer of 2011 has been spent finishing my thesis and publication work.

Background to the Project

This project began with a grant proposal in 2007 from Dr. Chimner to the United States Department of Energy National Institute for Climate Change Research. The original project was to be conducted entirely in the Seney National Wildlife Refuge (SNWR) near Seney, Michigan. The goal of the project was to document and compare carbon dynamics under different temperature and hydrologic regimes. The hydrologic regime at SNWR has been modified since the 1930's using dykes and other water control structures, providing a unique place to study long-term hydrologic changes in peatlands. Temperature enhancements were to be conducted using both open top chambers (OTCs) and infrared (IR) lamps. However, the logistics of establishing IR lamps were too costly due to the requirement of being in close proximity to a large power supply. This prompted the start-up of the Pequaming research site – home to the study which is detailed in this thesis – due to its proximity to a large power source and similarity in peatland composition to the SNWR sites.

Peatland Characteristics

In simplest terms, a peatland is an ecosystem with a substrate consisting of partially decayed organic matter (Charman 2002; Wieder et al. 2006). The partially decomposed organic matter which defines peatlands accumulates because the rate of carbon accumulation is greater than the rate of carbon decay and export. One common factor which is shared by all peatlands throughout the world is a limited rate of decomposition (Moore and Basiliko 2006). Most peatlands are also characterized by existing cool to cold (except tropical peatlands) and humid climates (Wieder et al. 2006). Peatland definitions are notoriously varied and have many regionally defined terms (Rydin and Jeglum 2006). One of the most commonly used alternatives for the term *peatland* is *mire* (Vitt 2006). Within this thesis, the two are used synonymously.

Peatlands exist in many forms but the most common peatland type in the world is the northern peatland of the subarctic, boreal, and hemiboreal regions (Rydin and Jeglum 2006). This type comprises more than 80% of the world's peatlands, nearly 3.5 million km^2 (Vitt 2006). Peatlands exist in other areas too. Tropical peatlands account for 15-20% of the earth's total peatland area according to Rydin and Jeglum (2006). This peatland type can be found throughout the world's tropical regions from Central and South America, to Africa, Asia, and the Pacific Islands (Rydin and Jeglum 2006).

Northern peatlands are commonly classified into two main categories based on their nutrient status and/or their connection to groundwater (e.g. Charman 2002). Peatlands that are influenced by groundwater, *geogenous* peatlands, are called *fens* and those that are not connected with the groundwater, *ombrogenous* peatlands, are called *bogs* (Rydin and Jeglum 2006). Fens can be further divided based on their nutrient status that is measured based on the pH of their porewater. Fens with a pH of 5 or greater are labeled rich fens; fens with a pH of 4 to 5 are called poor fens. Bogs have a low pH of less than 4.5. The vegetation of a peatland is dependent on nutrient status as well as other factors

(Rydin and Jeglum 2006). The pH of a peatland can be determined quite reliably based on the current vegetation community. The most characteristic aspect of a rich fen is its high content of sedges and sedge peat (Rydin and Jeglum 2006). The floral communities of bogs are dominated by acidophilic (acid-loving) species (Vitt 2006). Some of the most common acidophilic species include the following: cotton grass (a sedge), pitcher plant, sundew, leather leaf, sweet gale, black spruce, bog rosemary, and cranberry. Poor fens have vegetational aspects from bogs and fens (Rydin and Jeglum 2006; Vitt 2006).

Microtopography is a common feature of northern peatlands and refers to high (*hummocks*) and low (*hollows* or *pools*) areas that can occur very close to each other (<1 meter; Rydin and Jeglum 2006). An intermediate flat location, called a *lawn*, is used extensively in this thesis. Hummocks and hollows have many important biochemical differences. Hummocks (20-50 cm above the water table) are usually aerobic, support trees and shrubs, have a relatively high rate of aerobic CO_2 respiration, and have little to no CH_4 efflux (Rydin and Jeglum 2006). Hollows are usually saturated and anaerobic, support sedges and aquatic vascular plants, have little aerobic respiration, and may have high rates of CH_4 efflux (Rydin and Jeglum 2006). Lawns (5-20 cm above the water table) may have some characteristics of both hummocks and hollows, but generally support a sedge community and may be nearly saturated.

Carbon Storage and Gas Exchange

Peatlands are distinct from other ecosystems in their ability to store great amounts of biomass. Global estimates of peatland carbon storage vary widely, but common estimates range from around 250 Pg to slightly less than 500 Pg (1 petagram = 1 trillion kilograms; Vasander and Kettunen 2006). This represents 13 to 30% of the total terrestrial carbon on earth (Rydin and Jeglum 2006; Vasander and Kettunen 2006), yet peatlands cover only about 3% of the land surface (Rydin and Jeglum 2006). This large amount of stored carbon, found in just a small amount of the earth’s surface, is one of the reasons why peatlands are so important in regulating global climate.

Photosynthesis fixes atmospheric CO_2 into plant tissues via net primary production (NPP; Wieder 2006). NPP must exceed decay and export rates over a long time-span in order for a peatland to grow or maintain its carbon load (Wieder 2006). NPP is dependent on temperature, nutrient status, and water availability, but varies widely between *Sphagnum*, trees, sedges, and shrubs (Wieder 2006). *Sphagnum* moss is the most important peat-forming plant group in bogs and poor fens (Wieder 2006), while the peat of rich fens is often sedge dominated (Rydin and Jeglum 2006).

Decomposition rates are very low in poor fen and bog ecosystems (Rydin and Jeglum 2006). This is due to a number of factors including a low pH, low temperature, and a decay-resistant substrate including *Sphagnum* and ericaceous shrubs (Moore and Basiliko 2006). Carbon can exit a peatland in a number of ways. Heterotrophic microbial respiration creates the majority of CO_2 which leaves the system and is dependent on soil temperature, soil humidity and substrate quality (Moore and Basiliko 2006). Autotrophic plant respiration is a product of plant-related maintenance processes (Vasander and Kettunen 2006). Dissolved organic carbon (DOC) can leave the system through groundwater flowpaths and is dependent upon NPP and near-surface hydraulic conditions (Vasander and Kettunen 2006) as well as temperature (Fenner et al. 2007). Carbon losses from peatlands can also be affected by natural disturbances such as fire and flooding (e.g. Charman 2002), or through anthropogenic disturbances such as forestry or peat mining (e.g. Vasander 1996). Rates of primary production are low in peatlands (Vasander and Kettunen 2006), therefore even lower rates of decomposition must be maintained for the peatland to exist.

When CO_2 flux is measured, there are three portions to the total flux: gross ecosystem production (GEP), the photosynthetic component; ecosystem respiration (ER), the sum of heterotrophic and autotrophic respiration; and net ecosystem production or exchange (NEP or NEE), the difference between GEP and ER (e.g. Sullivan et al. 2008). The term NEP is often used somewhat interchangeably in the literature with NEE, but NEP is sometimes defined to include DOC exports and losses through fire, etc… (Lovett et al. 2006). Within this thesis I will use NEE.

Methane fluxes in peatlands are dependent on anaerobic conditions (Rydin and Jeglum 2006). One of the main differences between CO_2 and CH_4 respiration is that

CH_4 is produced in the absence of oxygen (Rydin and Jeglum 2006). The methane cycle is carried out through complicated acetate or hydrogen pathways where carbon is the food source and electron acceptor, and CH_4 is the byproduct (Vasander and Kettunen 2006). The acetate pathway dominates with cool temperatures and optimal carbon sources (Vasander and Kettunen 2006). CH_4 flux is predominantly limited by substrate quality. Labile, sugar-rich sedge roots are the best source for high CH_4 flux in peatlands (Rydin and Jeglum 2006). Temperature has some control over CH_4 flux, but it is not a driving force (Vasander and Kettunen 2006). CH_4 can be consumed by methanotrophic bacteria in the presence of oxygen with CO_2 as a byproduct (Rydin and Jeglum 2006; Vasander and Kettunen 2006).

Climate Change and Experimental Warming

Peatlands consume and release the greenhouse gases (GHGs) CO_2, CH_4, and nitrous oxide (N_2O; in nitrogen-rich peatlands only). When released into the atmosphere, GHGs absorb infrared radiation, reradiating heat back to the earth, thereby raising global temperatures. Storing up to 30% of the earth's carbon, peatlands have the potential to become huge sources of GHGs to the atmosphere. The fate of increasing temperatures on carbon storage is not totally clear (Davidson and Janssens 2006), but signs of warming-induced increases in GHG efflux have already been identified. Melting permafrost caused by increased temperatures has been shown to release old, frozen peat into lakes, releasing tremendous amounts of CH_4 into the atmosphere (Walter et al. 2006). Positive feedback loops may be created with GHGs and global temperatures as seen in the permafrost/CH_4 study described by Walter et al. (2006).

Peatlands have the potential to alter atmospheric levels of CO_2 and CH_4, in either a positive or negative sense. It is also well known that temperature plays a major role in this balance and increased temperatures may act as a positive or negative feedback to peatland gas fluxes (Davidson and Janssens 2006). Experimental warming allows in-depth studies of how an ecosystem will react to increased temperatures. Reactions to increasing temperatures in northern peatlands include but are not limited to changing rates of production, decomposition, and gas exchange as well as shifts in species composition and form (Charman 2002).

Open top chambers (OTCs) and infrared (IR) lamps are just two of the many methods for experimentally raising ecosystem temperatures (Aronson and McNulty 2009). Some other methods include underground heating cables, passive nighttime warming, and closed greenhouses (Shaver et al. 2000; Rustad et al. 2001). Warming experiments are not limited to peatlands either. Many warming experiments have taken place in forests, grasslands, and tundra (Rustad et al. 2001).

