AN ACROTELM TRANSPLANT EXPERIMENT ON A CUTOVER PEATLAND – EFFECTS ON MOSITURE DYNAMICS AND CO_2 EXCHANGE

By

JASON P. CAGAMPAN, BES

A Thesis

Submitted to the School of Graduate Studies

In Partial Fulfillment of the Requirements

For the Degree

Master of Science

McMaster University

© Copyright by Jason P. Cagampan, September 2006

MASTER OF SCIENCE (2006)
(Geography)

McMaster University
Hamilton, Ontario

TITLE: An Acrotelm Transplant Experiment on a Cutover Peatland – Effects on Moisture Dynamics and CO_2 Exchange

AUTHOR: Jason P. Cagampan

SUPERVISOR: Professor J. Michael Waddington

NUMBER OF PAGES: xi, 96

ABSTRACT

Natural peatlands are an important component of the global carbon cycle representing a net long-term sink of atmospheric carbon dioxide (CO_2). The natural carbon storage function of these ecosystems can be severely impacted due to peatland drainage and peat extraction leading to large and persistent sources of atmospheric CO_2 following peat extraction abandonment. Moreover, the cutover peatland has a low and variable water table position and high soil-water tension at the surface which creates harsh ecological and microclimatic conditions for vegetation reestablishment, particularly peat-forming *Sphagnum* moss. Standard restoration techniques aim to restore the peatland to a carbon accumulating system through various water management techniques to improve hydrological conditions and by reintroducing *Sphagnum* at the surface. However, restoring the hydrology of peatlands can be expensive due to the cost of implementing the various restoration techniques. The goal of this study is to examine a new extraction-restoration technique where the acrotelm is preserved and replaced on the cutover surface. More specifically, this thesis examines the effects of an acrotelm transplant experiment on the hydrology (i.e. water table, soil moisture and soil-water tension) and peatland-atmosphere CO_2 exchange at a cutover peatland.

The experimental acrotelm restoration technique maintained both high water table and moisture conditions providing sufficient water at the surface for *Sphagnum* moss. Furthermore, the high moisture conditions and low soil-water tensions compared to an adjacent natural site were maintained well above the measured critical *Sphagnum* threshold of 33% (-100 mb) VMC further providing favourable conditions for *Sphagnum* moss survival and growth.

Peat respiration at the experimental restored acrotelm (110.5 g C m^{-2}) was considerably lower than the natural peatland (144.8 and 203.7 g C m^{-2}). However, gross ecosystem production (GEP) at the experimental site (-54.0 and -34.4 g C m^{-2}) was significantly reduced compared to the natural site (-179.2 and -162.0 g C m^{-2}). Consequently this resulted in a shift towards a net source of CO_2 to the atmosphere over the season at the experimental site (78.5 and 56.5 g C m^{-2}) and a sink of CO_2 at the natural site (-17.6 and -22.8 g C m^{-2}).

Light response curves indicated that maximum GEP was considerably lower at the experimental site; however it is likely that the percentage of living and dead vegetation at the plots post restoration had a large control on this lower productivity as plots with more living vegetation had higher overall productivity (GEP). Despite wetter conditions at the experimental site, large diurnal variations in moisture (~30%) were observed suggesting disturbance to the peat structure. Although soil-water retention analysis and physical peat properties indicated that no apparent structural change in peat structure occurred, it is theorized that a change in volume in the capitula may enhance the wetting and drying cycles in moisture. Lateral expansion/contraction within the peat matrix may occur due to spaces (gaps/fissures) left between the replaced acrotelm blocks from the extraction-restoration process promoting large changes in moisture which consequently can affect the gas exchange process at the surface. Large changes in peat and capitual moisture have been shown to affect productivity leading to variable GEP and

enhanced respiration, making it important to limit the moisture variability at the surface from a carbon cycling perspective. Therefore it is likely that a combination of both physiological health of the vegetation and wetting/drying cycles contributed to lower GEP, suggesting the importance of limiting disturbance at the surface during the extraction and restoration process.

The new extraction-restoration technique has potential to return a peatland to both near-natural hydrological conditions and towards a net sink of atmospheric CO_2. The replaced acrotelm on the cutover surface aided in maintaining adequate moisture conditions thereby provided adequate conditions for *Sphagnum* survival and reestablishment. However, the ability of the system to remain a net sink of CO_2 as like the natural site was not observed post-disturbance due to differences in productivity. Nevertheless, the experimental site did maintain limited productivity post-extraction indicating that the carbon dynamics of the system was maintained due to this acrotelm restoration process potentially returning the ecosystem towards a natural sink of atmospheric CO_2 over a longer period time.

ACKNOWLEDGEMENTS

Funding was provided by a research grant from Premier Tech Lte. to Dr. J.M. Waddington and the Peatland Ecology Research Group. Thanks to Premier Tech Lte. for access to the research site and assistance with the logistics of the project.

Many thanks to Marie-Eve Lemieux for field assistance, Jacinthe Letendre for field-set up, and Dr. J.E. Smith for advice on the hydrology work of this project. As well, thanks to everyone who had a hand with the project over the past few years; your assistance was much appreciated.

Special thanks to Melissa Greenwood and Dr. Maria Strack for sharing all your expertise regarding carbon flux measurements and analysis. As well, thanks to Timothy Duval and Kristen Harrison for discussing ideas regarding this project over the last year. More importantly thanks to each one of you for discussing life in general, sharing many laughs, dropping the occasional dance move, falling in peatlands, and putting up with my antics over the years. I could not have asked for better lab mates and friends.

Last but not least thanks to Dr. J.M. Waddington for your support and guidance over the years with every aspect of this project; you have challenged me throughout this process to become a better wetland scientist. Moreover, thanks for always putting things in perspective both in and outside academia, bringing in the shotgun when needed, and sharing some miles along the way. Thanks for being Mike.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1: INTRODUCTION

1.1 Peatland Carbon Cycling

Natural peatlands are an important component of the global carbon cycle contributing to approximately one-third of the total global soil carbon stock with storage estimated at 455 Gt of carbon (Gorham, 1991). Furthermore, peatlands represent a net long-term sink of atmospheric carbon dioxide (CO_2) storing ~23-29 g C m^{-2} yr^{-1} (Gorham, 1991). Storage of carbon within a peatland is determined by the balance of primary production and decomposition (Clymo, 1984) where CO_2 is fixed through photosynthetic activity of surface vegetation to form organic carbon and losses to the atmosphere occur primarily by way of organic matter decomposition. Conversely, peatlands can also be large sources of methane (CH_4) to the atmosphere (Waddington and Roulet, 1996; Bartlett et al., 1992) releasing ~4.0 g C m^{-2} yr^{-1} (Gorham, 1991). Due to saturated conditions of a natural peatland, production of CH_4 occurs under reduced anaerobic conditions through methanogenesis. Moreover, CH_4 is approximately 21 times more effective at global warming than CO_2 (IPCC, 2001). Differences in carbon exchange can result from topographic variations and the arrangements in plant species assemblages. Variability due to surface topography (e.g. hummocks and hollows) leads to differences in soil moisture, temperature, vegetation type, and biomass (Moore et al. 2002) thereby creating spatial variability in gas exchange processes. Waddington and Roulet (1996) observed the spatial variability of CO_2 and CH_4 exchange over a number of scales in a northern peatland. Generally, topographically lower areas such as hollows, pools or margins exhibited higher CH_4 emissions and lower CO_2 uptake than the adjacent topographically higher areas such as hummocks, ridges, and plateaus. Waddington and Roulet (1996) found that hollows can be large sources of atmospheric CO_2 (96 and 1288 g CO_2 m^{-2} yr^{-1}) while hummocks are nets sinks of CO_2 (-180 and -58.7 g CO_2 m^{-2} yr^{-1}). Additionally, seasonal methane flux was also greater in the hollows (8.11 and 9.84 g CH_4 m^2 yr^{-1}) than in adjacent hummocks (0.18 and 0.0 g CH_4 m^2 yr^{-1}) where both represented atmospheric sources of CH_4 (Waddington and Roulet, 1996). Consequently, variability in gas exchange processes due to topographic differences can have implications in understanding and characterizing the exchange of carbon (i.e. CO_2 and CH_4) in a peatland

Furthermore, peatlands are also a large source of dissolved organic carbon (DOC) with export downstream from peatlands to be ~20 g C m^{-2} yr^{-1} (Gorham, 1991). However, contemporary studies (Waddington and Roulet, 1997, 2000; Moore, 1987) suggest that this value can be much lower (1.0 to 6 g C m^{-2} yr^{-1}). DOC are organic compounds (i.e. humic and fulvic acids) which contribute to the carbon cycle in water based ecosystems with peat soil water containing 2 to 40 mg L^{-1} of DOC (Waddington and Roulet, 1997; Moore, 1987). While CO_2 exchange does not represent the complete carbon balance, it is generally used as a measure of contemporary peatland storage since it represents ~90% of the carbon exchanged in these ecosystems (Gorham, 1995) and therefore will be the main focus within this study.

1.2 Peatland Formation and Structure

Northern peatlands cover approximately 364 x 10^6 ha (Gorham, 1991) of the Earth's surface. Ombrotrophic peatlands are ecosystems that form when the peatland surface rises above the regional water table due to peat accumulation creating what is referred to as a groundwater mound (Ingram 1983) or raised bog system. These systems become isolated from mineral-rich groundwater (Clymo, 1983) and are dependent on the input of water and nutrients from atmospheric sources of precipitation thus become ombrotrophic in nature. With time and as peat accumulates by way of dead organic matter within anaerobic conditions in the system, bogs can typically exhibit a patterned structure of hummock, hollow, and pool structures (i.e. Foster et al., 1983).

Peatland formation commonly leads to a two-layered soil structure within the peat profile referred to as the acrotelm and catotelm (Ingram, 1978; 1992). The acrotelm is the upper layer of peat where water table fluctuations occur and is characterized by a high organic content that is poorly decomposed with high specific yield and porosity (Ingram, 1983). In natural peatlands, the large pore structure of the acrotelm contributes to a high water storage capacity (Boelter, 1968), particularly specific yield, which aids in limiting water table fluctuations to the near surface (Price, 1996). Specific yield is the ratio of volume of water yielded by gravity drainage to the volume of the soil and because of the large pore size structure in the acrotelm; specific yield is high due to the ability of pores to drain with relative ease by gravity. Similarly, hydraulic conductivity in the acrotelm is high and generally decreases with depth (Boelter, 1965). In contrast, the catotelm is the lower and deeper layer that is permanently saturated containing highly decomposed organic material. Since catotelmic peat is degraded and consists of smaller pores, less water can be drained through gravity resulting in low specific yield therefore higher water retention. Hydraulic conductivity is also low however porosity can remain high due to the number of smaller pores within the peat (Boelter, 1965). Consequently, the structural differences of the acrotelm and the catotelm are important in determining the storage of water in bog systems (i.e. Romanov, 1968). High water storage capacity of the acrotelm and its ability to shrink and swell, acts as a regulatory function that minimizes water table fluctuations maintaining the water table close to the surface (Ingram 1983). In a natural bog, water table position generally remains very close to the surface therefore the peat surface is able to maintain relatively wet conditions (Price, 1996). Furthermore, it is suggested that the hydrological function of a peatland is controlled by the structure and deformable character of the peat matrix (i.e. subsidence) (Price, 2003) where changes in peat volume can result in changes in hydraulic parameters that govern water retention and flow (Price and Schlotzhauer, 1999). More specifically, bulk density (Price and Schlotzhauer, 1999), water retention (Schlotzhauer and Price, 1999), and hydraulic conductivity (Price, 2003) have been reported to be altered due to seasonal changes in peat surface elevation. Therefore the diplotelmic structure is important in terms of both water transport and water storage where disturbance to this structure can cause considerable changes to the hydrological functions.

1.3 Peatland Extraction

Within North America approximately two-thirds of the peat extraction for horticultural purposes occurs within Canada and the demand for horticultural peat in Canada over the past century has lead to the drainage and extraction of over 12 000 ha of peatlands (Cleary, 2005). In areas such as the St. Lawrence lowlands in Quebec losses of peatlands for peat extraction exceed 70% (Van Seters and Price, 2001). Drainage and extraction of peatlands create conditions that disturb the natural hydrological and carbon cycling regimes of the ecosystem. Block-cutting and vacuum extraction techniques have been used primarily for the peat horticulture industry in Canada. Early peat horticulture was typically performed by block-cutting where drainage of the peatland occurred with a series of ditches and subsequent extraction trenches. The acrotelm was removed and discarded to the side exposing the catotelmic peat used for horticultural where the extraction of this deeper peat was cut by hand into blocks on average to 60 cm depth (Girard, 2002) consequently leaving the landscape in an arrangement of alternating baulks (raised mounds) and trenches (e.g. Robert et al., 1999; Girard, 2002). The remaining acrotelm material discarded to the side was generally moved to the centre of the extracted trench as more trenches were cut (Girard, 2002). Rarely used commercially today, remnants of these systems still remain in both Europe and eastern North America (Price et al., 2003). By the mid-1970s mechanized cutting became the dominant peat extraction practice for commercial use. Occurring at a larger areal scale than block cutting, deeper and more frequent drainage ditches are used in order to facilitate adequate drainage to support heavy extraction machinery (Price et al., 2003). Similar to block-cutting, the acrotelm is removed however rather than discarded adjacent to the extraction site, the stripping spoil or skag (i.e. vegetation layer) is discarded completely (Heathwaite et al., 1993). The peat surface is then milled to facilitate drying and peat fragments are typically vacuumed from the surface (i.e. vacuum extraction) using heavy machinery to depth of ~75 to 100 cm (Price et al., 2003). Consequently, the peat extraction process creates unfavourable conditions at the peat surface especially for species such as *Sphagnum* moss, the main peat forming vegetation, to reestablish.

Impacts to hydrology

The exposed catotelm on the surface of a cutover peatland is composed of highly decomposed peat with reduced water storage capacity (Schlotzhauer and Price, 1999), smaller pore size, higher bulk density and increased water retention properties (Price, 1996). With increasing time after drainage and abandonment, the peat matrix can continue to change structurally due to primary consolidation, secondary compression, shrinkage and oxidation processes (Schothorst, 1977; Schlotzhauer and Price, 1999; McNeil and Waddington, 2002). As mentioned earlier the water-storage capacity of the acrotelm is relatively high, however in cutover peatlands, the processes governing water storage are transferred to the more decomposed peat of the catotelm, thereby altering hydrological function (Price, 1996). Van Seters and Price (2001) observed changes in bulk density, hydraulic conductivity and specific yield due to peat subsidence where it was observed that bulk density in cutover peat increased from 0.07 to 0.13 g cm^{-3}; mean saturated hydraulic conductivity declined from 4.1 x 10^{-5} to 1.3 x 10^{-5} cm s^{-1}; and specific yield of a natural bog changed from 0.6 to values in cutover peat ranging between 0.04 and 0.06. Similarly, Schlotzhauer and Price (1999) found increased bulk density leading to increased water retention and decreases in hydraulic conductivity. In a cutover peatland, low specific yield can result in a large lowering of the water table with only a small amount of water drained (Price et al., 2003) which can consequently lead to a deeper and more variable water table lowering the saturated moisture content and increasing soil-water tension (Price 1996). As a result, the water table can become disconnected from surface-atmosphere exchange resulting in a rapid decline of soil moisture conditions during drier periods which can impede upward capillary flow because a deep water table cannot meet the evapotranspiration demands at the peat surface (LaRose et al., 1997). Consequently, atmospheric water demands are then supplied from the unsaturated storage zone (Price, 1997) further decreasing soil moisture. As soil moisture decreases and soil-water tension increases, water can be held more tightly within the smaller pore structure of the decomposed peat further limiting water availability to plants, especially non-vascular *Sphagnum* mosses (Price and Whitehead, 2004).