OTCs function on the same basis as a greenhouse except there is an open top to minimize changes in precipitation and gas exchange. Shortwave radiation (direct from the sun) enters the OTC from the top or through the sides. After shortwave radiation strikes the soil and canopy surfaces it is emitted as longwave radiation, which is reflected off of the inside of the OTC. OTCs are relatively inexpensive and portable, but their warming efficacy is dependent upon surrounding biotic and abiotic factors (Marion et al. 1997). IR lamps emit longwave radiation directly to the canopy and soil surface. IR lamps are precise and mimic real conditions fairly well (Aronson and McNulty 2009; Kimball 2011), but they have a limited range and are expensive to operate due to their requirement for a large energy source (Aronson and McNulty 2009).

CHAPTER ONE

JOURNAL INTRODUCTION

Experimental warming provides a method to test how an ecosystem will respond to increased temperatures (Shaver et al. 2000; Aronson and McNulty 2009). The response from northern peatlands to increasing temperatures is of particular interest because they store great quantities of carbon and regulate greenhouse gases (Gorham 1991). There here have been many studies that have used experimental warming to investigate the role of temperature on the carbon balance of peatlands (e.g. Updegraff et al. 2001; Sullivan et al. 2008; Chivers et al. 2009), as well as in other ecosystems (e.g. Marchand et al. 2004; Welker et al. 2004). There is evidence that higher temperatures may cause increased carbon losses through elevated CO_2 respiration (Rustad et al. 2001), and reduced photosynthesis (Aljaste et al. 2011). Greater temperatures may also stimulate plant productivity, especially in cold regions (Rustad et al. 2001). Studying peatlands under varying temperature regimes can provide insight into the long term carbon balance under changing climatic conditions.

Changes in climate can impact the distribution of peatlands (e.g. Halsey et al. 2000). Throughout the Holocene period, fluctuations in temperature regimes have created conditions both favorable and unfavorable to peatland initiation and growth, causing spatial variation in the range of peatlands over time (Halsey et al. 2000). Today, one of the most southern ranges of *Sphagnum*-dominated peatlands resides within the Lake States of the US (Minnesota, Wisconsin, and Michigan; Heinselman 1965; Rydin and Jeglum 2006). This hemiboreal region contains approximately 60,700 km^2 of peatlands (Crum 2004), comprising about 1.8% of the total boreal and subarctic peatland area. According to the IPCC (2007), the surface air temperature of the Great Lakes region is expected to rise 3-5 ^oC by the end of the century. Because peatlands in this region already exist at the upper limit of their temperature tolerance, this area provides an outstanding place to study how global climate change may affect peatland dynamics.

With the onset of the International Tundra Experiment (ITEX) in the 1990's (Molau and Mølgaard 1996), open top chambers (OTCs) have been one of the most widely used methods for warming plots to determine the effect of higher ecosystem temperatures in high latitude regions (Aronson and McNulty 2009). Improving upon the use of closed greenhouses, OTCs provide the added benefit of allowing gas and water exchange between the ecosystem and atmosphere. OTCs have been used for studying the effects of increased temperature on gas fluxes (e.g. Welker et al. 2004; Sullivan et al. 2008; Turetsky et al. 2008; Chivers et al. 2009), vegetation and community dynamics (e.g. Welker et al. 2005; Kudernatsch et al. 2008; Gedan and Bertness 2009; Rinnan et al. 2009), and soil properties (e.g. Rinnan et al. 2009, etc...; A. Dabros et al. 2010; Carlyle et al. 2011). While OTCs are relatively inexpensive and portable, the efficacy of these units to warm the ecosystem is dependent on abiotic conditions (Aronson and McNulty 2009). Without enough solar loading OTCs will not induce warming. The amount of warming depends upon the day length, local weather conditions, ambient temperature, and soil moisture (Marion et al. 1997; Carlyle et al. 2011).

Infrared (IR) lamps provide an active method for warming ecosystem temperatures (Aronson and McNulty 2009). Unlike OTCs, IR lamps require large amounts of electricity, thereby limiting their range of use and making them expensive to operate. However, they allow the user to create a well defined warming environment (Aronson and McNulty 2009). Though used less often than OTCs, IR lamps have been successfully implemented for experimentally warming peatlands (e.g. Bridgham et al. 1999), alpine meadows (Harte et al. 1995), high latitude tundra (Marchand et al. 2004), temperate forest floors (e.g. Peterjohn et al. 1994), and other ecosystems.

Though OTCs and IR lamps have been widely used to enhance ecosystem temperatures, both in peatlands and other systems, there has not been a study that compares these methods side-by-side. Previous studies have compared the results of various warming methods, including IR lamps and OTCs, but these comparisons were between sites spanning different environmental conditions (Marion et al. 1997; Rustad et al. 2001; Oberbauer et al. 2007; Aronson and McNulty 2009). Because biotic and abiotic conditions are an important factor with experimental warming (especially OTCs), we believe a side-by-side comparison is necessary to determine the efficacy of these two warming methods. Furthermore, there is a lack of data from temperate latitude OTC studies (Aronson and McNulty 2009). Performing a warming experiment in a Lake States peatland will also provide insight into how hemiboreal peatlands respond to increased warming.

As a result, the goals of this study were to compare and contrast the warming behavior of OTCs and IR lamps and to investigate the resulting CO_2 and CH_4 flux rates in a Lake Superior peatland.

METHODS

Study Site

The study site was located in a peatland on the coast of Lake Superior in the Upper Peninsula of Michigan, USA near the town of Pequaming (46.85°N 88.37°W, Elev. 193m). The poor fen initiated approximately 2,225 years ago on a tombolo in Lake Superior and has 290 cm of sedge and *Sphagnum* peat overlying a sandy mineral soil (Boisvert 2009). The peatland is categorized as a barrier beach lagoon-tombolo (Albert et al. 2005). Hummock and lawn microtopography is prevalent (Rydin and Jeglum 2006) with vegetation typical for a poor fen (trees: *Picea mariana* and *Larix laricina*; shrubs: *Chamaedaphne calyculata*, *Ledum groenlandicum*, *Kalmia polifolia*, *Andromeda glaucophylla*, *Myrica gale, Vaccinium oxycoccos*; herbs: *Drosera rotundifolia*, *Sarracenia purpurea*; sedges: *Carex oligosperma, C. exilis, C. utriculata*; mosses: *Sphagnum fuscum, S. rubellum, S. magellanicum, S. papillosum*). The climate is cool, humid continental with long, cold winters and warm summers. The average yearly temperature is 4.5 ^{o}C with an average total precipitation of 833 mm. The average growing season temperature (May through September) is 14.8 ^{o}C and average winter temperature (December through March) is -7.5 ^{o}C (121 year average, Houghton County Airport CMX, 35 km from study site).

Experimental Design

Our site consisted of 18, 2 m by 1 m plots that were divided equally between hummocks and lawns. Plot locations were chosen based on available microtopography and randomly subdivided into 3 different treatments: OTCs, IR lamps, and controls. OTCs were constructed following International Tundra Experiment (ITEX) guidelines (Molau and Mølgaard 1996). The OTCs have a basal width of 208 cm, a side angle of 60^{o}, and 150 cm openings 58 cm above the peat surface. OTCs were constructed from transparent plexiglass with aluminum corners to increase durability. Each IR lamp (MRM-1215, Kalglo Electronics Company Ltd., Bethlehem, Pa, USA; 1,500 watts, 165 cm long) was positioned 124 cm above the plots on 1.9 cm diameter steel conduit that was anchored into the underlying sandy substrate. These lamps were similar to those used by Kimball (2005), although we did not use a control system. Control plots were not warmed and were free of overhead structures. In 2008, 60 cm square, stainless steel collars were carefully inserted about 10 cm into the peat in all plots to use as permanent collars for gas flux chambers. Collars were inserted in 2008 to give the peat surface many months to equilibrate. Elevated boardwalks and planks allowed access to all plots. Warming occurred in three different periods: 2008 from June to November (initiation phase, data not presented); 2009 from May to December; and 2010 from April to November.

Micrometeorology

The study area was instrumented with one air temperature/relative humidity sensor (CS-215, Campbell-Scientific Inc., Logan, UT, USA; 183 cm), one tipping rain gauge (TE525WS, Texas Instruments, Dallas, TX, USA; 100 cm), one pyranometer (LI200X, LI-COR, Lincoln, NE, USA; 200 cm), and one anemometer (RM Young Wind Sentry, Campbell-Scientific Inc.; 215 cm). Within each plot, a thermocouple (Type-T copper constantan, Campbell-Scientific Inc.) was installed 5 cm below the peat surface; all thermocouples were wired to a multiplexor (AM25T, Campbell-Scientific Inc). Three infrared radiometers (SI-111, Apogee Instruments Inc., Logan, UT, USA) were positioned 65 cm above the peat surface at a 10^{o} angle and offset 11.4 cm to capture a 0.23 m^2 area in the center of the plots while avoiding measurement of the steel collars. Each of the three infrared radiometers was positioned above one of the three heating treatments. One air temperature/relative humidity sensor (CS-215, Campbell-Scientific Inc.) was moved throughout the site and positioned 15 cm above the peat surface to use in comparison to the matching air temperature/relative humidity sensor which was positioned 183 cm above the peat surface. All sensors and the multiplexor were wired to a datalogger (CR1000, Campbell-Scientific Inc.) and measured every minute. Radiometer data were recorded every one minute, while other measurements were recorded over 20 minute averages. Soil temperature profiles (6.5 cm, 24.4 cm, and 41.6 cm) were measured in all plots in 2010 using multi-level thermocouples and measured every 20 or 60 minutes (I-buttons, Maxim Integrated Products, Sunnyvale, CA, USA). Lastly, water table levels were measured in a 1.5 m long, 10 cm diameter PVC well with a water table logger (Levellogger Junior, Solinst, Georgetown, Ontario) and a barometric pressure logger (Barrologger Gold, Solinst, Georgetown, Ontario).

Canopy Moisture

Saturated canopy conditions were predicted using the concept of a psychrometer (Campbell and Norman 1998). A psychrometer can be used to calculate vapor pressure based on the temperature difference of a wetbulb thermometer and a drybulb thermometer (Equation 1). In our calculation we used the infrared canopy temperature (as described above; SI-111) in place of the wetbulb temperature and we used the site-level air temperature (as described above; CS-215) for the drybulb temperature. The psychrometer derived vapor pressure was then plotted with the vapor pressure of the canopy surface temperature (calculated using the relative humidity of the air; CS-215, and canopy temperature; SI-111; Equation 2). If the vapor pressure of the canopy surface was equal to or greater than the vapor pressure of the wetbulb, we therefore assume that the canopy is saturated.

Carbon Dioxide Measurements

Carbon dioxide (CO_2) flux from the plots was measured in 2009 (n=19) and 2010 (n=14) during the snow-free season using a closed-system chamber and infrared gas analyzer (IRGA; EGM-4, PP Systems, Amesbury, Massachusetts, USA; e.g. Sullivan et al. 2008). Our chamber (60 cm x 60 cm x 60 cm) was built with 3 mm thick clear acrylic attached to aluminum edges and included two small fans to continuously mix the air. Weather sealing along the bottom edge ensured a gas-tight fit when placed onto the collars. A small hole in the top of the chamber was created to minimize pressure effects (Davidson et al. 2002). All 18 plots were measured during the same day between 10:00 and 15:00 EST during sunny and calm conditions to minimize weather effects. Net ecosystem exchange (NEE) was measured over a two minute interval after placement of the chamber onto the collar and time for equilibration had passed. The flux rate was calculated by the IRGA computer using the quadratic slope of the change in CO_2 over time. The chamber was well flushed before the next measurement. Ecosystem respiration (ER) was determined following the NEE measurement by covering the chamber with an opaque cloth which stopped photosynthesis. Gross ecosystem production (GEP) was calculated by subtracting ER from NEE.

Methane Measurements

Methane (CH_4) flux rates from the plots were determined in 2009 (n=7) and 2010 (n=9) on calm days throughout the snow-free season. Opaque chambers (60 cm x 60 cm x 30 cm) were equipped with one small fan to mix the air, weather sealing along the bottom edge to ensure a gas-tight fit onto the collars, and a small vent to minimize pressure differences between the chamber and surrounding atmosphere (Davidson et al. 2002). Five aliquots of the chamber atmosphere were removed with a needle and syringe from a septum fitted to the center of the chamber and injected into clean, evacuated 1.5 mL glass vials. Sampling began when the chamber was placed onto the collar and ended after 40 minutes. Samples were analyzed on a gas chromatograph (Varian CP3800, CP1177 injector, CarboPlot P7 column, 13.6 mL/min flow rate, 35-63

^{o}C temperature range) to determine CH_4 concentrations. The slope of the change in concentration of methane over time was used to calculate the flux rate (Equation 3).

Statistics

A two-way, repeated measures ANOVA was performed using PROC MIXED to test for warming treatment effects on ecosystem CO_2 and CH_4 flux (SAS Institute Inc., Cary, NC, USA). Warming treatment, microtopography, and interactions were treated as fixed effects, plots were treated as random effects, and sample dates were treated as repeated measures (e.g. Chimner et al. 2010). We used variance component covariance structure for repeated measures analysis as determined by looking at the fit statistics and the Kenward and Roger's correction for degrees of freedom (Littell et al. 2006). Comparisons between all treatments were conducted using Tukey's *post-hoc* test with differences at $P<0.05$ considered significant. Peat temperature was tested with warming treatment, microtopography, and interactions using a two-way ANOVA (SigmaPlot 11.0, Systat Software Inc., San Jose, CA, USA). Probabilities from Tukey's *post-hoc* test of less than 0.05 were considered significant. Canopy temperature was tested using a one-way ANOVA with Tukey's *post-hoc* $P< 0.05$ considered significant (SigmaPlot 11.0).

RESULTS

Environmental Parameters

The average growing season (May-September) air temperature was 15.4 ^{o}C and 16.0 ^{o}C in 2009 and 2010, respectively (Figure 1). Air temperature differences between years were most notable in May and September. The average monthly air temperature for May was lower in 2009 (8.8 ^{o}C) than in 2010 (10.6 ^{o}C), while the opposite was true in September (16.5 ^{o}C and 11.9 ^{o}C in 2009 and 2010, respectively). Water table levels were greater in 2009 than 2010 and were highest in the spring and declined throughout the summer (Figure 1). Between May and September of 2009 there were 36 days with rain totaling 343 mm, whereas 2010 had 59 days with rain totaling 483 mm (Figure 1). The average wind speed from May through September was 1.29 m/s in 2009 and 1.19 m/s in 2010 (data not shown). Average solar irradiance in 2009 was 0.22 KW/m^2 and in 2010 was 0.20 KW/m^2 (June through September, data not shown).

Peat Temperature

Average control peat temperature 5 cm below the surface during the study period was significantly greater ($P<0.001$, t-Test) in 2010 (16.5 ^{o}C) than in 2009 (15.4 ^{o}C) (Figure 2). The greatest difference between years was in July, when mean monthly peat temperatures were 3.7 ^{o}C warmer in 2010 than 2009 (Figure 3). September was the only month when 2009 monthly temperatures were greater than 2010 temperatures (Figure 3). Mean IR lamp peat temperatures were significantly warmer than OTCs and controls for both years, while there was no significant difference in peat temperature between OTCs and controls (Figure 2). In 2009, the average mean seasonal peat temperature difference between IR lamps and controls was 1.4 ^{o}C, while in 2010 it was 1.9 ^{o}C; OTCs were 0.05 ^{o}C warmer in 2009 and 0.12 ^{o}C cooler in 2010 compared to controls (Figure 2). There was not a significant difference ($P>0.05$, t-Test) between hummocks and lawns in all warming-month-year pairs except for the following: IR lamp-July-2009 ($P=0.04$), IR lamp-June-2010 ($P=0.02$), and IR lamp-July-2010 ($P=0.008$).

The average monthly diurnal patterns of warming varied between microtopography, years, and warming method (Figure 4). Nighttime warming of the peat by IR lamps was 1-3 ^{o}C above control plots in all months (Figure 4a-h). OTCs were cooler than controls at night in most, but not all months (see Figure 4a,e,h). Daytime IR lamp temperature differences dropped by 1-3 ^{o}C during the daytime hours compared to the night in 2009 (Figure 4a-d); in 2010 the daytime pattern was variable (Figure 4e-h). OTC daytime temperature was greater than controls in 2009 in all cases except within the lawn plots during June (Figure 4a-d). In 2010, OTC hummock plots were cooler than the controls during the daytime, while lawn temperature varied (Figure 4e-h).

Average peat temperature on CO_2 sampling days showed strong diurnal fluctuations (Figure 5). The average OTC temperature difference was 0.0 and 0.02 ^oC above controls in lawn plots and 0.35 and 0.68 ^oC below controls in hummock plots in 2009 and 2010, respectively. IR lamp temperature was 1.25 and 1.96 ^oC above controls in lawn plots and 0.88 and 1.23 ^oC above controls in hummock plots in 2009 and 2010, respectively.

There were significant changes to the peat temperature when measured to a depth of 41.6 cm (Table 2). IR lamps were significantly warmer (ANOVA, $P<0.001$) than OTCs and controls at 6.5, 24.4, and 41.6 cm below the peat surface. IR lamp plots were 1.43 ^oC warmer than OTC plots at 41.6 cm in the hummocks, the difference was 0.56 ^oC in the lawn plots (Table 2). OTCs were cooler than control plots at all depths within hummocks and lawns.

Canopy Temperature

Canopy temperature follows the same patterns as peat temperature (Table 3). Averaged between warming treatments, the canopy temperature was 3.32 ^oC warmer in 2010 than in 2009. IR lamps were 2.31 and 2.54 ^oC warmer than control plots in 2009 and 2010, respectively. OTCs were 0.20 and 0.48 ^oC cooler than control plots in 2009 and 2010, respectively. Monthly diurnal canopy temperature patterns were similar to peat temperature patterns (data not shown, see Figure 4).

Canopy Moisture

Nighttime OTC cooling correlated with the predicted wet canopy (Figure 5). Figure 5a shows that the time when the canopy vapor pressure falls below the wetbulb vapor pressure (just before 8:00) is the same time when OTC canopy temperature rises above the control temperature. This pattern does not hold true for the IR lamps; heating occurs throughout the night while the canopy vapor pressure is below the wetbulb pressure. Canopy vapor pressure was equal to or greater than the wetbulb vapor pressure nearly every night during the study period when OTC temperatures were lower than control temperatures (data not shown).