Sphagnum mosses are non-vascular plants that have no control of their rate of water loss and are not tolerant to prolonged desiccation (McNeil and Waddington, 2003; Hayward and Clymo, 1982). *Sphagnum* growth is dependent on an assured water supply and draws its moisture from the soil using capillary tension generated within its internal network of pendent branches and stems (Hayward and Clymo, 1982). If *Sphagnum* cannot generate capillary forces needed to extract moisture from the surface, desiccation will occur and the moss will die. When soil-water tension within *Sphagnum* reaches -100 mb (-100 cm), water films break between pendent branches and stems, intra-cellular hyaline cells drain and the plant loses its ability to conduct water upward by capillary action (Hayward and Clymo, 1982). In cutover peatlands, Price (1997) suggests that -100 mb is the critical threshold value within peat which *Sphagnum* cannot generate sufficient capillary forces to extract soil moisture. Moreover, Price (1997) also observed that soil-water tension in a bare cutover peatland can drop to values lower than -300 mb creating an extremely hostile environment for both *Sphagnum* survival and reestablishment.

Impacts to carbon exchange

Hydrological and biological conditions necessary for long-term peat accumulation rarely return to functional ecosystems after abandonment (Price, 1997). Extraction of peat for horticultural *Sphagnum* severely alters the ecosystem where the process of drainage, removal of vegetation, and abandonment affects the potential of *Sphagnum* moss to recolonize over the cutover surface, therefore sequester atmospheric CO_2. Recent studies suggest that cutover peatlands represent a persistent source of atmospheric CO_2 with carbon loss estimated at 300 to 400 g C m^{-2} year $^{-1}$ (Waddington and Price, 2000; Waddington and McNeil, 2002; Petrone et al., 2003). In cutover peatlands, unvegetated soils lead to increased oxidation and decomposition of peat that can dominate over carbon sequestration (Waddington et al., 2002) creating a shift towards a net source of atmospheric CO_2, which can be affected by water table dynamics. Schothorst (1977) suggested that CO_2 losses should decrease with time from abandonment due to decreasing quality of the substrate (i.e. less labile carbon sources). However, Waddington et al (2002) observed that older abandoned sites lost more carbon than recently abandoned and wetter sites suggesting that cutover peatlands can act as a significant carbon source over time. Moreover, a number of field and lab studies have indicated that in a peat extraction or climate change scenario an increase in CO_2 emissions can occur with a lower water table position (Gorham, 1991; Freeman et al., 1993; Moore and Dalva, 1993). In an undisturbed Finnish peatland, net release of CO_2 was 2.4 to 3.6 g CO_2 m^{-2} d^{-1} and increased to 7.2 to 9.6 g CO_2 m^{-2} d^{-1} when the water table was lowered (Silvola, 1986). Similarly, Komulainen et al. (1999) and Alm et al.

(1998) observed increased CO_2 efflux from a natural peatland with decreased water tables releasing between 10 to 117 g C m. Consequently, photosynthesis and respiration have a strong dependence on water availability (Silvola, 1990; Komulainen et al. 1999) suggesting growth and survival are reliant on a stable water supply. Similarly, a study by McNeil and Waddington (2003) suggests that *Sphagnum* growth in a cutover peatland is limited not only by water availability but also by drying and wetting cycles. These moisture cycles can suppress photosynthesis for a prolonged period of time and enhance respiration losses thereby indicating the importance of stable moisture conditions. Studies have also shown (e.g. Price, 1996; Van Seters and Price, 2001) that soil conditions critical to carbon exchange are dominated by the evaporative water loss over the summer therefore leading to a strong coupling between the moisture regime and carbon dynamics within a peatland (Waddington and Price, 2000).

While it is apparent that an increase in CO_2 towards the atmosphere occurs from cutover peatlands, drainage of peatlands can cause a reduction in CH_4 production as the water table decreases (e.g. Moore and Knowles 1989; Freeman et al 1993). Increased oxidation of CH_4 occurs with water table draw down due to an increased aerobic zone reducing production with depth. However, CH_4 emissions from cutover peatlands have also shown to be high in drainage ditches (Waddington and Price 2000; Day, 2003) indicating an important source of CH_4.

1.4 Peatland Restoration

Peatland extraction alters the ecohydrology of the system where the physical and hydrological conditions necessary for *Sphagnum* reestablishment and carbon sequestration are removed (Price, 1997; Van Seters and Price, 2001). As mentioned earlier, the hydrological function of extracted peatlands is left highly variable leaving surface conditions unsuitable for *Sphagnum* growth and survival. Natural regeneration of peatlands can occur but often leads to limited recovery of pre-extraction functions. Block-cut peatlands can regenerate to an extent due to *Sphagnum* diasporas that remain combined with residual microtopography of the baulks and trenches which aid in sustaining adequate soil moisture and soil-water tension for *Sphagnum* reestablishment (Price and Whitehead, 2001). However, only 17.5% of abandoned blocked-cut bog trenches in Quebec had *Sphagnum* covers greater than 50% (Lavoie and Rochefort, 1996). It was observed that high and stable water conditions (Campeau and Rochefort, 1996) contribute to elevated water levels leading to higher soil moisture conditions and lower soil-water tension at the peat surface (Price, 1997) favourable for *Sphagnum* growth. Conversely, the potential for vacuum extracted peatland natural regeneration is much lower because of greater degraded hydrological conditions that exist from mechanized extraction and complete removal of plant material. Ferland and Rochefort (1997) observed that the vacuumed peat surfaces dry out quickly even if the water table is close to the surface which consequently increases soil-water tension (Price, 1997) hindering the ability of *Sphagnum* to reestablish on the peat surface. Thus, management of peatlands is often required after abandonment where restoration techniques are introduced in order to create favourable hydrological conditions for vegetation reestablishment. Establishing *Sphagnum* mosses at the cutover surface is important due to its potential to sequester atmospheric CO_2 thus potentially returning the peatland to a carbon accumulating system (Waddington et al., 2003). Gorham and Rochefort (2003) suggest that peatland restoration occur immediately after extraction to reduce degradation at the peat surface preventing irreversible hydrological changes (Price, 1997) and potentially returning the carbon sink functions of the ecosystems (Waddington and Price, 2000).

In order to return hydrological functions at the surface, standard restoration techniques have included blocking of ditches (Eggelsmann, 1988), passive and pumped seepage reservoirs (LaRose et al 1997; Price 1998), artificial topography (Price et al., 1998), companion species (Ferland and Rochefort, 1997), and straw mulch application (Quinty and Rochefort, 1996; Price, 1997). Consequently, this elevates the water table, reducing soil-water tension at the surface and increases soil moisture (Price, 1997) to more favourable conditions at the surface. Schouwenaars (1988) suggested that effective *Sphagnum* re-establishment in cutover peatlands should occur where the water table does not drop below -40 cm. However, Price (1996) argued that water table depth is not as important as the soil-water tension in the surface layer. Price and Whitehead (2001) investigated an abandoned trench in a block-cut peatland where naturally regenerated mosses had established. Areas in which *Sphagnum* had recolonized were characterized by a high water table, soil moisture above 50%, and soil-water tension above -100 mb (Price and Whitehead, 2001). It was observed that the topographically low areas such as shallow ditches and lower skags adjacent to ditches maintained favourable soil moisture and soil-water tension (Price and Whitehead, 2001). Conversely, elevated areas were less favourable for *Sphagnum* reestablishment where lower soil moisture and higher soil-water tension existed. Moreover, Whitehead (1999) also observed that the existence of a capillary fringe (e.g. Gillham, 1983) in moderately decomposed peat can reach 30 cm above the water table helping to sustain an adequate water supply to the evaporate surface. Thus, hydrologically controlling the rewetting and evaporation of the site are important since both influence changes in soil moisture, water table, soil-water tension and hydraulic properties of the peat surface. From a restoration perspective, reestablishment of key vegetative species such as *Sphagnum* mosses will be the indicator in measuring the success of restoration.

Recent research suggests that understanding the nature and variability in soil moisture is important for the restoration process as well as for efficient monitoring and modeling (Petrone et al., 2004). It was observed in a restored peatland that the predominance of mosses existed in the wetter areas with moss presence strongly correlated with both spatial patterns in soil moisture and with vascular plant cover in drier conditions (Petrone et al., 2004). The latter observation is in accordance with McNeil and Waddington (2003) and Landriault (2004), where it was found that growth of *Sphagnum* moss are strongly dependent on the presence of vascular plants (i.e. ericaceous shrubs). Vascular shrubs tend to emerge before any considerable moss cover where observed spatial patterns suggest that diasporas germinated adjacent or under vascular shrubs (McNeil and Waddington, 2001; 2003). Landriault (2004) observed that *Sphagnum* cushions with vascular vegetation generally had higher soil moisture contents (7-24%) than those that had no vascular vegetation (3-12%). Hence, an important linkage exists between spatial patterns in soil moisture and vegetation cover. Moreover, understanding the nature of the spatial and temporal interactions with surface vegetation and soil moisture will facilitate a better understanding of the carbon exchange process especially in a restored peatland where the surface cover is changing (Petrone et al., 2004).

Due to the current understanding of the processes affecting restoration, management of peatlands need to consider surface moisture conditions in terms of water table, volumetric water content and soil-water tension. Moreover, effective modeling of cutover peatlands need to consider dynamically variable hydraulic parameters (i.e. hydraulic conductivity and soil-water tension relationships) to reflect the shrinking and swelling of the peat surface – a component not addressed in most hydrological models of peatlands (Price, 2003). As a result, Kennedy and Price (2005) developed a model to simulate peat deformation and its effects on soil hydraulic properties in both unsaturated and saturated conditions. Results indicated that the compressibility of the peat (i.e. elevation change) affected soil moisture and soil-water tension thus is important in describing the hydrological function of a natural and cutover bog. More importantly, analysis indicated that the preservation of the characteristically high compressibility and porous structure of the peat aids in maintaining sufficiently wet moisture conditions for *Sphagnum* recolonization (Price and Kennedy, 2005). Price and Kennedy (2005) further suggest that restoration techniques occur soon after abandonment where the use of extraction techniques that minimize soil compaction can greatly improve the restorability of a bog. Moreover, the reestablishment of *Sphagnum* may aid in the carbon sequestration (i.e. peat accumulation) (Waddington and Price, 2000) and may return the cutover peatlands to net carbon sinks (Tuitillia et al., 1999) promoting the reestablishment of the acrotelm allowing hydrological functions to return to more natural conditions.

While moisture conditions can considerably improve in a restored site immediately, restoration techniques may not return the peatland back towards a carbon sink post-restoration. While studies have shown that decreased CO_2 efflux can occur due to rewetting of the surface, respiration can remain quite high post restoration (Waddington and Warner, 2001). Moreover, Waddington et al. (2003) observed that addition of mulch to the surface can represent a short-term source of atmospheric CO_2 due to decomposition over time. Similarly, Petrone et al. (2001) determined that a restored peatland was a larger source of CO_2 than an adjacent cutover site due to mulch decomposition exceeding the production of the newly emergent mosses and vascular vegetation. Mulch addition, blocking of ditches with old vegetation, and new emergent vegetation with restoration will also likely contribute to increased DOC leaching (Toth, 2002). In a restored peatland, DOC concentrations increased in the outflow, which is likely contributed to the wetter conditions post restoration (Toth, 2002). However, while CO_2 fluxes may have increased post restoration (478 g C m^{-2} y^{-1}), DOC export represented only a small portion (0.7%) of the total CO_2 flux (Toth, 2002) from the ecosystem. Additionally, restoration of peatlands leads to an increase in CH_4 production where fluxes can be significantly larger than cutover sites. It is suggested that a rise in water table and establishment of vascular vegetation post-restoration increases CH_4 flux due to increased labile carbon sources and enhanced CH_4 transport through the vegetation

(Day, 2003). An increase in CH_4 was observed from 19 mg CH_4 m^{-2} y^{-1} to 1352 mg CH_4 m^{-2} y^{-1} three years post-restoration (Day, 2003) representing over a 70 times increases in CH_4. These findings are consistent with observations of natural peatlands being sources of atmospheric CH_4 (e.g. Waddington and Price, 2000; Waddington and Roulet, 1996).

In contrast, restored peatlands have been shown to return to a net carbon sink (Komulainen et al., 1999; Tuittilia et al., 1999). Furthermore, results suggest that active restoration techniques have the potential to return the cutover peatland to a net sink of atmospheric CO_2 within three to five years, where increased storage of CO_2 was attributed to reduced peat respiration via active rewetting and increase of ecosystem productivity from evolving vegetation (Greenwood, 2005).

1.5 Trench Extraction-Restoration

Recently a new peat extraction-restoration technique has been developed that increases peat extraction while attempting to minimize ecosystem impact by incorporating restoration straight into the process. The trench extraction-restoration technique removes peat similarly to traditional block-cut methods (e.g. Girard, 2002). Extraction of the peat is performed mechanically with a back-hoe by creating extraction trenches parallel to a long and deep (~4 m x 3m) cut drainage ditch (Figure 1.1a). Initially a ~20-30 cm deep section of the acrotelm containing the surface vegetation (mosses and shrubs) within a ~5 x 5 m plot is removed and placed beside the extraction zone (Figure 1.1b). Peat is then mechanically removed to the depth of interest (~2 m) containing the viable peat for horticultural purposes (Figure 1.1c). The extracted peat is then placed onto a train located within the peatland and transported to drying and processing facilities onsite. Once extraction is complete, the acrotelm that was retained is then replaced mechanically over the older and more decomposed catotelm peat in the extraction zone (Figure 1.1d). This creates a trench topography in which the surrounding natural peatland is higher than the extraction zone. The process is then repeated along the transect, thereby expanding the trench. Subsequent trenches are created parallel to the extracted-restored trench decreasing the overall elevation of the peatland over time (Figure 1.1e).

The replacement of the vegetation into the trench is considered the 'restoration' or rehabilitation process since the acrotelm structure is retained (Figure 1.2). Standard restoration techniques attempt to revegetate and reestablish a new acrotelm from a bare cutover surface – a process that is estimated to take years or even decades to develop. The retention of the surface layer is hypothesized to increase the restoration process since both the original vegetation and acrotelm is intact. However, the ability of the acrotelm and vegetation to maintain its hydrological and carbon exchange functions prior to the disturbance remains to be determined.

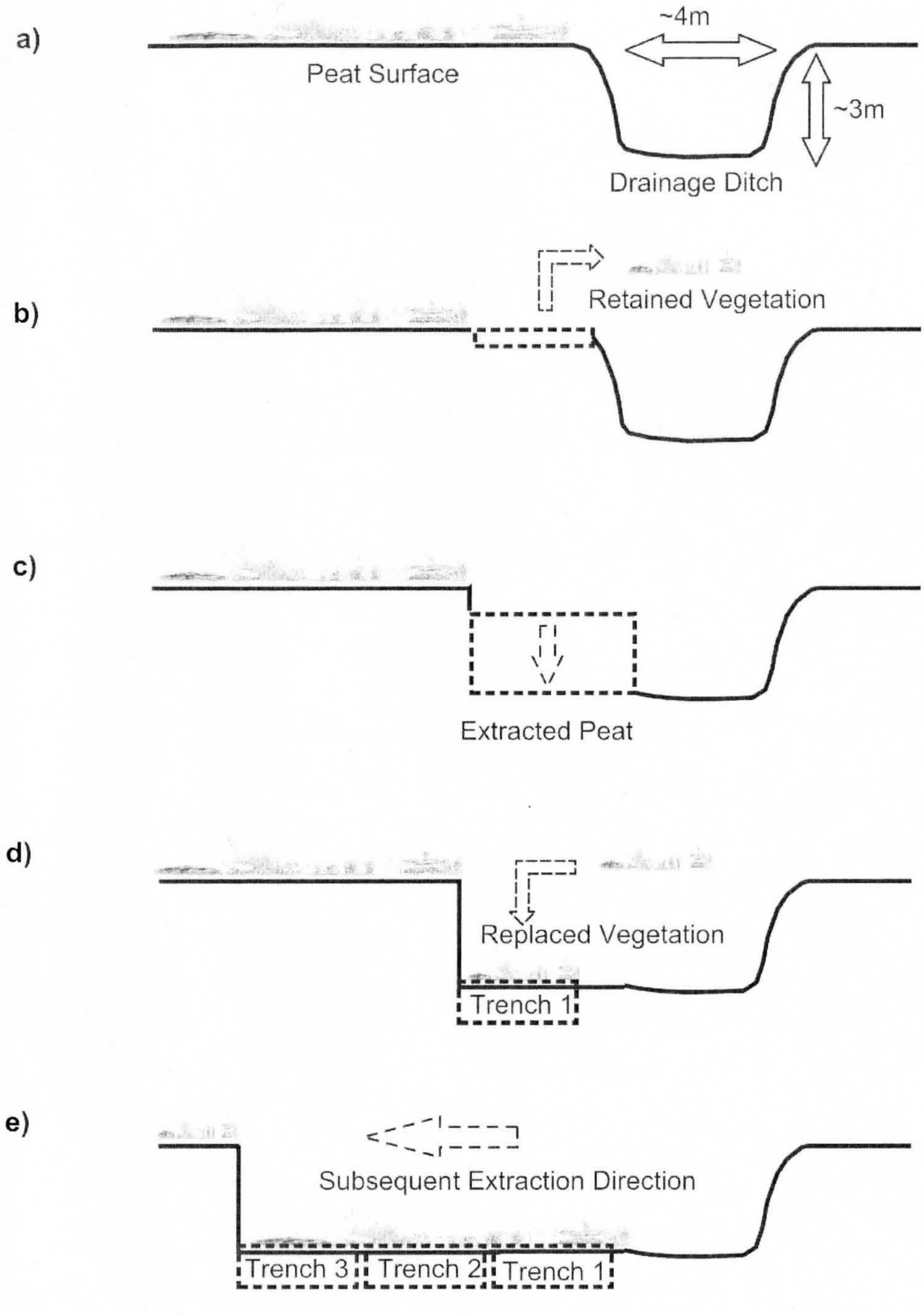

Figure 1.1: The trench extraction-restoration technique. a) A natural peatland prior to extraction adjacent to a large drainage ditch. b) ~20-30 cm of surface vegetation-acrotelm is removed and retained. c) Extracted peat d) Retained vegetation-acrotelm replaced on cutover surface. e) Extraction-restoration continues parallel and away from the ditch and moves into the peatland as subsequent trenches are created.

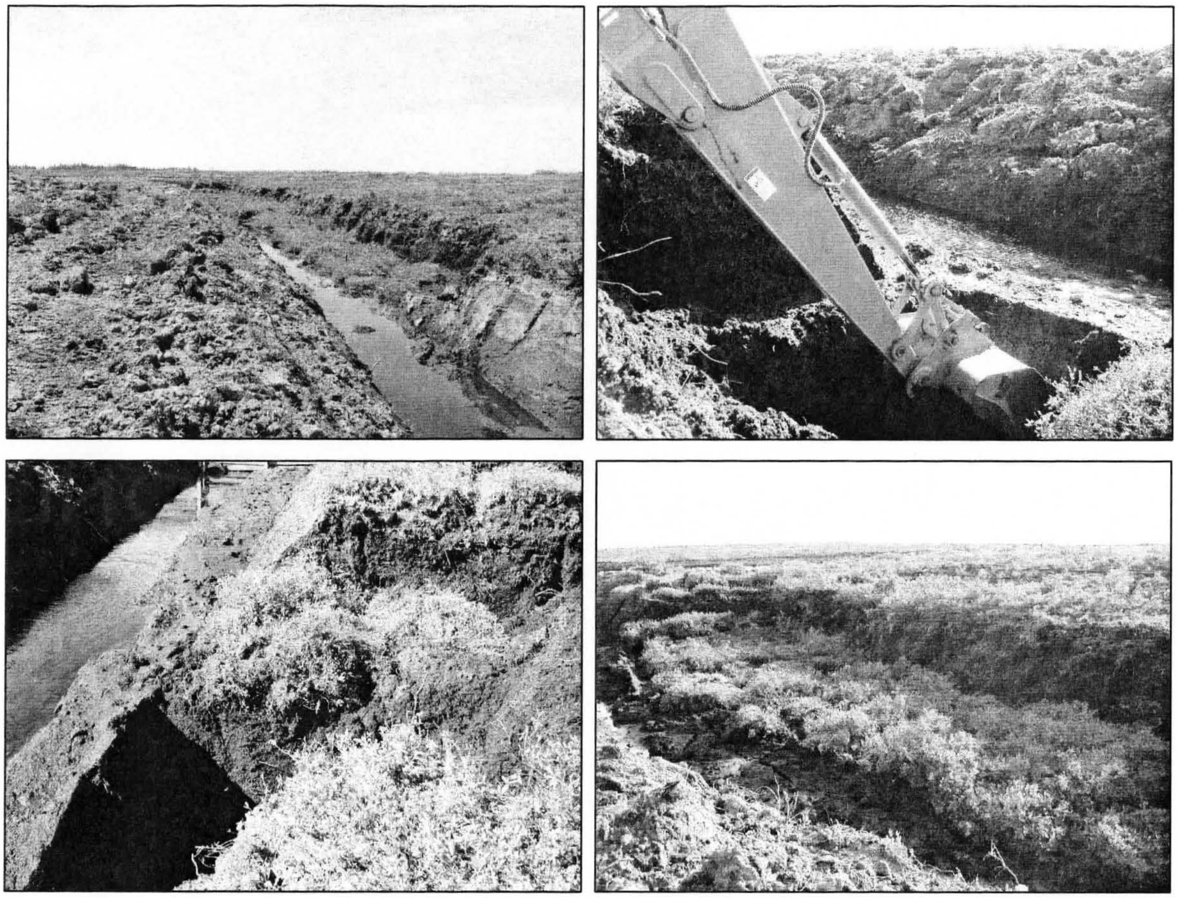

Figure 1.2: Natural peatland with large drainage ditch prior to extraction (Top L), Peat extraction with a back-hoe after top 20-30 cm of vegetation-acrotelm removed (Top R), Transplanted vegetation-acrotelm into the extracted trench (Bottom L), Restored trench after subsequent extraction (Bottom R).

1.6 Objectives

Studies support the need to understand the processes governing water and gas exchange so that appropriate management plans for peatland restoration can be developed (Waddington and Price, 2000). While it has been shown that standard restoration practices can return the peatland to more natural hydrological and carbon cycling conditions (i.e. Shantz and Price 2005; Greenwood, 2005), it may take many years post restoration for the acrotelm to fully redevelop, which is hypothesized to stabilize the hydrology and subsequently restore the carbon exchange functions of a peatland (McNeil and Waddington, 2003). This thesis examines a new peat extraction technique in which restoration is incorporated into the design. While standard extraction techniques remove and discard the acrotelm, this extraction-restoration technique retains the upper surface of the acrotelm and replaces it over cutover surface 'restoring' the peatland in the process. Due to the water regulatory functions that that acrotelm provides, it is hypothesized that the preservation of the acrotelm, will aid in maintaining close to natural hydrological conditions on the cutover surface post-extraction. More specifically, water table position will be close to natural near-surface conditions thereby stabilizing soil moisture content. By maintaining adequate water table, soil moisture, and soil-water tensions conditions, this allows suitable conditions for *Sphagnum* mosses survival and growth at the surface. Furthermore, it is hypothesized that the preservation of the acrotelm and the vegetation may improve overall carbon storage reducing large sources of atmospheric CO_2 emissions post-extraction. Consequently, the immediate presence of the acrotelm-vegetation cover over the cutover surface may return these ecosystems towards a net sink of atmospheric CO_2 sooner than traditional restoration techniques. More specifically the objectives of this thesis are to:

1. Determine the moisture dynamics and hydrophysical properties of a natural and acrotelm transplanted cutover peatland by:
    a) Characterizing spatial and temporal trends in soil moisture and water table position,
    b) Characterizing trends in peat soil-water tension in relation to *Sphagnum* thresholds and,
2. Determine the controls and CO_2 exchange at a natural and acrotelm transplanted cutover peatland through:
    a) Measuring spatial and temporal net ecosystem CO_2 exchange and,
    b) Determining the dominant ecohydrological processes controlling CO_2 exchange.

CHAPTER 2: METHODOLOGY

2.1 Study Area

This study was conducted at the Point-Lebel peatland, ~20 km south of the town of Baie Comeau, Québec (49° 7′N, 68° 12′W) (Figure 2.1). The average annual temperature at the Baie Comeau airport (~3 km from the research site), is 1.5°C with a mean January and July temperature of -14.4°C and 15.6°C respectively. The 30-year normal (1971-2000) annual precipitation is 1014.4 mm of which 684.1 mm is rain (Environment Canada, 2006).

The Pointe-Lebel peatland is situated on top of deltaic sands adjacent to the St. Lawrence River forming a 92 ha shrub (*Chamaedaphne calyculata, Kalmia angustifola, Picea mariana* and *Ledum groenlandicum*), *Sphagnum* moss (*S. Rubellum, S. Fuscum*) and scattered open water pool bog complex. At the southern end of this complex a small section of the peatland was subdivided into two sites for this study – natural and experimental (Figure 2.1). The natural site served as the control site and comprised a pristine section of the peatland that was not impacted by any peat extraction or peatland drainage. In June 2005, an experimental trench (~6 m x 12 m) was extracted parallel to a (~2 m x 1 m) drainage ditch within the peat extraction zone and was used as an experimental site. The peat depth in the peatland ranges from 5 to 6 m.

Measurements of peatland hydrology and CO_2 exchange were undertaken from May 20th to August 18th (day of year 140-230) representing the spring and summer growing periods.

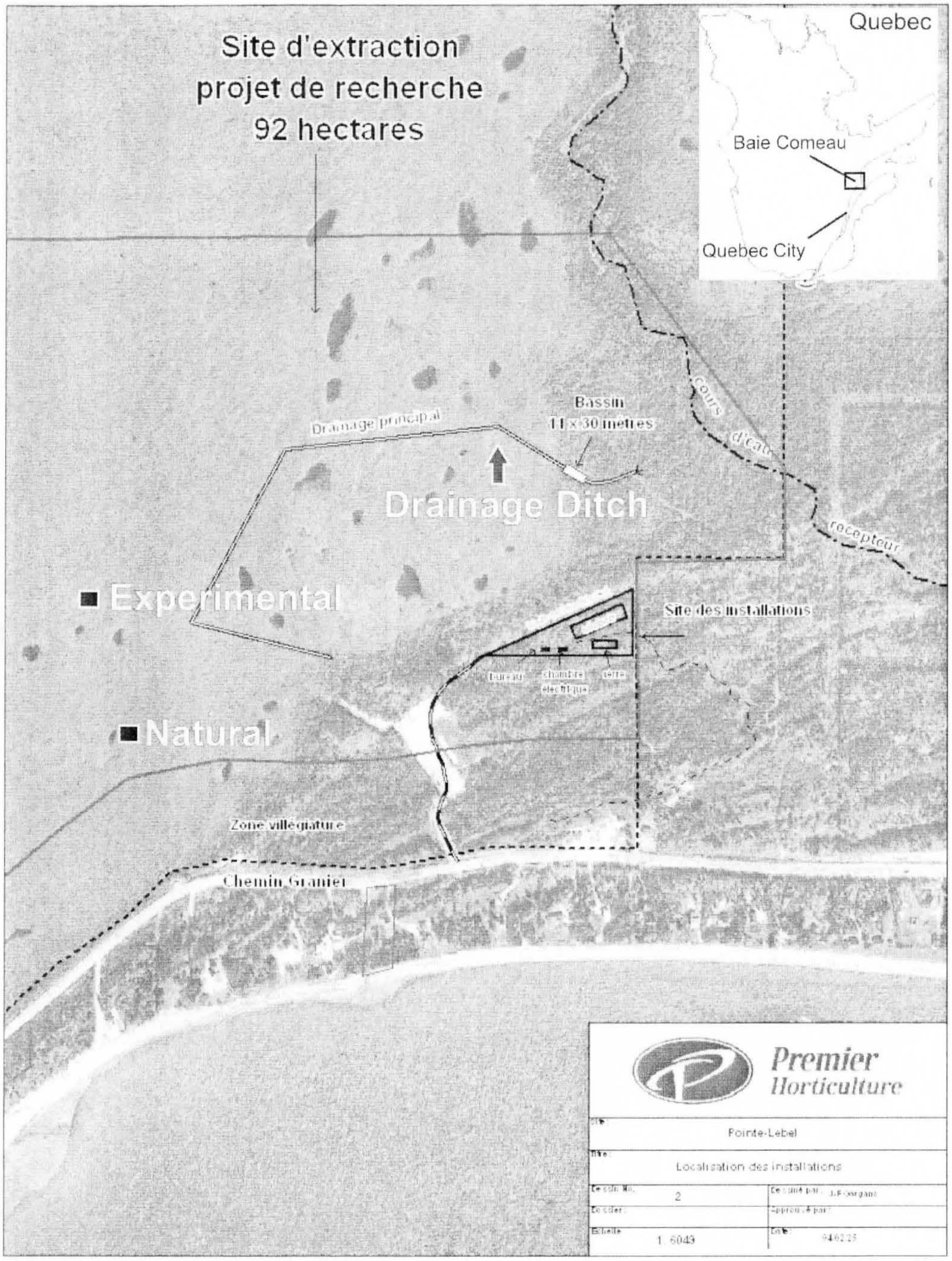

Figure 2.1: Pointe-Lebel peatland study area showing the location of the natural and experimental sites

2.2 Meteorological Variables

Air temperature was measured using a Campbell Scientific T107 (Alberta, Canada) air temperature probe and a series of thermocouples (Type E) installed at various depths (5, 10, 15, 30 and 60 cm). Precipitation was measured using a Texas Electronic (Campbell Scientific Inc.) tipping bucket rain gauge at the natural site and additional precipitation data was collected from the adjacent Baie Comeau airport weather station (Environment Canada, 2006). PAR was measured using a Li-COR (Lincoln, Nebraska) quantum light sensor (μmol m^{-2} s^{-1}). These variables, logged every 20 minutes at both the natural and experimental sites using Campbell Scientific CR10X dataloggers (Alberta, Canada), were used to establish empirical relationships with CO_2 flux (see section 2.4) over the season.