Carbon Dioxide Exchange

In hummock plots, the two year averaged GEP was significantly greater under IR lamps compared to controls and OTCs (ANOVA $P<0.001$; Figure 7a). IR lamps and OTCs both had significantly greater average ER values compared to controls. Similar to the GEP measurement, NEE was significantly greater in the IR lamp plots and there was no difference between controls and OTCs. In the lawn plots, averaged between years, there was no difference between warming treatments in the NEE and GEP measurements (Figure 7b). ER was significantly greater with OTCs compared to IR lamps.

Patterns of CO_2 exchange also varied between years (Figure 8). NEE was significantly greater in 2009 than 2010 within control and IR lamp hummock plots (t-Test, $P<0.05$); GEP was significantly greater in 2009 within IR lamp hummock plots ($P<0.05$); NEE was significantly greater in 2009 within IR lamp lawn plots ($P<0.05$). The only CO_2 measurement significantly greater in 2010 was ER within OTC hummock plots ($P<0.05$).

In 2009, IR lamp hummock plots had a significantly greater NEE and GEP flux compared with controls and OTCs, while there was no significant difference in ER between warming treatments (Figure 8a). In 2010, there was no significant difference in NEE between warming treatments, OTCs had a significantly greater ER flux compared to controls, and IR lamps had a significantly greater GEP flux compared to controls. There were no significant differences within lawn plots in any year or warming treatment (Figure 8b).

Methane Flux

CH_4 flux was significantly greater (t-Test, $P<0.05$) from lawn plots than from hummocks in both years and in all warming treatments (Figure 9). There was no significant difference between years within the same warming treatment (t-Test, *P*>0.05). There was no significant difference between warming treatments within the same year for both hummocks and lawns (ANOVA, *P*>0.05).

DISCUSSION

Infrared Lamp Efficacy

IR lamps provided a predictable increase in average peat temperature by 1-2 ^{o}C. This is consistent with reports from other authors who have used IR lamps to warm ecosystem temperatures. A mesocosm peat study in Minnesota used IR lamps to warm their plots by 1.6 to 4.1 ^{o}C throughout the study period (Bridgham et al. 1999; Chen et al. 2008). Marchand et al. (2004) warmed the soil, air, and canopy by 1.8, 1.1, and 2.5 ^{o}C, respectively, using infrared lamps on tundra in Greenland. Harte et al. (1995) found warming as high as 3 ^{o}C using infrared lamps in a study on an alpine meadow in the Rocky Mountains.

Infrared lamps may also cause cooling effects. Harte et al. (1995) reported midday cooling with IR lamps in the lower zone (a wet zone) of that study. Chen et al. (2008) report midday cooling under IR lamps in the fen plots (especially the wettest plots) within their mesocosm study. This midday cooling pattern is consistent with our study when analyzing the average monthly diurnal temperature trends. Figure 4a,b,e and Figure 5a all show IR lamp temperature falling to or below the temperature of the control plots during midday. Chen et al. (2008) explain that this pattern is most likely due to an increase in latent heat loss caused by increased heating and excess moisture. Harte et al. (1995) also link the differences in warming between wet and dry sites to an excess of moisture which uses up much of the energy from the IR lamps for evaporating moisture and not raising temperature.

The majority of warming from IR lamps occurred during nighttime hours, while daytime temperature differences were closer to, or below control temperatures. This pattern of warming is typical for constant flux IR lamp arrays (Kimball 2011). In order to achieve a few degrees of warming above controls during the daytime with constant flux units, nighttime temperatures would be very high. (Kimball 2011).

Open Top Chamber Efficacy

The heating pattern of OTCs was not as consistent as IR lamps. The majority of studies which have used OTCs have reported warming of the soil and air by 0.5 to 3.0 ^{o}C (see Table 4). In contrast, we did not find any significant long term warming from the OTCs. There were a few days when OTCs warmed the peat 1-2 ^{o}C above controls (data not shown) and one month when the OTC hummock peat temperature was more than 0.5 ^{o}C above controls (September 2009, Figure 3a), but our results indicate that the conditions present during the two study years were not conducive to experimental warming by OTCs. OTC cooling has been reported by other authors (Marion et al. 1997; Hollister et al. 2006; A. Dabros et al. 2010), but our results demonstrate the worst performance of OTCs that we could find.

The diurnal patterns of OTC heating in our study are partially consistent with that reported by others (Marion et al. 1997; Hollister et al. 2006; Carlyle et al. 2011). The general trend reported by these authors is that OTC soil temperature falls below the control temperature at night and rises above controls during the daytime. This is what we would expect as shortwave solar radiation enters the OTCs when the sun is shining and longwave radiation is emitted by the surface of the plant canopy and is absorbed and then reemitted off the inside of the OTCs, creating a warmer environment. There are, however, many variables that can influence OTC heating performance such as wind, solar radiation, day length, soil conditions, and vegetative cover (Marion et al. 1997; Hollister et al. 2006; Carlyle et al. 2011).

Daytime heating maximums are often considered the key to overall heating gains in OTCs (Marion et al. 1997; Hollister et al. 2006; Carlyle et al. 2011). One of the reasons why we did not measure a long-term warming effect in OTCs is largely because of a lack of strong midday heating peaks. Cloudy and rainy weather conditions, temperate day length hours, and daytime latent heat loss all impede daytime heating peaks.

Furthermore, as OTC canopies are often wet during nighttime hours, daytime heating is delayed until all of the moisture has evaporated off of the leaf surfaces.

Daytime temperatures often drop lower than controls on sunny days in OTC plots. Dabros et al. (2010) reported a 1.0 ^{o}C decrease in soil temperature measured at 12 cm and a 0.4 to 2.2 ^{o}C increase in air temperature. Hollister et al. (2006) reported a decrease of 0.8 ^{o}C in July soil temperature at 10 cm depth averaged over three years under the OTC treatments with an increase in air temperature. In the review by Marion et al. (1997), there was a decrease in soil temperature of 0.24 ^{o}C at the Salix site but with an increase of 1.24 ^{o}C in air temperature. All three of the studies that report an OTC induced soil cooling effect also report warmer air temperatures in the same plots. Wet soil conditions and improper placement of temperature sensors are two explanations offered to explain the cooler soil/warmer air result (Marion et al. 1997). Latent heat loss through evapotranspiration (ET) most likely explains how air temperatures may be warmer than controls while soil temperatures are cooler. Daytime latent heat loss can be seen in our study on sunny days when moisture is sufficient (Figure 5 lawn plots).

During the night hours, we found OTC temperatures to remain below control temperatures during many clear nights when the air was saturated. The strongest diurnal patterns of OTC heating and cooling are seen in 2009 (Figure 4a-d and Figure 5a). We see that cooling occurs in the evening hours with temperatures remaining steady throughout the night. When this pattern was present we also found our saturated canopy/wetbulb calculation to hold true. We therefore know that the OTC canopies are often wetter than controls, but the cooling mechanism is still unknown. Since the atmosphere was nearly saturated with water on these cool nights, evaporative cooling would not play a major role. We can only speculate on this mechanism with the data we have (see “chimney effect” in Conclusions and Recommendations section).

One of the major differences between this study and other similar studies is that our site was located south of the boreal zone. In contrast, most OTC studies have been conducted at much higher latitudes. In the review by Aronson and McNulty (2009), 18 of the 22 studies which used passive field chambers (including hexagonal OTCs) were done at latitudes greater than 60^{o}. Studies from high latitudes have a longer day-length and a larger potential for greater solar loading at the site during summer months.

Another general trend of high latitude studies is a lower average temperature compared to temperate areas. Oberbauer et al. (2007) reported July temperatures at four sites in northern Alaska (68°N to 78°N) to range from 3.7 to 11.6 °C. This is much lower than the July averages from our study (17.92 and 20.91 °C in 2009 and 2010, respectively). Carlyle et al. (2011) show that the efficacy of OTC heating may be reduced with increasing background temperature. They found warming to be the strongest when air temperature was below 16.3 °C and found no significant heating above 22.2 °C. This trend was not apparent in our data, but it may be masked by other factors that influence temperature.

Warming Treatment Effects on Gas Fluxes

Within lawn plots, warming treatments did not have an effect on CO_2 flux, even considering that IR lamps warmed lawns more than hummocks. Aljaste et al. (2011) found that photosynthetic uptake by the sedge *Carex utriculata* does not exhibit any response to increased warming. In our study sedges comprise, on average, 33% cover in lawn plots, offering a plausible explanation for the muted warming effect on GEP. ER did not respond to warming probably because lawn plots are usually saturated and anaerobic, conditions which are not favorable for microbial CO_2 respiration (Marchand et al. 2004). The lack of CO_2 flux response to IR lamps in the lawns is likely due to a combination of limited aerobic respiration and plant species, such as sedges, that do not respond very well to warming. The failed response of OTC treatments to stimulate changes in CO_2 flux in lawns could be simply explained by a lack of long-term warming (Figure 2b) and midday OTC temperatures that were below control temperatures during CO_2 sampling days (Figure 5).

Within hummock plots, OTCs had no significant effect on GEP, an effect which we would expect since OTCs failed to create warmer conditions. Unexpectedly, there was a significantly greater ER flux in 2010 within OTC plots, though there was not any long-term or midday warming. Upon looking at the 2010 ER values of each of the three plots which represent replicates for the OTC-hummock combination, plot 11 had an average ER flux nearly double the average of the other two plots (-7.73 μmols CO_2 m^{-2} sec^{-1} in plot 11 and -3.20 and -4.70 µmols CO_2 m^{-2} sec^{-1} in the other plots). It is likely that this result is an artifact of a high degree of variability within biological systems and low numbers of replication (n=3).