2.3 Hydrological Measurements

Water table position

Water table levels were measured at two locations (natural and experimental) using a pulley system potentiometric water level recorder and logged every minute and averaged every 20 minutes using the dataloggers. Additional manual point water table measurements were taken at 12 permanent slotted PVC wells located adjacent to CO_2 flux plots (see section 2.4) in each of the natural and experimental sites on a weekly basis for determining relationships with the CO_2 measurements (see section 2.4).

Volumetric moisture content

Within the ~25 cm acrotelm, two depths were chosen to measure volumetric moisture content (VMC), specifically the *Sphagnum* capitula (0 to 4 cm) where surface moisture content changes have been shown to affect photosynthesis (Rydin and McDonald, 1985) and a lower acrotelm depth chosen to represent the mean acrotelm moisture condition (10 to 14 cm). These measurement depths (zones) are hereafter referred to as *capitula* and *mid-acrotelm.*

Due to the issues of destructive sampling methods (e.g. gravimetric water content), volumetric moisture content (VMC) measurements were used to assess peat soil moisture with the consideration to the issues of compressibility in these environments. VMC at the 2 cm capitula depth (θ_c) was determined using dual pulse heat probes (DPHP) (East 30 Sensors, Washington) attached to a multiplexer (Campbell Scientific AM16/32, Alberta, Canada) and datalogger logging at 60-minute intervals. The DPHP sensors consist of a pair of 30 mm steel needles spaced six mm apart. One end contained an Evanohm heater and the other a chromel-constantan (Type E) thermocouple (East 30 Sensors, Washington). A current is applied to the heater for a specified time and the temperature rise of the thermocouple is monitored. The specific heat of the material (e.g. peat) is inversely proportional to the height of the sensed temperature rise and the thermal diffusivity of the material is related to the time taken for the heat pulse peak to pass the temperature sensor (East 30 Sensors, Washington). Properties such as thermal diffusivity, specific heat, and VMC can be calculated from the output of the measurement. A DPHP was installed at a lawn and hummock microform at each site to determine temporal changes in θ_c over the season.

Similarly, Campbell Scientific CS615 (Alberta, Canada) water content reflectometers were used to measure volumetric moisture content at the 10 cm mid-acrotelm depth (θ_a) at each site. The probe consists of two 30 cm long steel probes using time-domain measurement methods that are sensitive to dielectric permittivity to calculate moisture content (Campbell Scientific, Alberta).

Spatial moisture surveys were taken at a 10 m x 10 m plot at the natural site and a 12 m x 1 m plot at the experimental site. Measurements were taken over three periods at natural (June-August) and two periods at experimental (July-August). θ_c were taken with an instantaneous portable Campbell Scientific Hydrosense (CD620) soil moisture TDR (12 cm probe length and ±3% accuracy) (Campbell Scientific, Alberta, Canada) which integrated the upper 5 cm surface layer and was calibrated in the laboratory for peat soils. A total of 400 point–VMC measurements were taken per plot (at each period) using a grid sampling technique to characterize the spatial variability of θ_c over the season. However, different sampling regimes (i.e. measurement intervals) were used due to the space limitation at the experimental trench site. These point measurements were then inputted into a contour surface-mapping program (Surfer 8.0, Golden Software, Colorado) to map the spatial distribution of θ_c at each site.

Soil-Water Retention Curves

Large intact peat blocks (~26 x 33 x 24 cm) were removed from the natural and experimental sites in August 2005. The samples were carefully placed in coolers and transported back to the laboratory within 48 hours and frozen. The soil blocks were then cut into several cylindrical capitula and mid-acrotelm cores (8 cm diameter, 4 cm deep) with a hole-saw while frozen to prevent compression and disturbance to the physical structure during cutting. Capitula cores were taken from 0-4 cm and mid-acrotelm were taken from the 10-14 cm. Replicates of 8 sub samples at each depth for both sites were analyzed to determine differences between sites and depths in soil-water retention curve characteristics and to evaluate the spatial variability.

Soil-water retention curves were determined on all cores using a methodology fully described by Dane and Hopmans (2002) and Klute (1986). Briefly, the frozen soil samples (contained in PVC rings) were saturated and thawed in de-aired water for 48 hrs prior to testing to achieve full saturation of the peat. Samples were then placed on top of a high flow 0.5 bar porous ceramic plate cell (effective pore size 6.0 micron, hydraulic conductivity 3.11 x 10^{-5} cm/sec and approximate porosity of 50% by volume) within a 5 bar pressure plate extractor (Model 1600, Soil Moisture Equipment Corp., Santa Barbara) and sealed. Various tensions were applied (20, 40, 60, 80, 100 and 120 mb) using a pressure manifold (±1% accuracy) (Model 700-3, Soil Moisture Equipment Corp. Santa Barbara) until equilibrium of the samples was reached within the pressure cell. A water outflow tube was connected from the pressure extractor into a graduated glass beaker to measure the water outflow from the samples. Equilibrium of the samples at each tension increase was reached when the outflow of water had ceased (generally 1 to 3 days). Samples were weighed prior to moisture extraction (100% saturation) and after each tension change once equilibrium was observed. Moisture content was determined at equilibrium using the following equation:

$$\theta = \frac{(M_{WET} - M_{DRY})}{\rho_w * V_s} \qquad [2]$$

where M_{WET} is the mass (g) of the moist soil at equilibrium, M_{DRY} is the mass (g) of the oven-dry soil, ρ_w is the density of water (g/cm^3), and V_s is the volume of soil sample (cm^3). The soil-water retention relationship is then described using tension and moisture values. Additionally, peat physical properties such as peat bulk density (ρ) [3]:

$$\rho = \frac{M_{DRY}}{V_s} \qquad [3]$$

where M_{DRY} is the mass (g) of the oven-dry soil and V_s is the volume of soil sample (cm^3)

and porosity [4]:

$$\phi = 1 - \frac{\rho}{\varphi} \qquad [4]$$

where ρ is bulk density and φ is particle density (1.4 g/cm^3) based on literature values for peat (Skempton and Petley, 1970) were determined to further describe the hydrophysical characteristics of the peat.

Spatial variability of the 5 cm capitula surface soil-water tension (θ_c) was determined using the data collected from both the spatial VMC survey (θ_c) measurements and soil-water retention curves. Changes in soil-water tension were assessed at a number of periods at the natural site (June-August) and experimental site

(July-August). A simple polynomial relationship describing the soil-water tension relationship was derived from the laboratory soil-water retention curves and applied to the θ_c survey point measurements to calculate the relative ψ_c. The θ_c values were then inputted into a contour surface-mapping program (Surfer 8.0, Golden Software, Colorado) to map the spatial distribution of soil-water tension (ψ_c) and variability at each site. This 'best estimate' approach to determine field ψ_c was used since field measurements of ψ_c are very to difficult to measure directly on natural peatland environments.

2.4 CO_2 Exchange Measurements

The static chamber technique (e.g. Griffis et al. 2000) was used to measure the net ecosystem exchange of CO_2. Permanent sampling locations were located within each site that included the dominant vegetation structures of shrub (*Chamaedaphne calyculata, Kalmia angustifola, Picea mariana* and *Ledum groenlandicum)* and *Sphagnum* moss species (*S. Rubellum*, *S. Fuscum*). Twelve sampling locations were installed at each site (24 total) to ensure representativeness of the flux measurements and characterization of the vegetative structure. Square metal collars (60 x 60 cm) were inserted into the peat and maintained as permanent sampling stations (plots). A clear square Plexiglas chamber (area = 1200 cm^2, volume = 120 L) was placed and sealed over the collars to measure net ecosystem exchange (NEE). Temperature within the chamber was monitored and an internal cooling system maintained ambient temperature conditions during light conditions. Respiration (R_{TOT}) was measured by placing an opaque plastic tarp over the chamber. Gross ecosystem production (GEP) was determined as the difference between measured NEE and R_{TOT} values from the plot over the same sampling period. NEE and PAR relationships were established using a series of mesh shrouds of various sizes placed over the clear chamber to measure NEE under reduced light conditions. The concentration of CO_2 in the chamber headspace was measured using a portable infrared gas analyzer (IRGA) (EMG-2 PP-Systems, Amesbury MA) at 30-second intervals over a three-minute period. Instantaneous measurements of peat temperature, volumetric moisture content (VMC), water table, and photosynthetic active radiation (PAR) (PAR-1, PP-Systems Amesbury MA) were recorded at each collar during chamber sampling. Peat temperature (°C) was measured using a Barnant temperature probe (Barnant, USA) and VMC of underlying peat was measured using a Campbell Scientific Hydrosense TDR. Temperature, VMC, and water table were used to establish empirical relationships with CO_2 flux. CO_2 fluxes were calculated from the slope of the gas concentration over time and quality control of fluxes was performed. Slopes with r^2 values of less than 0.70 were excluded from calculations except for the case of zero flux. Regression analysis was conducted to determine relationships between the measured environmental variables to CO_2 flux. A statistical analysis package was used (SPSS Inc., Chicago) for multiple regression analysis and ANOVA testing of measured data at each site to determine both empirical relationships and significance of fluxes respectively.

Ecophysiological parameters of CO_2 fluxes were characterized by creating light response curves, which models the relationship between the gross ecosystem production

(GEP) and photosynthetically active radiation (PAR) and is fitted empirically using an equation for a rectangular hyperbola:

$$GEP = \frac{(\alpha * PAR * GP_{MAX})}{(\alpha * PAR) + GP_{MAX})} - R_{TOT} \qquad [1]$$

where PAR is measured PAR (μmol m^{-2} s^{-1}), GP_{MAX} is the empirically derived gross photosynthetic exchange of CO_2 and α is the initial slope of GEP versus PAR. Respiration (R_{TOT}) was modeled separately using a simple linear or multiple regression relationship from chamber-based measurements with peat temperature, water table and/or moisture at some plots.

The growing season was divided into three general periods in order to model daily CO_2 exchange over the season. The early (May 20th to June 2nd), mid (June 10th to July 31st), and late (August 4th to August 18th) periods evaluate the differences in the light response curves at both the initial slope of GEP (α) and maximum GEP (GP_{MAX}) over the season. The light response curve relationships for each period and each plot were applied to continuous daily PAR measurements (days 140-230) and averaged over a 24-hour period to obtain daily averages for GEP. R_{TOT} was calculated similarly using the environmental controls stated above and NEE was calculated as the addition of GEP and R_{TOT}.

2.5 Vegetation survey

The extraction-restoration process of the new peat extraction technique allows ~20-30 cm of the surface vegetation to be retained. This retained portion is subsequently replaced back into the cutover trench shortly after peat extraction resulting in an immediate restoration/rehabilitation of the cutover surface. However, the extraction process may disturb the vegetative structure thereby affecting both the hydrological and carbon exchange functions of the original surface cover. Plot vegetation surveys at each plot were performed to identify the dominant individual vegetation species at both the natural and experimental sites. These species were then further grouped broadly into mosses and shrubs and a relative percent cover within the plots was applied to classify dominant vegetation type. Determination of the dominant vegetation is important in understanding the composition of each plot since mosses and shrubs respond differently in terms of CO_2 exchange; however the physiological condition (i.e. health) of the vegetation post disturbance particularly at the experimental site may influence the productivity at the site. From the vegetation survey it was apparent that vegetation had experienced some disturbance (i.e. living and dead vegetation) therefore plots were correlated to maximum measured GEP to determine the productivity differences between disturbed and non-disturbed plots.

CHAPTER 3: MOISTURE DYNAMICS AND HYDROPHYSICAL PROPERTIES OF A TRANSPLANTED ACROTELM

3.1 Introduction

Peatland drainage and peat extraction generates harsh ecological and microclimatic conditions for bog vegetation to reestablish following peat extraction and abandonment. During this abandoned stage the water table becomes more variable, there is a lowering in saturated moisture content and increases in soil-water tension (Price, 1996) leading to an increase in peat decomposition (Waddington et al., 2002) and low vegetation productivity (Greenwood, 2005). As soil moisture and soil-water tension decrease, water can be held more tightly within small pores of decomposed peat limiting water availability to plants, especially non-vascular peat-forming *Sphagnum* mosses (Price and Whitehead, 2004). In order for *Sphagnum* moss to reestablish on the cutover surface, water management techniques such as blocking of ditches (Eggelsmann, 1998), bund construction (Eggelsmann and Blankenburg, 1993), and straw mulch application (Price 1997, Quinty and Rochefort, 1996) are required to significantly improve the hydrological conditions on cutover peatlands. However, restoring the hydrology of a cutover peatland can be very expensive due to the costs of implementing the various restoration techniques and often occurs many years after abandonment which consequently can lead to a large source of atmospheric CO_2 due to the decomposing peat and the unvegetated surface (Waddington et al., 2002). Moreover, the restored peatland hydrology does note resemble that of a natural peatland within the first few years post-restoration (Shantz and Price, 2005) and it has been suggested that this will not occur until a new acrotelm is established on the cutover surface (Shantz and Price, 2005). In natural peatlands the acrotelm has a very high specific yield and as such it assists in regulating and maintaining the water table close to the surface (Ingram, 1984) aiding in governing peatland water storage and water transport properties. In this study a new peatland restoration technique is examined in which ~20-30 cm of the upper acrotelm with vegetation intact is retained during the peat extraction process and placed directly on a cutover peat surface. It is hypothesized that the retention and replacement of the upper acrotelm layer in this new restoration technique will maintain close to natural hydrological conditions post extraction. More specifically, it is hypothesized that the water table would remain close to natural near-surface level conditions thereby stabilizing soil moisture content. However, due to the movement of the peat surface during extraction and replacement of the peat, it is expected that structural changes could occur in the transplanted acrotelm peat causing large pores within the peat to collapse thereby affecting moisture retention and water movement properties.

This chapter characterizes the moisture and hydrophysical conditions of a natural and trench-extracted experimental site. More specifically the temporal variation in volumetric moisture content at the capitula (2 and 5 cm) and mid-acrotelm (10 cm) layers is evaluated; the surface soil-water tension in context to *Sphagnum* physiological thresholds and structural differences is determined; and an assessment of the spatial variability in volumetric moisture content and soil-water tension is made at each site.

3.2 Precipitation and water table position

Precipitation during the study season totaled 253 mm, which was much lower than the long-term precipitation normal (1971-2000) for the Baie Comeau meteorological station of 340 mm over the same period (Environment Canada, 2006). Frequent precipitation events occurred during the first half of the study season (days 140-180) where 153.5 mm of rain fell compared to 100.5 mm during the latter half of the study season (days 181-230) (Figure 3.1). Major precipitation events occurred on days 142, 161 and 195 with rainfall depths of 24, 37 and 36.5 mm, respectively. Additionally, from days 160-165 a total of 60 mm of precipitation fell within a 5-day period. During this time, the experimental site experienced a large flooding event shortly after the trench extraction process was complete. Water table position (wt) reached above surface levels due to a backup of water at the site until adequate draining occurred post-harvesting after which wt levels returned to close to surface conditions. The experimental site wt declined throughout the season and ranged from a depth -13.1 cm to +6.6 cm with a mean of -8.4 ± 4.2 cm. Natural site wt reached a maximum and minimum depth of -25.6 and -0.2 cm respectively with a mean of -12.7 ± 6.0 cm.

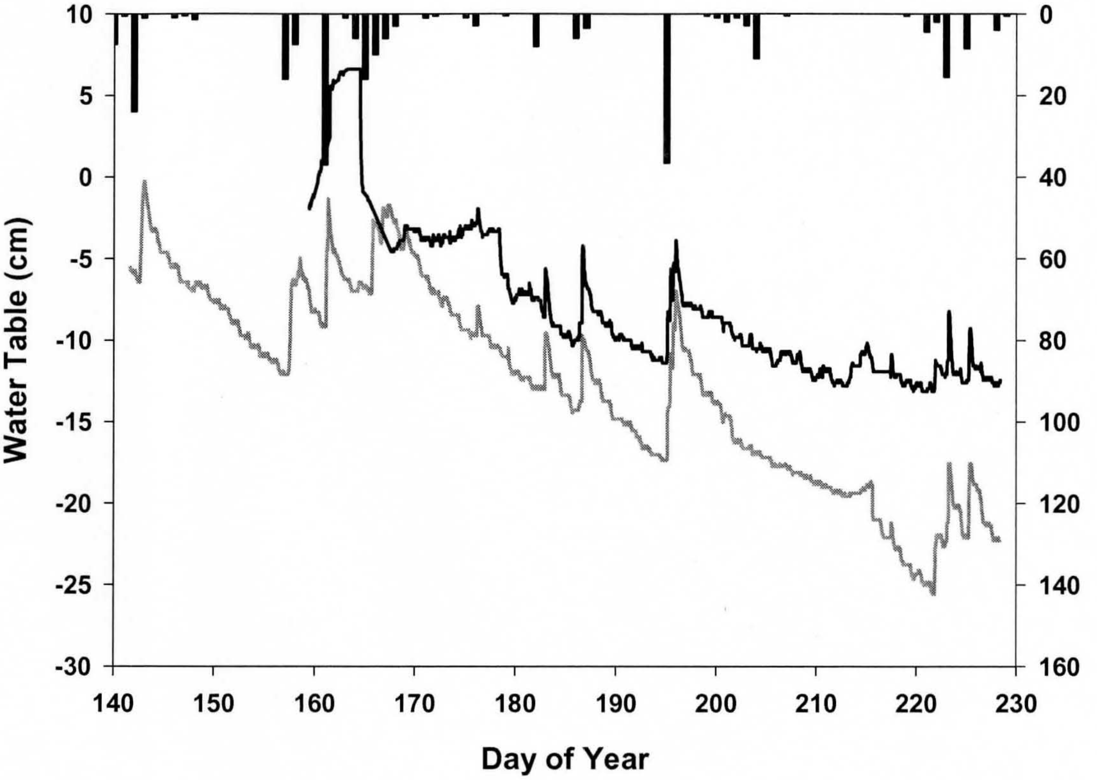

Figure 3.1: Daily precipitation (upper panel) and continuous water table position at the experimental (black line) and natural (grey line) sites.

3.3 Volumetric moisture content

Seasonal variability in mid acrotelm VMC

A decline in the mid-acrotelm at 10 cm depth (θ_a) occurred throughout the season at both sites however the temporal variability of θ_a at the experimental site was much larger over the season (Figure 3.2). The experimental site was very sensitive to precipitation events enhancing the moisture variability where rapid increases and decreases in moisture were observed throughout the season. For example, precipitation events (e.g. days 183 and 195) allowed moisture content to rise considerably after large rainfall events followed by a rapid decline during dry periods. Conversely, the natural site θ_a was very stable, decreasing gradually over the season. Due to variability, volumetric moisture content was significantly different ($p<0.05$) at the natural site (90.4 ± 1.6%) than the experimental site (89.2 ± 7.0%) despite similar means. Moreover, θ_a at both sites remained above 50% throughout the season.

Seasonal variability in capitulum VMC

Volumetric moisture content in the capitula at 2 cm depth (θ_c) was 76.8 ± 5.6% and 65.2 ± 4.0% for the natural site lawn and hummock respectively. Conversely, the experimental site lawn and hummock averaged 82.4 ± 5.0% and 56.2 ± 22.1% over the season. θ_c at the natural site was higher at the hummock however the lawn was greater at the experimental site over the season.

The natural site lawn θ_c (76.8 ± 5.6%) was significantly higher ($p<0.05$) than the natural site hummock (65.2 ± 4.0%) (Figure 3.3a). Lawn capitula maintained stable moisture content that slowly declined as the season progressed. Furthermore, a moderately rapid decline in θ_c was observed at the natural site hummock followed by more stable moisture conditions. θ_c variation at both microforms remained low due to fairly stable moisture contents over the season however the lawn appeared to have a slightly greater daily θ_c change compared to the hummock. Additionally, the hummock appeared to be more sensitive to rain events since large increases in θ_c corresponded with large precipitation events.

At the experimental site lawn, θ_c (82.4 ± 5.0%) was significantly higher ($p<0.05$) than hummock θ_c (56.2 ± 22.1%) (Figure 3.3b). Both the experimental hummock and lawn θ_c started the season under saturated conditions during the flooding event and declined rapidly as the season progressed. The hummock however, experienced a much greater decline after flooding and remained variable throughout the season. θ_c variability at the experimental hummock was quite large with considerable changes in moisture observed on a daily basis. Although the hummock microform at the natural site experienced a heat pulse probe failure during the last half of the season, it may be reasonable to postulate that a declining trend in moisture would have occurred over the season with possible daily changes in VMC (as observed at the experimental site) being generated, however at much lower variability (Kettridge, pers. comm.). Furthermore, θ_c at the natural site never dropped below 50% whereas the experimental site experienced surface moisture levels below this level at only the hummock microform.

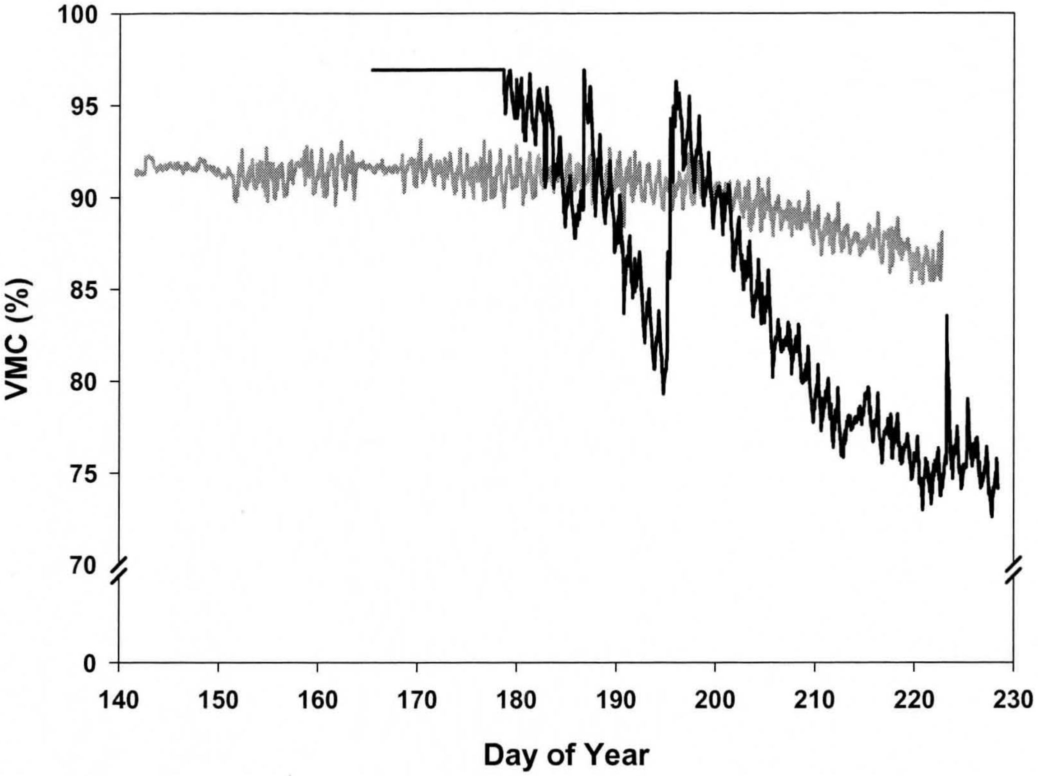

Figure 3.2: 10 cm VMC (θ_a) at the natural (grey line) and experimental (black line) sites.

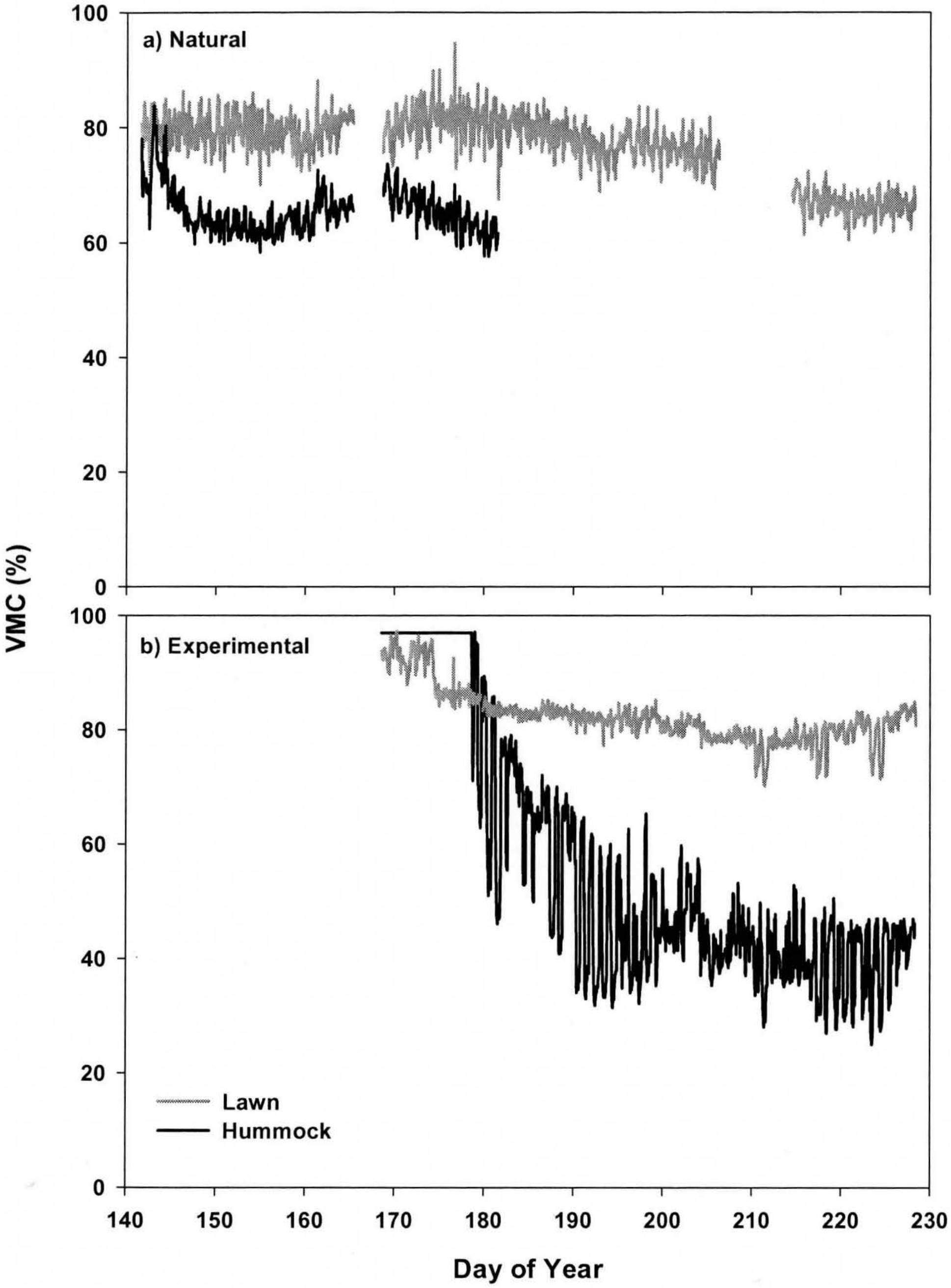

Figure 3.3: 2 cm VMC (θ_c) at a) natural and b) experimental lawn (grey) and hummock (black) microforms. *Natural hummock VMC probe failure from DOY 182-230

Diurnal variability in capitula VMC

A time series spectral plot with a Tukey-Hamming spectral window (SPSS, Chicago, Illinois) revealed that a 24 hour diurnal cycle for θ_c existed at all microforms at the natural and experimental sites over the season. Spectral density and frequency plots showed that the signal strength of the diurnal cycles differed between microforms and sites. Generally, the natural lawn showed stronger diurnal signals compared to the experimental lawn, however, the experimental hummock exhibited much stronger daily diurnal cycles than the natural hummock. A well-defined moisture pattern at experimental hummock existed during high light periods where wetting and drying cycles were very pronounced (Figure 3.4a). During low light periods, the diurnal cycle was much more suppressed and patterns in θ_c were not very apparent (Figure 3.4b). A post wetting event revealed a different pattern with capitula moisture content moderately stronger than the low light period (Figure 3.4c). Moreover, the experimental lawn microform showed a much lower suppressed diurnal signal compared to the experimental hummock. Conversely, the natural site hummock revealed a lower diurnal signal than the experimental hummock during the high light periods (Figure 3.5a). The low light period responded similarly to the high light period with moderately less variation (Figure 3.5b) and slightly stronger diurnal pattern emerged during a post wetting event compared to a full light period (Figure 3.5c). Moreover, the natural site lawn microform responded very similarly to the natural hummock diurnal patterns.