IR lamps had significantly greater GEP than controls in hummock plots. With a heating increase of 1-2 °C, our results are consistent with other studies reporting similar increases in GEP (i.e., Marchand et al. 2004). There was no correlation between ER and temperature in hummock plots, a result contrary to studies showing increasing CO_2 efflux with increasing temperatures (e.g. Chapman and Thurlow 1998). There are some possible explanations, however. First, the sensitivity of respiration to temperature enhancement decreases with increasing temperature (Marchand et al. 2004). At our site, average peat temperatures were often more than 20 °C, with daily maximums often exceeding 30 °C. These temperatures are greater than the normal conditions in which northern peatlands have developed (Wieder et al. 2006). Secondly, the temperature difference was at a minimum during midday when gas flux measurements were made. A greater temperature difference may have stimulated a stronger response. Thirdly, hummocks are inherently resistant to decay (Rydin and Jeglum 2006). Hummocks consist largely of *S. fuscum* and woody plants (low amounts of labile carbon), have a low pH, and are dry; all of which are conditions that do not facilitate respiration (Moore and Basiliko 2006). Lastly, IR lamps have been shown to dry soil at a greater rate than controls (Kimball 2011), a factor that further reduces potential respiration. Hence, the lack of ER in hummock plots may be explained considering the magnitude of background temperatures, minimal midday temperature differences, and a decay-resistant substrate.

CH_4 flux was significantly greater in lawns than in hummocks, results consistent with the reports of many others studying the effects of water level on CH_4 production (e.g. Macdonald et al. 1998; Updegraff et al. 2001; Turetsky et al. 2008). Hummock plots had very little CH_4 respiration most likely due to the dry conditions and decay-resistant organic matter which is common in hummocks (Rydin and Jeglum 2006). Within lawn plots there was no clear trend between CH_4 efflux and temperature. This is expected considering temperature is not a primary driver of methane flux, and ambient temperatures were already high. Also, acetate derived CH_4 flux, which is most prevalent in peatland CH_4 fluxes, is greatest at lower temperatures (Vasander and Kettunen 2006).

Conclusions and Recommendations

IR lamps warmed our plots on average by 1-2 ^{o}C but there was a diurnal heating pattern. The greatest amount of warming occurred during the nighttime hours while daytime heating differences were less than 1 ^{o}C. A computer controlled IR lamp system could alleviate the diurnal pattern and allow for a greater amount of daytime warming, thereby more closely mimicking real (atmospheric warming) conditions (Kimball 2005). Increased midday temperature differences may have had a greater effect on gas flux changes. IR lamps may increase ET rates above controls, drying the substrate. Therefore watering is necessary to maintain real warming conditions (Kimball 2011) and to minimize “plot effects” when comparing treatments. Increased drying may have affected CO_2 flux response on drought intolerant plants such as *Sphagnum*.

OTC temperatures did not show the widely reported temperature increases cited in similar studies from high-latitude regions. A temperate latitude day-length coupled with cloudy and saturated conditions hindered daytime heating peaks. During sunrise, OTCs with saturated canopies took longer than controls to warm up, further reducing the amount of midday warming. During nighttime hours, OTC hummocks were often saturated and cooler than controls, but the mechanism responsible for this is still unknown. One theory is a “chimney effect”. When wind passes over the top of OTCs low pressure may be created. If located on a large hummock, air could be drawn in from below the OTC since hummocks are very porous when dry. Looking at Table 2, we see that hummock OTC temperatures are 1.05 ^{o}C cooler than controls even at 41.6 cm below the surface. A chimney effect would be a plausible mechanism for this deep cooling.

CO_2 flux rate correlations to temperature did not follow the results of other temperature enhancement studies. When considering the effect of OTCs on flux rates, we were not surprised to see no significant changes since OTCs provided minimal heating at best. IR lamps did provide long term heating but mostly at night. During midday, the time when gas sampling occurred, heating differences were minimal. Increasing daytime heating differences may have provided for more warming-induced changes in CO_2 flux. Midday sampling may not pick up on differences that are present during other times of day. Since heating has such a pronounced diurnal pattern in this study, diurnal gas sampling should have been implemented as well.

There were no significant changes in CH_4 efflux between warming treatments. Though CH_4 efflux was occurring in lawn plots, IR lamp warming did not stimulate an increase in efflux. The amount of warming applied was likely not great enough to increase CH_4 production in an already warm substrate. The small warming area may also be a factor because belowground processes likely occur in a larger area.

Using OTCs in the cloudy and humid climate of the southern Lake Superior region is not an effective method for experimentally warming ecosystem temperatures. Future studies should explore the efficacy of OTCs in other regions and ecosystems in temperate latitudes. A greater amount of sunny days, coupled with less humidity and soil moisture, may improve OTC warming. Though IR lamps worked well to increase ecosystem temperatures by 1-2 ^{o}C, computer controlled mechanisms could increase daytime temperature differences, thereby possibly affecting CO_2 and CH_4 flux to a greater extent. Sampling CO_2 and CH_4 diurnally may pick up on differences between warming treatments not seen when sampling during midday only. Larger plot sizes may reduce any “edge effects” that may be present. A larger plot area will reduce the proportion of the study plot that is influenced by outside biotic and abiotic factors (such as groundwater flow and tree roots).

THESIS CONCLUSION

This study represents many *firsts* within the peatland and climate change communities. This was the first study which could be found that directly compared OTCs and IR lamps. This was also the first study to present the results of an experimentally controlled OTC study in a Great Lakes peatland. Hemiboreal peatlands exist in a climate which represents the limit of heat tolerance and therefore have less response to increased temperatures compared with peatlands existing in a cold climate. This study is also the first to present results demonstrating a lack of long-term OTC heating. OTCs are highly dependent on external conditions and therefore should be used with caution and/or an array of micromet equipment to document the changes. It is not wise to cite results from other studies and assume you will get the same result. Diurnal heating graphs were especially effective in highlighting the heating differences between IR lamps and OTCs.

I learned a great deal from my experience as a Masters Research Assistant. Besides sharpening my peatland ecology knowledge, I greatly enjoyed learning the biophysics involved with this study. The tremendous amount of data that was generated from the micromet equipment forced me to develop data management skills. I also spent a massive amount of time making graphs. I now feel very confident in my ability to make a quality graph. Organizational skills, logistics, time-management, and of course writing are all general skills which are necessary to complete a Masters project like this. This research project has taught me a valuable lesson about careful planning and consideration when making research decisions. Small problems encountered at the beginning of a project can lead to big headaches when some unforeseeable issue arises. Taking daily notes and staying organized are some of the most important aspects to managing research work. From this research experience I feel confident in my ability to be a productive and successful PhD student and career scientist.

Studying in Finland and Sweden though the ATLANTIS exchange program has been one of the greatest experiences of my life. Living abroad for nine months, and doing so in the two countries I would have chosen, has changed my life forever.

Learning the cultures and ways of life from all of the people I met while abroad was an invaluable life-lesson.

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FIGURES

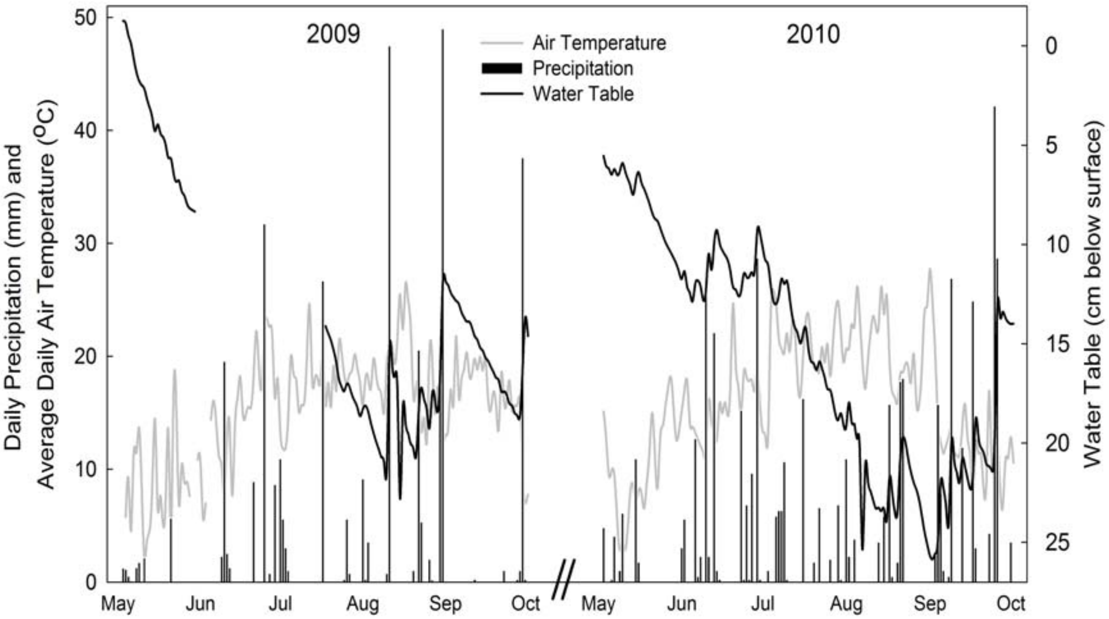

Figure 1. Average daily air temperature, water table level, and daily total precipitation. Air temperature, water table level, and precipitation were measured continuously throughout the study period using data loggers. Notice the left y-axis has two values: daily precipitation (mm) and average daily air temperature (^{o}C). The x-axis breaks in the center to separate 2009 and 2010. The missing data in June and July 2009 was due to instrument error.

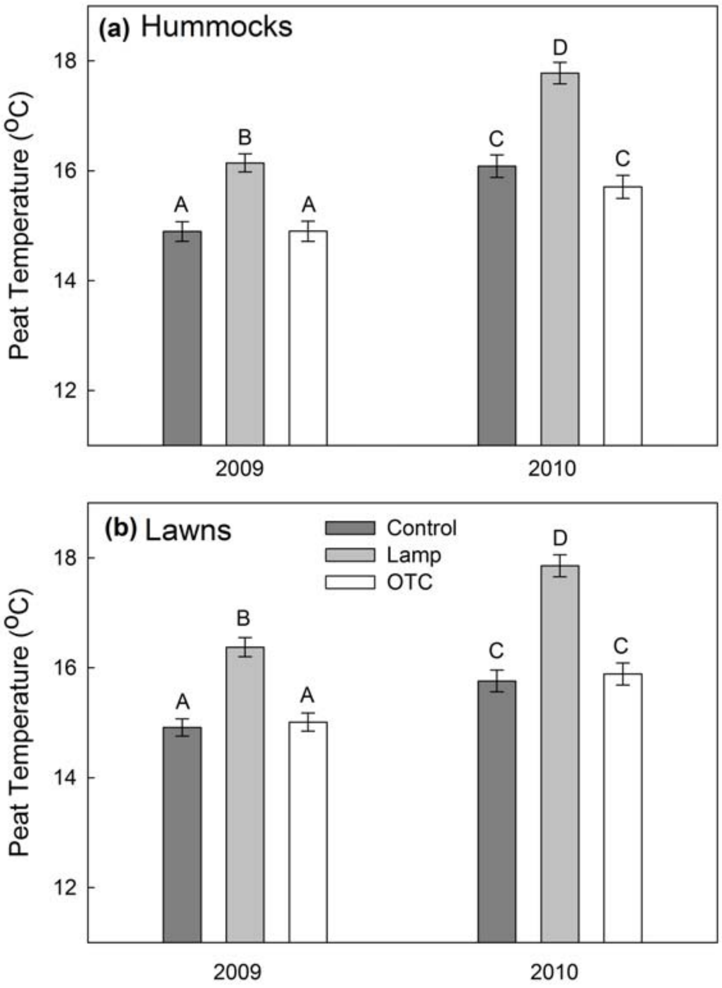

Figure 2. Average monthly peat temperature. Peat temperature at 5 cm depth measured continuously in all plots using thermocouples. Error bars represent standard error mean. Letters represent significant differences (ANOVA; $P<0.05$; lower case letters 2009, capital letters 2010) between warming treatments. There is a significant difference (t-Test, $P<.001$) between years for each treatment during all months. Data from May 2009 only includes the dates of 10 May to 27 May. There were 3 out of 30 t-Tests which were significantly different when comparing between topography (Lamp July 2009, $P=.04$; Lamp June 2010, $P=.02$; and Lamp July 2010, $P=.008$).

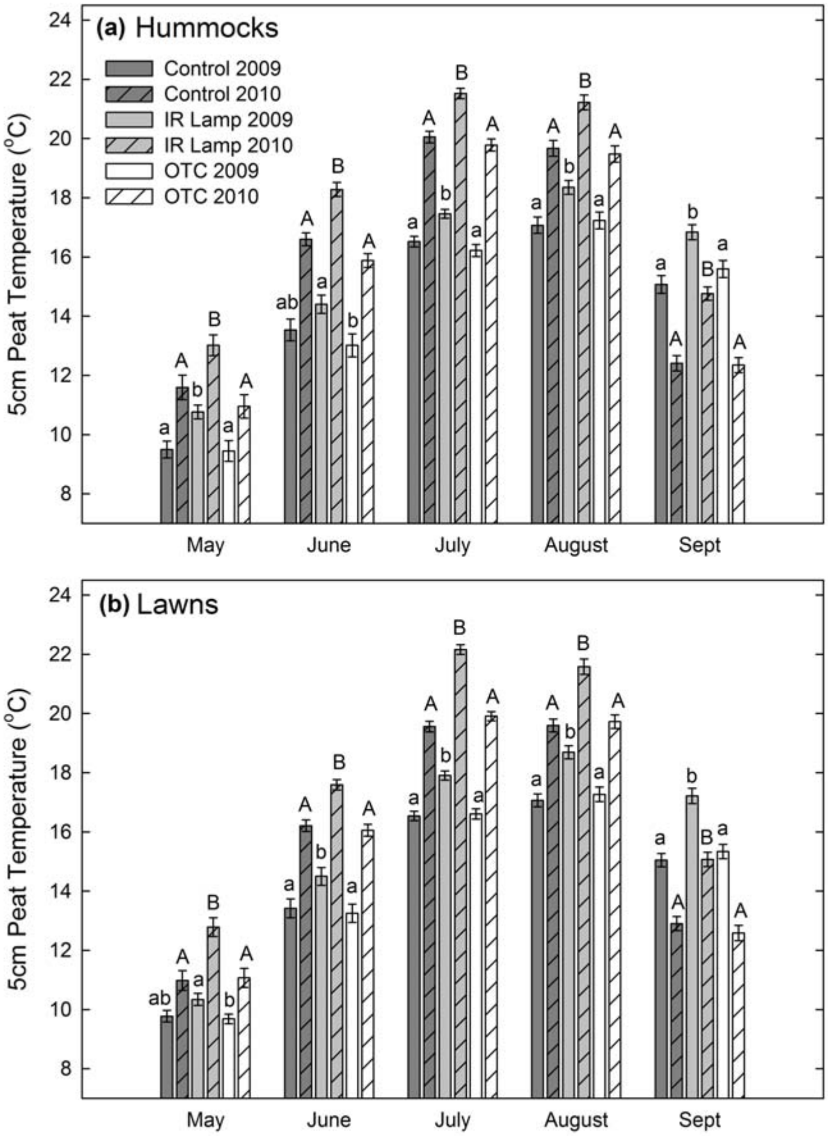

Figure 3. Seasonal averaged peat temperature. Peat temperature at 5cm depth measured continuously in all plots using thermocouples. Error bars represent standard error mean. Letters represent significant differences (ANOVA; $P<0.05$).

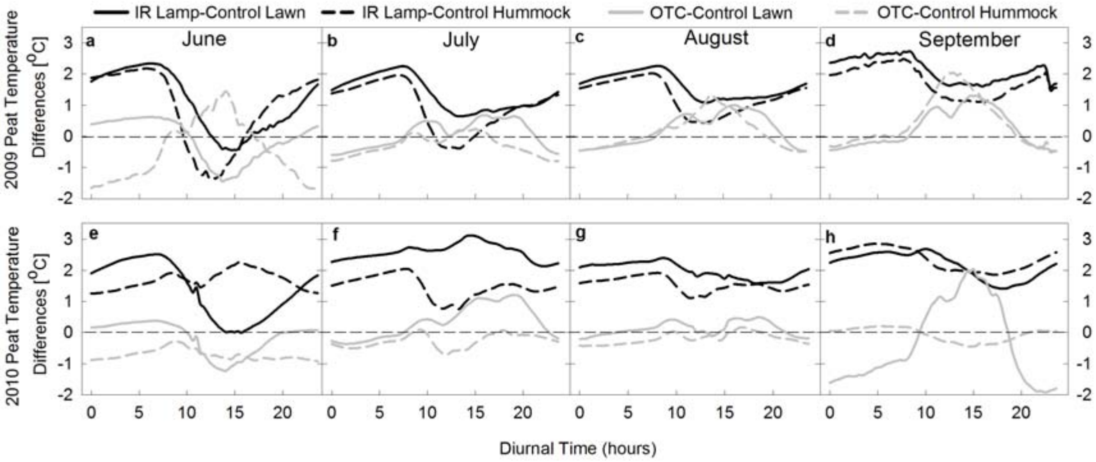

Figure 4. Average monthly diurnal peat temperature difference. Average monthly diurnal peat temperature differences. Values are reported as the difference in temperature between heating treatment (OTC or IR lamp) and control plots. Positive values indicate a greater temperature than controls while negative values indicate cooler temperatures than controls. Peat temperature was measured continuously at 5 cm with thermocouples in all plots. Data for each month was sorted based on time and then averaged in 20 minute intervals throughout the day.