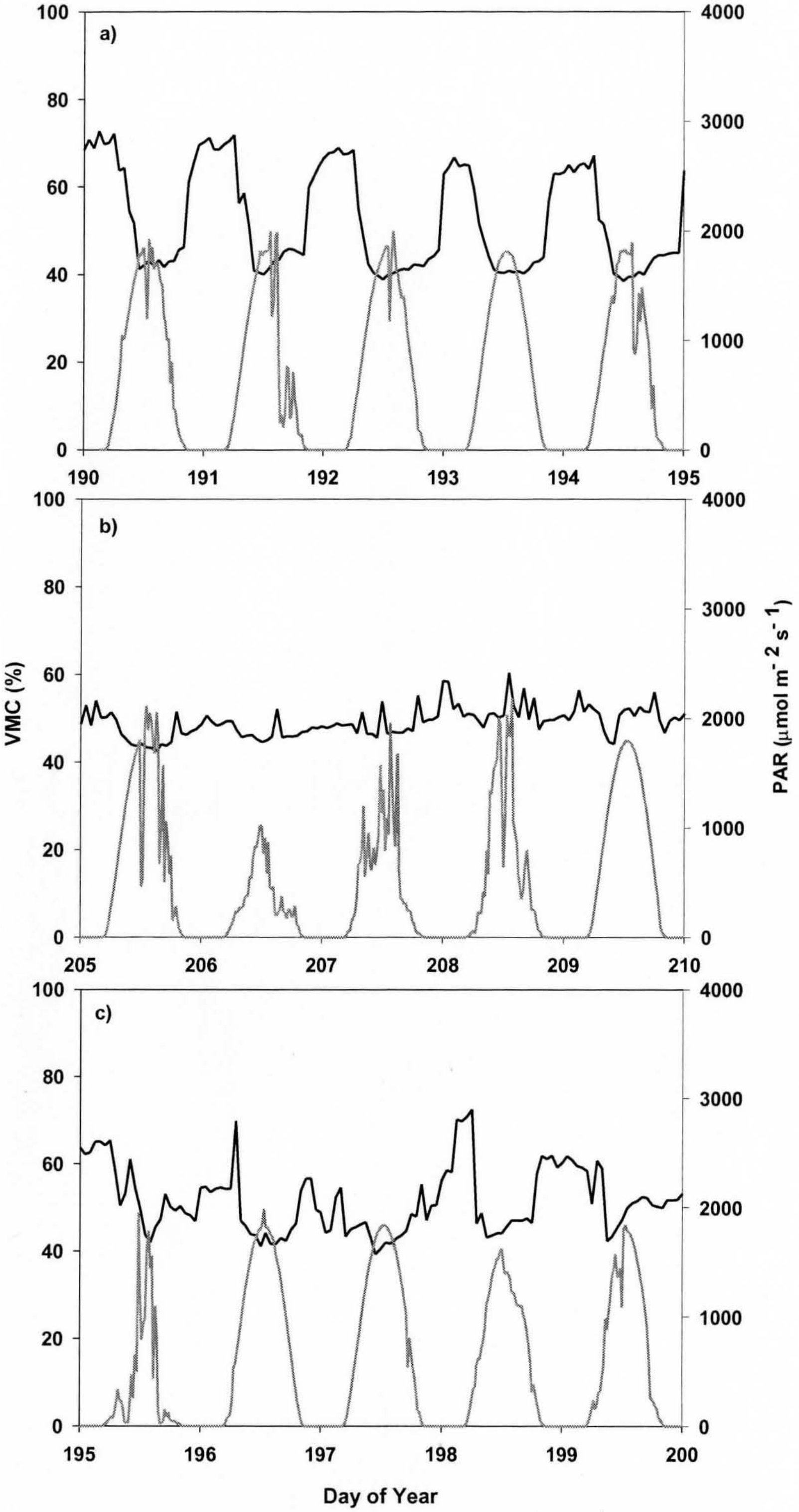

Figure 3.4: Experimental site diurnal variation in capitula VMC (θ_c) during a) high light, b) low light, and c) post-precipitation conditions.

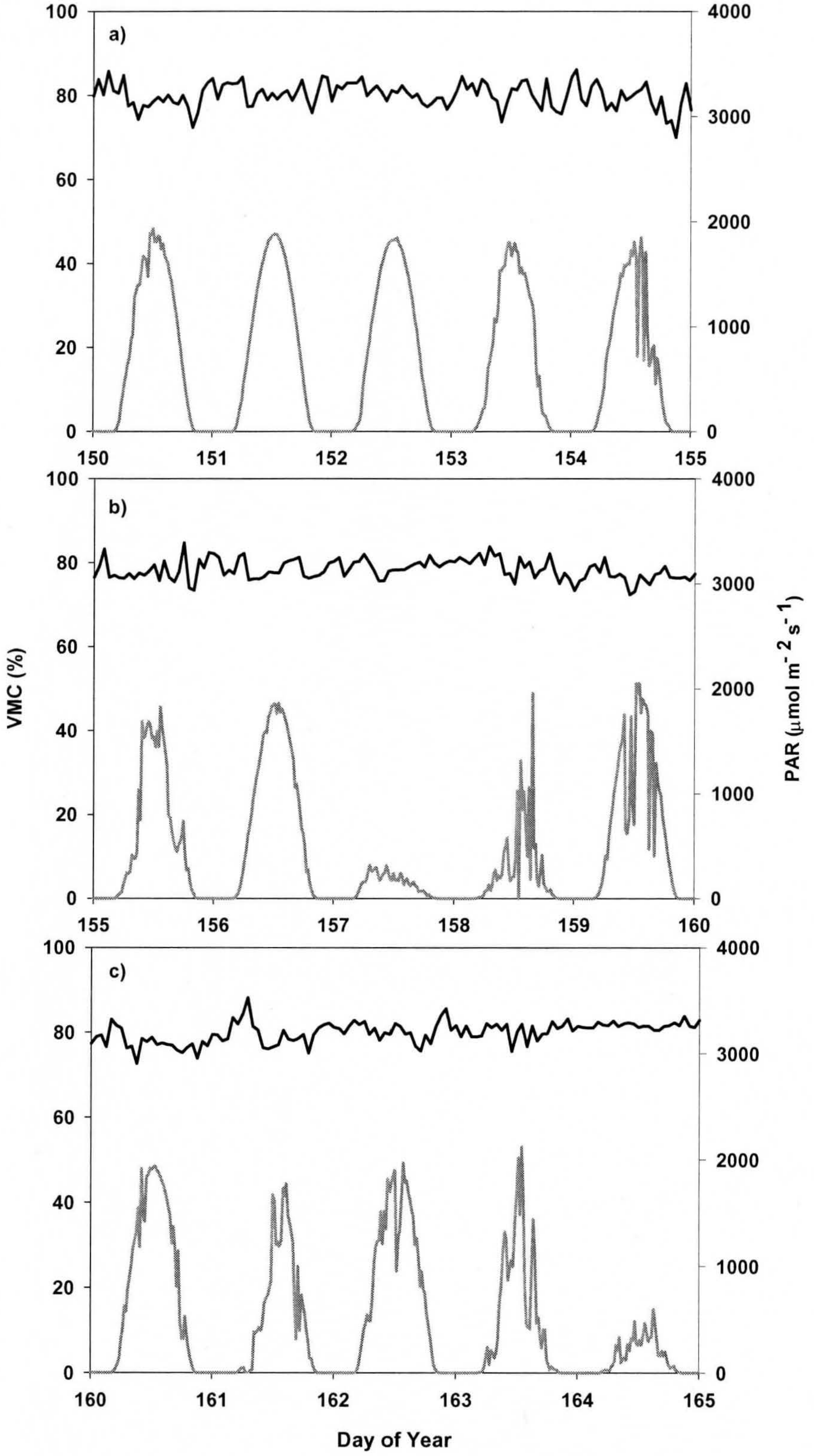

Figure 3.5: Natural site diurnal variation in capitula VMC (θ_c) during a) high light, b) low light, and c) post-precipitation conditions

3.4 Spatial variability in VMC

The natural site started with high surface moisture (θ_c) levels at the beginning of the season that generally decreased as the summer progressed whereas the experimental site had consistently higher θ_c and did not vary much over the two periods post disturbance (Figure 3.6). During the three measurement periods the natural site θ_c averaged 52.4 ± 22.7%, 39.9 ± 17.1% and 38.0 ± 14.1% respectively. The experimental site over the last two periods averaged 93.1 ± 7.1 % and 90.6 ± 9.9%. The spatial variability in θ_c was larger at the natural site with coefficients of variation (CV) of 0.43, 0.43 and 0.37 for the three periods compared to 0.08 and 0.11 for the last two periods at the experimental site (Table 3.1). Furthermore, the wetter areas at each site commonly corresponded with lawn microforms and drier areas corresponded to hummock microforms.

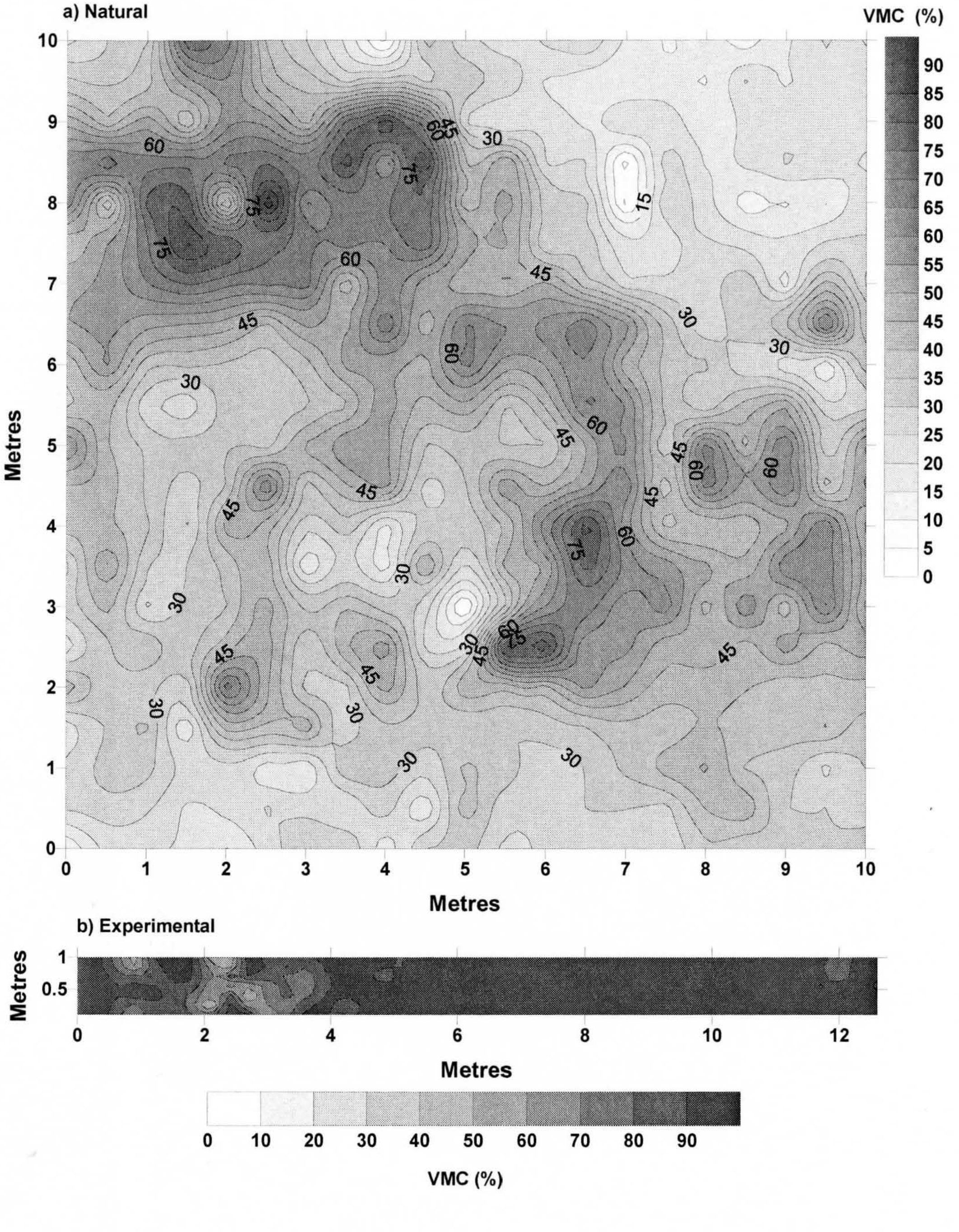

Figure 3.6: Spatial variability in capitula VMC (θ_c) for the late summer period (August) at a) natural b) experimental sites.

Moisture (%)	Minimum	Maximum	Average	Standard Deviation	CV
Natural					
June	3	95	52	23	0.43
July	3	96	40	17	0.43
August	12	81	38	14	0.37
Experimental					
July	30	101	93	7	0.08
August	36	100	91	10	0.11

Estimated Tension (mb)	Minimum	Maximum	Average	Standard Deviation	CV
Natural					
June	14	214	50	37	0.73
July	14	214	69	39	0.56
August	14	159	70	34	0.48
Experimental					
July	0	76	7	7	0.99
August	0	65	9	9	0.99

Table 3.1 Spatial variability in capitula VMC (θ_c) and estimated spatial tension statistics at the natural and experimental sites for June-August periods

3.5 Soil-water retention curves

Surface soil-water tension at the capitula 0-4 cm depth ranges were similar for both the natural and experimental site (Figure 3.7a) however, applied tension of 80-120 mb showed slight differences in the shape of the retention curve. In particular, the average moisture content at 100 mb tension was moderately higher at the experimental site (32.6 ± 8.9%) than at the natural site (30.2 ± 4.5%) suggesting moderately greater θ_c at the experimental site for higher tensions.

Retention curves at the mid-acrotelm 10-14 cm depth for natural and experimental site also displayed a similar shape (Figure 3.7b). Greater retention of moisture at lower applied tensions allowed for a less steep initial slope for the acrotelm samples. At the 100 mb, moisture at natural site averaged 38.0 ± 2.0% and 35.8 ± 5.5%. at the experimental site. Furthermore, moisture differed at 20 and 60 mb where average moisture was 77.1 ± 2.8% and 45.9 ± 2.1% at the natural site and 84.3 ± 5.1% and 39.1 ± 5.1% at the experimental site respectively. However, no significant ($p<0.05$) differences existed between sites. Furthermore, variability in θ_a at the experimental site was moderately higher than at the natural site.