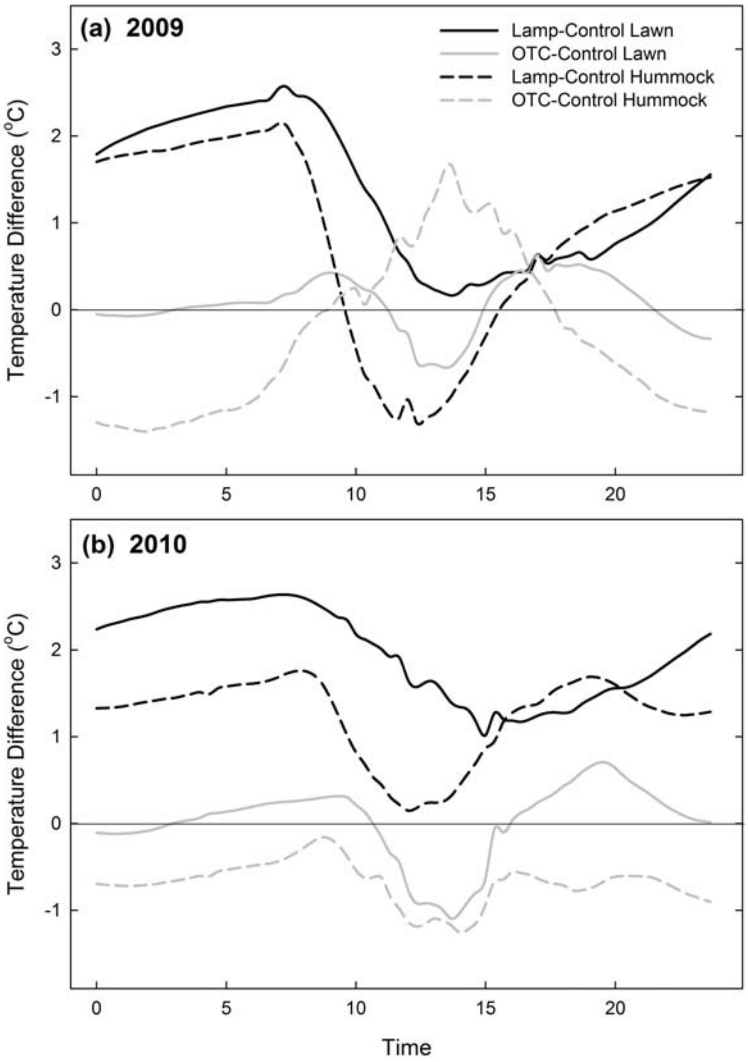

Figure 5. Averaged diurnal temperature from CO_2 sampling days. Average diurnal peat temperature during CO_2 sampling days in 2009 and 2010. Values are reported as the difference in temperature between heating treatment (OTC or IR lamp) and control plots. Positive values indicate a greater temperature than controls while negative values indicate cooler temperatures than controls. Peat temperature was measured continuously at 5 cm with thermocouples in all plots. Data for each year was sorted based on time and then averaged in 20 minute intervals throughout the day.

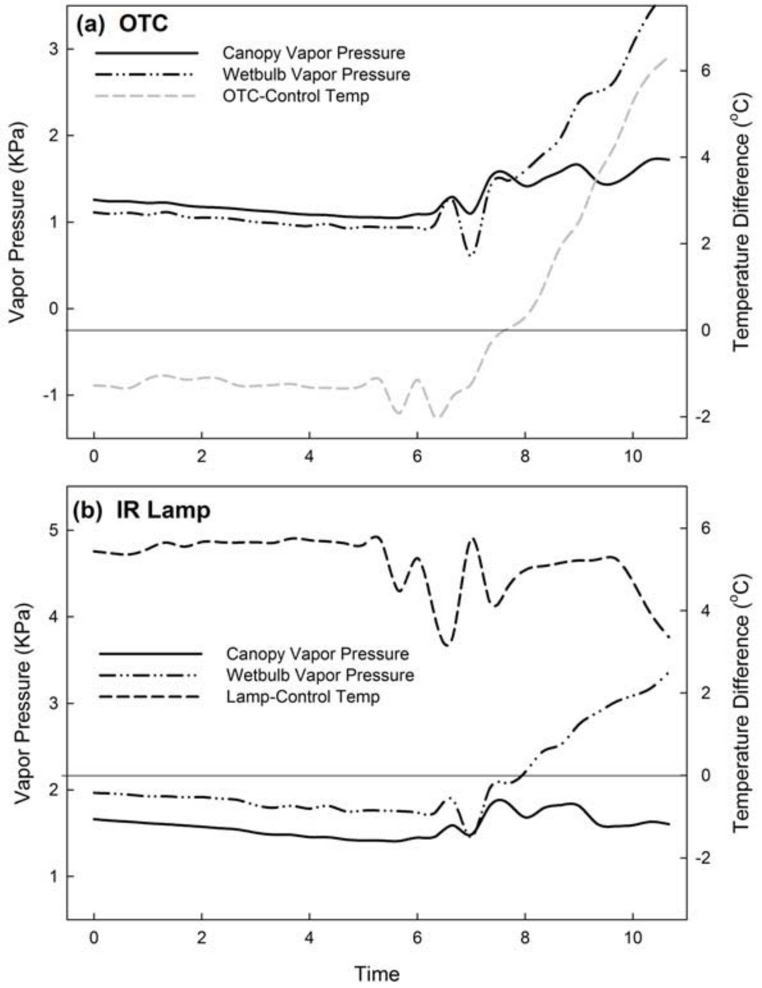

Figure 6. Canopy moisture prediction and temperature difference, 04 July 2009. Saturated canopy conditions were predicted using the concept of a psychrometer. When the vapor pressure of the leaf surface was greater than that of a wetbulb, it is understood that the canopy is acting as a wetbulb and therefore saturated.

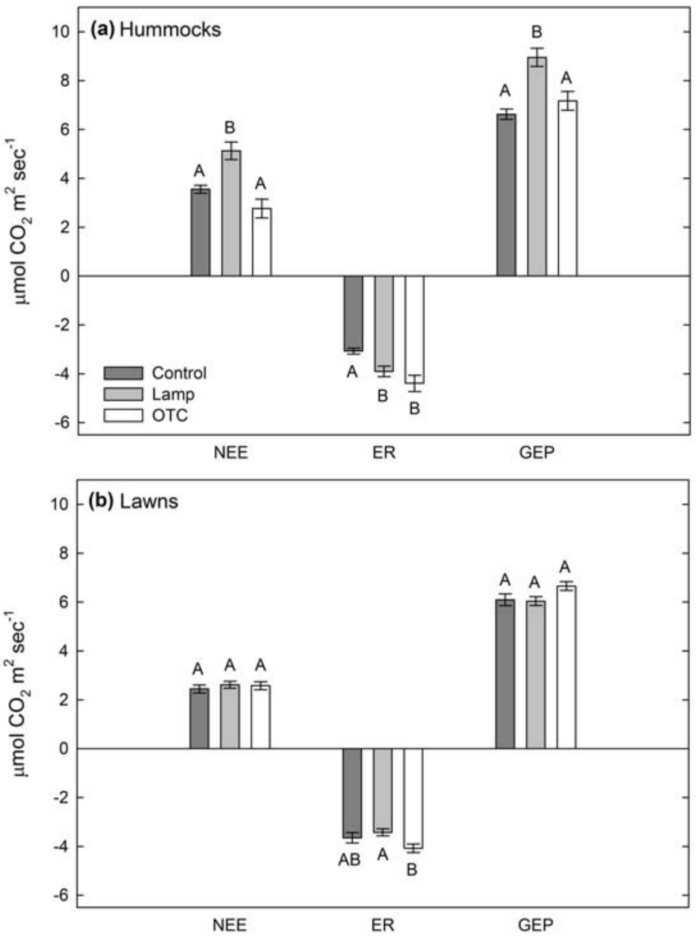

Figure 7. Averaged 2009 and 2010 NEE, ER, and GEP. NEE, ER, and GEP averaged between 2009 and 2010 (n=33) and split between hummocks and lawns. Positive values indicate an uptake of CO_2 from the atmosphere into the ecosystem. Negative values indicate a loss of CO_2 from the ecosystem to the atmosphere. Error bars represent SEM. Letters represent significant differences (ANOVA; $P<0.05$) between warming treatments.

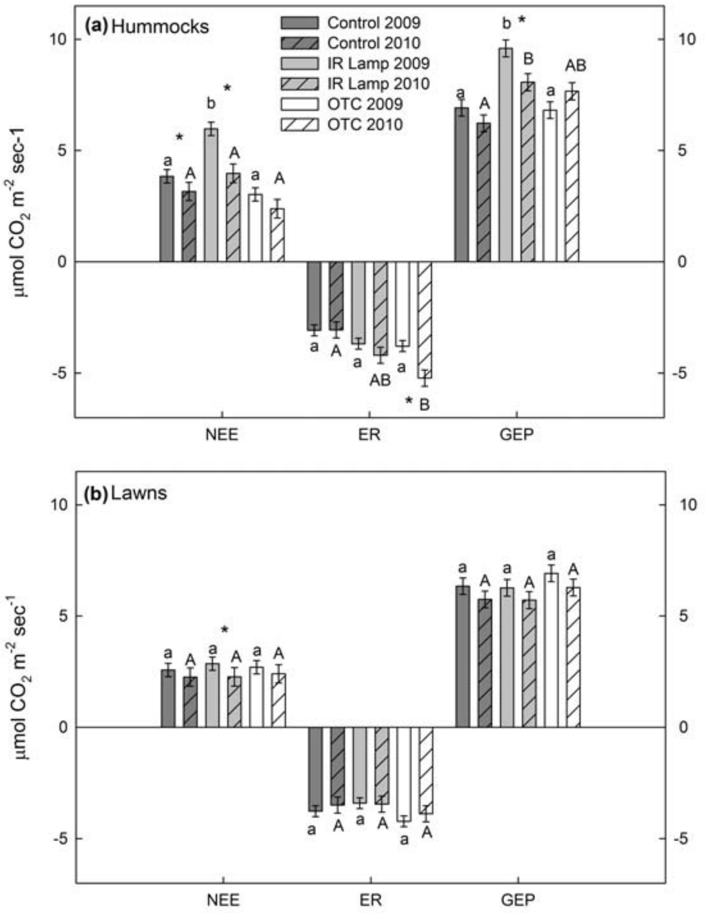

Figure 8. Seasonal average NEE, ER, and GEP. CO_2 flux measurements in 2009 (n=19) and 2010 (n=14) split between hummocks and lawns. Positive values indicate an uptake of CO_2 from the atmosphere into the ecosystem. Negative values indicate a loss of CO_2 from the ecosystem to the atmosphere. Error bars represent SEM. Letters represent significant differences (ANOVA; $P<0.05$; lower case letters 2009, capital letters 2010) between warming treatments. Significant differences (t-Test; $P<0.05$) between years within the same treatment are marked with an asterisk (*).

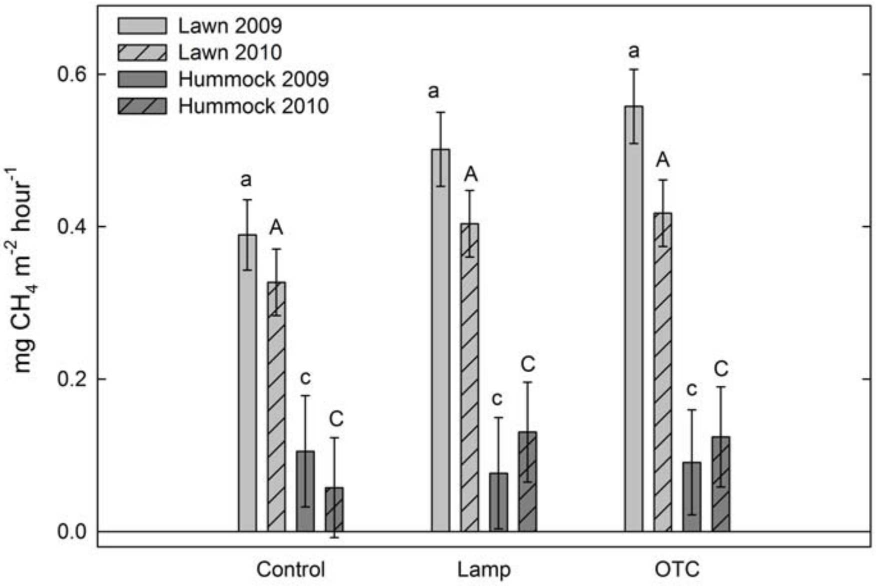

Figure 9. Average seasonal CH_4 flux rates. Methane flux rates in 2009 (n=7) and 2010 (n=9) hummocks and lawns. Positive values here represent an efflux of CH_4 from the ecosystem to the atmosphere. There were no significant differences between warming treatments (ANOVA, *P*>0.05). All lawn flux rates were significantly greater (t-Test, *P*>0.05) than hummocks.

TABLES

Table 1

ANOVA results for CO_2 and CH_4 exchange. Repeated measures analysis of variance (ANOVA) for the three components of CO_2 flux (NEE, ER, and GEP) and CH_4 flux for 2009 and 2010. Warming treatment, micro-topography, and interactions were treated as fixed effects, plots were treated as random effects, and sample dates were treated as repeated measures. Values in bold represent statistically significant probabilities (*P*<0.05).

Source of Variation	d.f. (num, den)		F		P	
	2009	2010	2009	2010	2009	2010
Net Ecosystem Exchange (NEE)						
Warming	2, 333	2, 242	14.76	1.54	**<.0001**	0.218
Topography	1, 333	1, 242	41.00	6.55	**<.0001**	**0.011**
Topography * Warming	2, 333	2, 242	11.19	2.16	**<.0001**	0.118
Ecosystem Respiration (ER)						
Warming	2, 333	2, 244	3.11	6.19	**0.046**	**0.002**
Topography	1, 333	1, 244	2.00	3.48	0.158	0.063
Topography * Warming	2, 333	2, 244	2.06	3.10	0.129	**0.047**
Gross Ecosystem Production (GEP)						
Warming	2, 333	2, 242	6.78	4.17	**0.001**	**0.017**
Topography	1, 333	1, 242	17.00	20.26	**<.0001**	**<.0001**
Topography * Warming	2, 333	2, 242	11.72	3.04	**<.0001**	**0.050**
Methane (CH_4) Flux						
Warming	2, 75	2, 111	0.82	1.27	0.444	0.285
Topography	1, 75	1, 111	62.24	37.56	**<.0001**	**<.0001**
Topography * Warming	2, 75	2, 111	1.25	0.03	0.292	0.974

Table 2

Peat temperature profile. Average peat temperature (standard error) measured at 3 different depths in all plots using multi-sensor thermocouples, I-buttons. Data shown is from 11 July to 31 August 2010. IR Lamp plots were significantly warmer (*, ANOVA, *P*<.001) than controls and OTCs at all levels within hummocks and lawns.

	Hummock			Lawn		
	Control	Lamp	OTC	Control	Lamp	OTC
6.5 cm	20.72 (.06)	23.18* (.05)	19.10 (.05)	21.13 (.07)	23.11* (.05)	20.60 (.06)
24.4 cm	18.23 (.02)	19.56* (.02)	16.77 (.01)	18.14 (.01)	19.04* (.02)	17.55 (.01)
41.6 cm	16.12 (.01)	16.50* (.01)	15.07 (.01)	16.43 (.01)	16.59* (.02)	16.03 (.01)

Table 3

Average seasonal canopy temperature. Average canopy temperature from 2009 (12 June to 10 September) and 2010 (19 June to 31 September) measured with an infrared radiometer. Each of the three radiometers was placed above one of the warming treatments at the correct height and angle to measure the canopy temperature of a $0.24m^2$ area.

	2009	2010
Control	17.41 (.02)	20.75 (.02)
Lamp	19.72 (.02)	23.29 (.02)
OTC	17.21 (.02)	20.27 (.02)

Table 4

A comparison of selected OTC studies found in the literature. A brief list of some studies which have used OTCs for experimental warming. The change in soil and/or air temperature (compared to controls) is listed with the depth (soil) or height (air) of measurement given in parentheses. Temperatures reported are listed as averages or ranges of values. Numbers in bold represent average cooling or no change.

Article	Location	Latitude	Δ Soil Temp. (^{o}C)	Δ Air Temp. (^{o}C)	Other measurements (ecosystem)
Carlyle *et al.* (2011)	Canada	50.76^{o}N	0.2 (5cm)	not measured	Soil moisture (grassland)
Dabros and Fyles (2010)	Canada	49^{o}37'N	**-1.0 (12cm)**	0.4-2.2	Soil biogeochemistry (forest and peatland)
Gedan and Bertness (2009)	New England	41^{o}-42^{o}N	not measured	0.33-3.28 (10cm)	Vegetation diversity (salt marsh)
Rinnan *et al.* (2009)	Finland	69^{o}30'N	0.5 (5cm)	1.2 (5cm)	Vegetation and soil microbiology (peatland)
Chivers *et al.* (2009) and Turetsky *et al.* (2008)	Alaska	64.28^{o}N	0.6-0.9 (2cm)	not measured	CO_2 and CH_4 (peatland)
Kudernatsch *et al.* (2008)	German Alps		0.2-0.8 (2cm)	0.7-1.4 (2cm)	Vegetation growth (alpine)
Sullivan *et al.* (2008)	Greenland	76^{o}33'N	0.8-1.2 (5cm)	1.9 (20cm)	Vegetation and CO_2 dynamics (peatland)
Hollister *et al.* (2006) and Hollister & Webber (2000)	Alaska	71^{o}18'N	**-0.8-0.7 (10cm)**	0.6-2.2 (13cm)	Vegetation growth (peatland)
Welker *et al.* (2005)	Alaska	68^{o}38'N	1.0-1.9	1.1-1.6	Vegetation chemistry (tundra)
Welker *et al.* (2004)	Canada	78^{o}54'N	0.4-1.8 (1cm)	1.0-1.5 (10cm)	CO_2 (tundra)
Marion et al. (1997)	Canada	78^{o}54'N 79^{o}08'N	0.99-2.09 (3cm) 1.11 (3cm)	1.94 (10cm)	Micromet (tundra)
This study	N. Michigan	46.85^{o}N	**-0.12-0.05 (5cm)**	**0 (15cm)**	CO_2 and CH_4 (peatland)

EQUATIONS

Equation 1. Psychrometer derived vapor pressure

$$e_a = e_s(T_w) - \gamma p_a(T_a - T_w)$$

This formula calculates vapor pressure from a psychrometer. In this application T_w equals the canopy temperature, T_a is air temperature, and $e_s T_w$ is the saturation vapor pressure (Formula 2). If the vapor pressure derived from this equation (e_a) was equal to or lower that the actual vapor pressure of the canopy temperature we concluded that the leaf surface must be acting as a wetbulb and therefore saturated (Campbell and Norman 1998).

Equation 2. Teton's formula for calculating saturation vapor pressure

$$e_s(T) = a \exp \frac{bT}{T + c}$$

Teton's formula estimates saturation vapor pressure from a given temperature. In this case, canopy temperature was used to calculate what the saturation vapor would be at the given time. The given constants are as follows: a = 0.611 kPa, b = 17.502, and c = 240.97°C (Campbell and Norman 1998).

Equation 3. Methane flux calculation

$$\left(\frac{\mu mol}{mol/sec}\right)\left(\frac{1\ \text{mol}}{22.4\ L}\right)\left(\frac{108\ L}{0.36\ m^2}\right) = \frac{ppm}{m^2/sec}$$

To calculate the flux rate from a set of methane samples (usually 5), we first calculated the slope of the change in concentration (ppm) of methane over the change in time ($\frac{\mu mol}{mol/s}$), divided by the volume of gas at STP ($22.4\ L$), and adjusted for the chamber volume ($108\ L$) and area ($0.36\ m^2$).