Soil water retention curves indicate that no statistical differences at any of the applied tensions suggesting no significant structural and θ_c differences between the natural and experimental sites. Nevertheless, greater variability of θ_c and θ_a at the experimental site suggests that some physical disturbance was caused with the cutting and replacement of the vegetation. However, physical properties measured from the soil water retention samples further indicate no considerable structural change occurred. Bulk density averaged 0.035 ± 0.002 and 0.040 ± 0.002 at the natural capitula and mid-acrotelm where experimental site averaged 0.048 ± 0.010 and 0.050 ± 0.017 respectively. Furthermore, porosity at the natural site capitula and mid-acrotelm averaged 0.975 ± 0.001 and 0.971 ± 0.002 whereas the experimental site averaged 0.966 ± 0.007 and 0.964 ± 0.012 respectively.

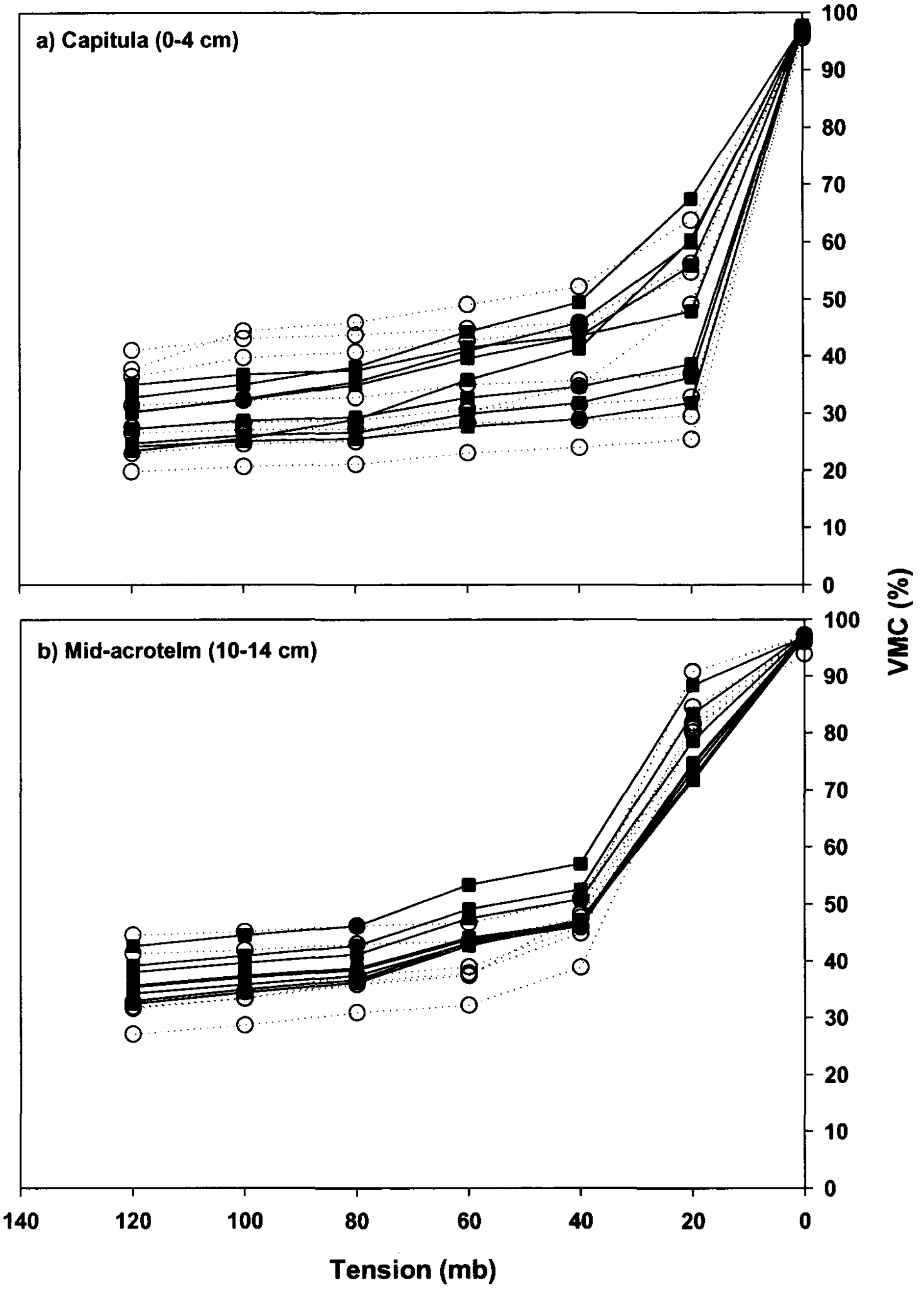

Figure 3.7: Soil moisture retention curves at the natural (squares) and experimental (circles) sites for a) capitula 0-4cm b) mid-acrotelm 10-14 cm

3.6 Spatial Surface Tension Variability

At the natural site the surface soil-water tension spatially changed through the season from low to high as the season progressed. Conversely, the experimental site did not experience a dramatic change where generally the site experienced similar soil-water tension ranges through the season (Figure 3.8). Surface soil-water tension over the three periods at the natural site averaged -50 ± -37 mb, -69 ± -39 mb, and -70 ± -34 mb, whereas the experimental site averaged -7 ± -7 mb and -9 ± -9 mb over the latter two periods. Surface soil-water tension at the experimental site did not exceed -100 mb over the two periods where maximum soil-water tension reached was -76 mb. However, the natural site did exceed -100 mb over the season where 8.3%, 18.2% and 15% of the surface area at each period (June-August) respectively exceeded this surface soil-water tension. Moreover, a maximum soil-water tension of -214 mb was reached suggesting greater potential for water stressed vegetation, particularly *Sphagnum* moss. The experimental site was more variable with a CV of 0.99 over the two periods. Conversely, the natural site CV was lower at 0.73, 0.56, and 0.48 over the three periods respectively. However, soil-water tension at the experimental was quite low in most areas except where a small area of high soil-water tension existed. Due to the skewed soil-water tension at the site, a high CV may have resulted due to the non-uniformed distribution.

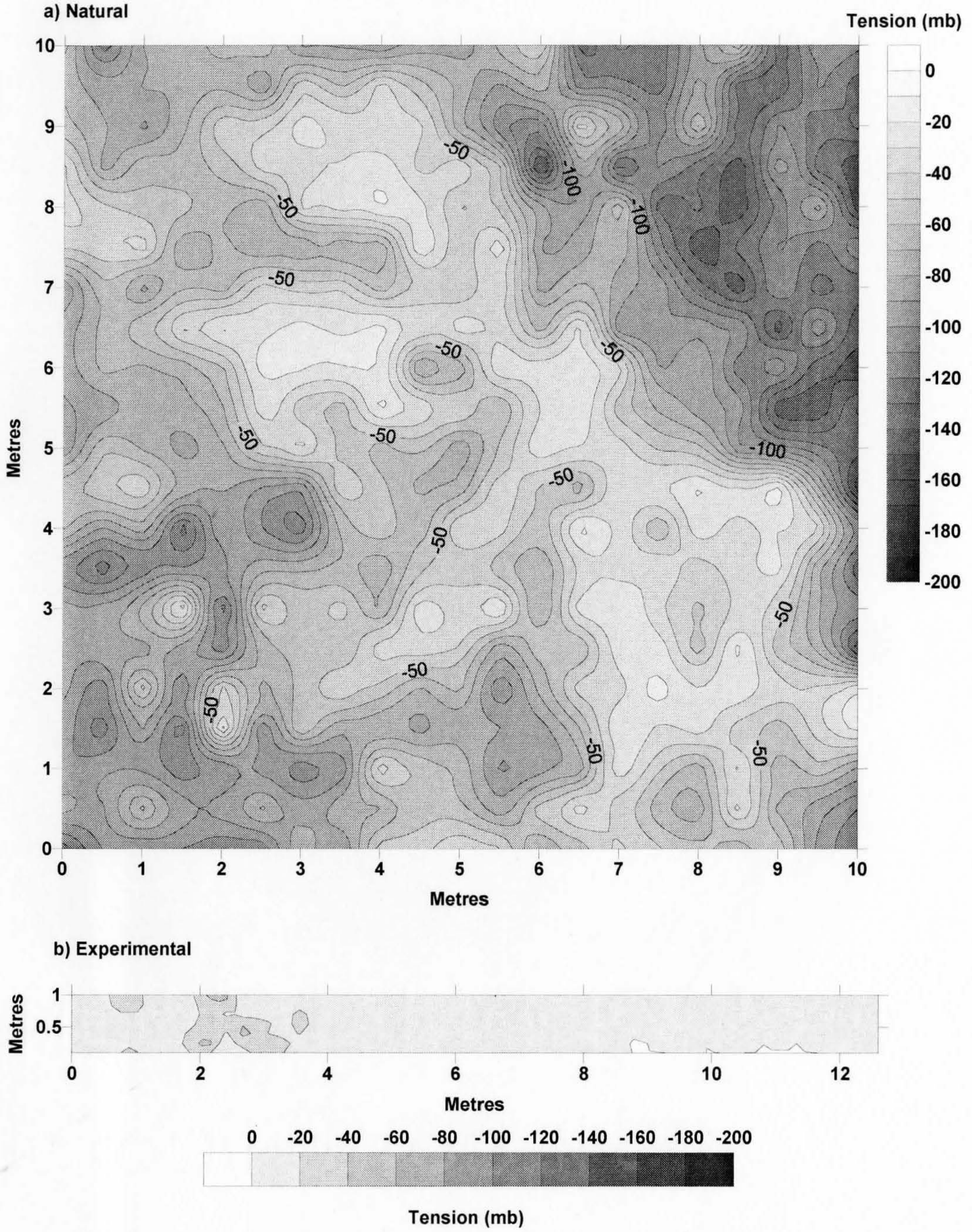

Figure 3.8: Estimated spatial tension survey for the late summer period (August) at the a) natural b) experimental sites

3.7 Discussion

Water table position and temporal VMC within a transplanted acrotelm

Natural bogs have a two-layered soil structure where the upper layer of peat, referred to as the acrotelm, is characterized by a high organic content with poorly decomposed mosses that are loosely structured and permeable (Ingram 1984). Due to the large pore structure, the acrotelm contributes to a high water storage capacity (Boelter, 1968) particularly specific yield, which aids in limiting water table fluctuations to the near surface (Price, 1996). However, peatland drainage and subsequent extraction removes the acrotelm causing enhanced subsidence due to oxidation and compression (Schothorst, 1977) thereby reducing water storage due to the smaller pore sizes (Okruszko, 1995; Schlotzhauer and Price, 1999), leading to a more variable water table (Price, 1996). Consequently, this can lead to high temporal variability in gas exchange processes particularly at the cutover surface (Waddington and Price, 2000). In contrast, the new extraction technique removes a portion of the upper acrotelm with the vegetation intact and is retained and replaced directly on the cutover peat surface immediately after peat extraction in turn 'restoring' the peatland in the process. It was hypothesized that the retention and replacement of the upper acrotelm would aid in keeping the water table close to natural near-surface conditions thereby maintaining stable and high soil moisture content. When the water table drops sufficiently (40-50cm) (Schouwenaars, 1988; Price et al., 2003) below a cutover surface, it ceases to contribute to evaporative water loss and as such soil moisture is depleted due to water demands being supplied by way of the unsaturated zone (Price, 1997; LaRose et al., 1997).

The experimental site in this study actually maintained an elevated water table (wt) depth (-8.4 ± 4.2 cm), which was higher relative to the natural site (-12.7 ± 6.0 cm) post-restoration. Despite the higher wt position, VMC at the experimental site in both the mid-acrotelm (θ_a) and the capitula (θ_c) zones were generally lower than the natural site. θ_a was very similar at both the natural (90.4 ± 1.6%) and experimental sites (89.2 ± 7.0%), however the sensitivity to precipitation events increased variability considerably at the experimental site. The experimental lawns (82.4 ± 5.0%) on average were 6% higher in VMC however showed a larger decrease (9%) at the hummocks (56.2 ± 22.1) compared to the natural site microforms respectively (76.8 ± 5.6% and 65.2 ± 4.0%). Since wt was higher at the experimental site, it would have been expected that soil moisture would have been higher compared to the natural site due to the greater availability of water; however this was not the case (i.e. hummocks and mid-acrotelm) over the season. It is possible that the removal and replacement of the acrotelm may have damaged the peat structurally, particularly closer to the surface where variability in VMC was the greatest (i.e. θ_c), potentially impeding water movement through the peat profile for atmospheric exchange processes. Price (1996) noted that as saturated moisture decreases, soil-water tension can increase where water is held tightly within the micropores of the decomposed peat further limiting water availability to plants, particularly non-vascular *Sphagnum* mosses (Price and Whitehead, 2004).

Laboratory soil-water retention curves showed that with increasing applied tension, VMC within the peat decreased at both the natural and experimental sites however, retention over a range of tensions (0-120 mb) were not significantly different between the sites. In fact, soil-water tension relationships in the capitula and acrotelm layers were very similar on average suggesting that the cutting and movement of the acrotelm did not damage the peat structure thereby impeding water movement within the peat. Interestingly, the experimental site had moderately higher variability and overall greater moisture retention on average relative to the natural site suggesting that a minor disturbance to the peat structure may have occurred changing pore structure allowing for the slight increase in moisture retention. However, measured physical peat properties of bulk density and porosity fell within similar ranges further indicating if the pore structure within the peat matrix did change (i.e. through compression, shrinkage etc.), it would have been very negligible.

Spatial Variability in VMC and Soil-water Tension

While relatively few studies have characterized *Sphagnum* soil-water tension thresholds spatially within the field, areas where *Sphagnum* had recolonized naturally on a cutover peat surface were characterized by a high water table, soil moisture above 50%, and soil-water tension above -100 mb (Price and Whitehead, 2001) confirming the suggestion by Price (1997) that *Sphagnum* cannot extract moisture with soil-water tension lower than this threshold. Moreover, Price and Whitehead (2001) observed that topographically wetter and lower areas within a block-cut peatland such as trenches were favourable (i.e. high moisture and low soil-water tension) to *Sphagnum* reestablishment whereas higher and drier areas such as the baulks were less favourable (i.e. low moisture and high soil-water tension). Similarly, the microtopography at the both the natural and experimental sites showed that lawns tended to have high VMC and low soil-water tension whereas hummocks had low VMC and high soil-water tension. However, this study showed that the capitula soil-water tension relationship critical to *Sphagnum* survival corresponded to 33% VMC at the experimental site and 30% VMC at the natural site. Spatial VMC surveys (θ_c) indicated that the experimental site was generally wetter on average where surface VMC ranged between 90-93% with a minimum θ_c reaching 30%. However, θ_c at the natural site was much more variable and lower on average with VMC between 38-52% with a minimum VMC of 3%. Spatial VMC across both sites suggests that the critical soil-water tension threshold of 30 and 33% (-100 mb) was reached at both the natural and experimental sites respectively at some point over the season as suggested by the spatial survey, however the variability at the natural site indicates that VMC reached the critical soil-water tensions with more frequency.

Duration analysis of temporal VMC at the individual vegetation plots (i.e. wet and dry) within the experimental site indicates that VMC remained above the soil-water tension threshold (33%) for 100% of the season suggesting that the variability of low moisture conditions (i.e. 30%) associated with the spatial θ_c survey were likely minimal and were not captured at these individual plots. Conversely, duration analysis at a number of natural plots revealed that temporal VMC exceeded the soil-water tension threshold (30%) with durations ranging from 5-50% of the season. Price and Whitehead (2001) observed soil-water tension fall below -100 mb for 75% of the season on a cutover surface suggesting that prolonged periods below the threshold were detrimental to both *Sphagnum* survival and reestablishment. Moreover, Price (1997) observed soil-water tension in a bare cutover peatland could drop to values lower than -300 mb creating an extremely hostile environment for *Sphagnum* development. Within this study, spatial variability of soil-water tension at the natural site suggests that soil-water tension exceeded -200 mb indicating that even natural peatlands can reach considerably low soil-water tensions over the season. However, the experimental site was wetter thereby contributing to low soil-water tensions throughout the site suggesting more favourable conditions for *Sphagnum*. While it has been shown that *Sphagnum* cannot survive extended dry periods (Sagot and Rochefort, 1996), it is also suggested that even short periods of high soil-water tensions may prevent *Sphagnum* growth even within wetter conditions (Whitehead and Price 2001).

Diurnal variation in surface VMC

Indeed the experimental site had lower average moisture than the natural site, however the diurnal variation in capitula moisture (θ_c) was especially high at the experimental plots with observed wetting and drying cycles of ~30% in moisture change on a daily basis. In contrast, the natural site also revealed a similar diurnal trend however change in VMC was 3 times lower at ~10%. Studies have shown that evaporation can range from 2.7 to 2.9 mm d^{-1} at natural peatlands, 2.9 to 3.1 mm d^{-1} at bare/harvested peatlands, and 2.6 to 2.9 mm d^{-1} at partially restored peatlands (mulch covered) (Van Seters and Price, 2001; Price, 1996; Price et al., 1998). However, the θ_c changes at the experimental site capitula represent a daily loss of ~10 mm, over 3-times greater than studied natural and standard restored sites. While a 10 mm d^{-1} moisture change is considerably large for evaporative processes, it is more likely that the change in capitula moisture is related partially to structural changes within the peat opposed to evaporation alone. While soil-water retention and porosity properties suggest that no apparent change in structure occurred, peat is highly compressible and elastic where changes in peat volume can occur due to water table changes (Price and Schlotzhauer, 1999). Natural and cutover peatlands undergo seasonal water table changes (e.g. Kellner and Halldin, 2002; Roulet, 1991; Schlotzhauer and Price, 1999) where shrinking and swelling can result affecting both physical and hydraulic properties of peat (e.g. water retention, hydraulic conductivity). However, there was little draw down of the water table at the experimental site suggesting that any water storage and moisture changes observed were not a large function of vertical movement of the peat. Consequently, the natural site water table was moderately lower than the experimental site however observed diurnal moisture changes were only ~4-5 mm d^{-1} at the capitula and could be reasonably related to evaporation.

When the acrotelm is extracted and replaced back together over the cutover peat, large spaces (gaps/fissures) are left between the acrotelm blocks (around each side) which may cause considerable changes to the peat structure. While there may be some natural vertical movement of the peat due to shrinking and swelling, it is likely that lateral movement of the peat may be enhancing the apparent changes in moisture within the capitula because of these spaces between the peat. Daily lateral expansion and contraction into/out of these gaps may be possible causing changes in VMC where an expansion of the capitula surface during the day can cause a decrease in moisture and a contraction during the night can lead to an increase in moisture. The upper acrotelm (0-5cm) layer is likely where the movement in peat is limited since the loose *Sphagnum* moss at the surface would allow the expansion/contraction necessary to affect moisture content. Moreover, it is mainly a change in volume rather than moisture itself which is reflecting the variation in VMC, hence changes in pore size is occurring. For instance, as the peat expands laterally, peat pore size would increase or become larger increasing the overall volume thereby decreasing VMC. Similarly, contraction of the peat would increase moisture content due to pores decreasing in size and decreasing overall volume. While a 30% change in volume is large, expansion/contraction calculations suggest that lateral movement is possible. For example, a lateral expansion of peat in the capitula zone of approximately 2 cm (at each side) with a subsequent increase in surface elevation (1.5 cm) can lead to an increased volume lowering VMC (~30%). Conversely, a contraction of peat with decrease in surface level (i.e. 2 cm and 1.5 cm) would decrease volume, thereby elevate VMC. Consequently, changes in volume affects pore size (expand/contract) which can change capillarity of *Sphagnum* mosses if VMC frequently varies above and below the soil-water tension thresholds due to peat volume change.

As the acrotelm resettles and regeneration of mosses and vascular vegetation occurs, these spaces between the transplanted sections may infill reducing lateral movement within the peat and create more stable moisture conditions in the capitula. Furthermore, stable moisture conditions are important especially from a gas exchange perspective where McNeil and Waddington (2003) observed that wetting and drying cycles can negatively affect *Sphagnum* primary production and consequently net ecosystem CO_2 exchange (see Chapter 4).

Conclusions and Implications for Restoration

Hydrologically controlling the rewetting and evaporation of cutover peatlands are important since both influence changes in soil moisture, water table position, soil-water tension and hydraulic properties of the peat. While current management techniques aim to rewet the cutover surface, blocking of ditches (Eggelsmann, 1988) can restore water balance to more natural peatland conditions; it does not necessarily prevent a deep and variable water table (Price, 1996) or high soil-water tension at the surface (Price, 1997) from occurring. Additional restoration techniques such as seepage reservoirs (LaRose et al 1997; Price 1998), artificial topography (Price et al., 1998), companion species (Ferland and Rochefort, 1997), and straw mulch application (Quinty and Rochefort, 1996; Price, 1997), can all aid in reducing soil-water tension and thereby increasing water depth and moisture. Furthermore, Price et al (2003) have shown that a number of these water management techniques can improve the hydrological conditions on cutover peatlands and may assist in *Sphagnum* reestablishment on the peat surface. However, these techniques are both costly and labour intensive to conduct where peatlands can be abandoned for many years before restoration is even considered. Moreover, the increasing time after abandonment leads to additional changes to the peat structure through the processes of oxidation, compression and shrinkage (Schothorst, 1977; Schlotzhauer and Price, 1999) reducing the hydrological conditions even further promoting higher surface soil-water tensions unsuitable for *Sphagnum* survival. Therefore it is important to restore a peatland as soon as possible (Price, 1997) in order to limit harsh hydrological conditions thereby aiding in reestablishing key vegetative species such as *Sphagnum* moss.

Results indicate that the new extraction-restoration technique aided in restoring the hydrological processes at a plot scale. The transplanted acrotelm maintained both stable and high water table and moisture conditions that were above the critical *Sphagnum* threshold of 33% (-100 mb) at the surface thereby spatially decreasing soil-water tension considerably compared to the natural site. Duration analysis showed that at individual plots, soil-water tension never exceeded -100 mb suggesting that conditions at the surface were generally favourable. In comparison, the natural site appeared to exceed the soil-water tension threshold of 30% VMC more frequently due to the greater spatial variability in moisture across the site. Duration analysis at individual plots suggests that the threshold was exceeded for up to 50% of the time over the season. Since the primary issue in restoration is water availability to prevent desiccation of *Sphagnum* (Sagot and Rochefort, 1996), it appears that the acrotelm restoration technique maintained favourable hydrological conditions preventing low moisture and high soil-water tension conditions at the surface. Additionally results suggest that the peat structurally did not undergo any major changes, however, a volume change at the peat surface may have enhanced wetting and drying cycles in the capitula. Due to the acrotelm removal and subsequent transplant, spaces (gap/fissures) are left between the replaced surfaces that may cause lateral expansion/contraction within the peat matrix. This can lead to a volume change where large changes in VMC (30%) were observed leading to variable moisture conditions at the surface. Consequently, diurnal variation may vary soil-water tension causing unfavourable conditions for *Sphagnum* and potentially have an even greater effect on gas exchange process at the surface.

Nevertheless, from a management perspective, the acrotelm transplant technique has real potential to be an improved restoration method since the cutover peatland is restored almost immediately after extraction reducing the adverse hydrological affects of abandonment and permitting hydrological conditions sufficient for *Sphagnum* growth and survival. Moreover, the acrotelm, which is important in governing peatland water storage and *Sphagnum* growth, is present immediately. Conversely, standard restoration techniques estimate that the reestablishment of the acrotelm may takes years or even decades to return thereby hydrological conditions may be variable many years post-restoration.

It is suggested that if transplanting of the acrotelm was replaced using greater care by positioning the acrotelm sections closer together, it may be possible to limit or even remove the spaces between the peat potentially reducing possible lateral movement; stabilizing surface moisture and soil-water tension conditions. From a gas exchange perspective, stable surface moisture conditions are particularly important since highly variable moisture can negatively affect *Sphagnum* primary production and consequently net ecosystem CO_2 exchange (McNeil and Waddington, 2003). However, to determine if this technique is suitable for *Sphagnum* growth an analysis of CO_2 exchange processes is required (see Chapter 4).

CHAPTER 4: CO_2 EXCHANGE OF A TRANSPLANTED ACROTELM ON A CUTOVER PEAT SURFACE

4.1 Introduction

Natural peatlands are an important component of the global carbon cycle contributing approximately one-third of the total soil carbon (Gorham, 1991). It is estimated that a net long term sink of ~23-28 g C m^{-2} of atmospheric carbon dioxide (CO_2) is stored annually in peatlands. The natural carbon storage function of these ecosystems can be severely impacted due to peatland drainage and peat extraction (e.g. Waddington et al., 2002) and are generally left abandoned for many years before any type of restoration occurs. Consequently, this can lead to large and persistent sources of atmospheric CO_2 following abandonment (Waddington et al., 2002; Petrone et al. 2003) due to the decomposing peat and the unvegetated surface at the abandoned cutover site. Moreover, the longer a peatland remains abandoned the larger the atmospheric CO_2 source (Waddington and McNeil, 2002). However, it has been shown that extracted peatlands can return to a carbon-accumulating ecosystem at a plot scale (Waddington and Warner, 2001) with recent evidence further demonstrating that ecosystem scale restoration techniques can return cutover peatlands to a net sink of atmospheric CO_2 within three to five years (Greenwood, 2005). However, it is hypothesized the natural carbon cycle will not be restored until a suitable depth or moss accumulates – a new acrotelm (McNeil and Waddington, 2003). In this chapter a new extraction technique is examined where impacts of drainage and removal and discarding of surface vegetation are minimized. This new restoration process occurs immediately post-extraction further reducing potential impacts by the preservation of the acrotelm and subsequent replacement on the cutover surface. It is hypothesized that the preservation of the acrotelm and vegetation and improved hydrological conditions (Chapter 3) will improve carbon storage function post extraction and further reduce large sources of atmospheric CO_2 emissions compared to standard restoration practices. Furthermore, the immediate presence of the acrotelm-vegetation at the cutover surface may return these ecosystems towards a net sink of atmospheric CO_2 sooner than standard restoration techniques. This chapter characterizes the CO_2 exchange at the surface of a natural and experimental site and compares the fluxes over the season to determine if differences exist from a natural to that of a cutover-restored state. Moreover, the controls on CO_2 exchange are examined to describe the differences and assess the potential implications on fluxes.

4.2 Plot classification

For CO_2 exchange analysis (measured and modeled) each plot at the natural and experimental sites were categorized into wet and dry plots based on relative VMC measurements (Hydrosense data). Once categorized, capitula 5 cm VMC (θ_c) at natural dry plots (N_{DRY}) averaged 41.3 ± 6.0% and natural wet plots (N_{WET}) 83.9 ± 9.5% over the season. The experimental θ_c site plots averaged 74.7 ± 13.3% and 92.2 ± 2.8% for dry (E_{DRY}) and wet (E_{WET}) respectively (Figure 4.1). A clear difference in θ_c for wet and dry plots existed therefore CO_2 exchange measurements used the same classification for analysis and comparison of sites and plots.

4.3 Gross Ecosystem Production (GEP)

At the natural site, the daily measured response of CO_2 exchange differed between wet and dry collars (N_{WET} and N_{DRY}) (Figure 4.2a). Measured gross ecosystem production (GEP) ranged from -5.0 to -22.6 g CO_2 m^{-2} d^{-1} at N_{DRY} and from -2.6 to -18.9 g CO_2 m^{-2} d^{-1} at N_{WET}. GEP at the beginning of the season was low and the highest fluxes occurred during mid-summer (days 175-205). Over the season GEP at N_{DRY} was greater than N_{WET}; however responses in fluxes were similar and variability was low at each site.

The experimental site measured GEP was significantly lower ($p<0.05$) than the natural site over the season (Figure 4.2b). Measured GEP ranged from -8.4 to -1.2 g CO_2 m^{-2} d^{-1} at experimental dry (E_{DRY}) and -0.8 to -4.8 g CO_2 m^{-2} d^{-1} at experimental wet (E_{WET}) respectively. Overall GEP at E_{DRY} was greater than E_{WET} with variability being low and responses of fluxes being similar between sites. Peak GEP at these sites occurred from mid-to-late summer (days 180-230).

4.4 Total Ecosystem Respiration (R_{TOT})

Measured total ecosystem respiration (R_{TOT}) at N_{DRY} and N_{WET} ranged from 4.7 to 12.8 g CO_2 m^{-2} d^{-1} and 1.7 to 11.8 g CO_2 m^{-2} d^{-1} respectively (Figure 4.2a). R_{TOT} at each site responded similarly where fluxes at the beginning (days 145-160) and at end of the season (days 210-228) were very similar. Variability in flux was low at the wet and dry sites; however N_{WET} was moderately lower over the peak summer (days 175-205) period compared to N_{DRY}.

Total measured E_{DRY} and E_{WET} respiration ranged from 3.4 to 9.5 g CO_2 m^{-2} d^{-1} and 2.4 to 5.9 g CO_2 m^{-2} d^{-1} respectively (Figure 4.2b). The response of CO_2 flux was similar at each site however E_{DRY} had greater overall R_{TOT} than E_{WET}. Peak R_{TOT} occurred during mid to late summer (days 180-210) and remained stable over this period. In comparison to the natural site, E_{DRY} responded similarly to N_{DRY} however E_{WET} had lower R_{TOT} compared to N_{WET}.

Average daily ground temperature at 5 cm depth generally corresponded well with respiration over the season at the natural site. Similarly the experimental site corresponded with 10 cm ground temperature (Figure 4.3a). As the daily 5 and 10 cm average ground temperature increased over the season at the natural site, respiration flux responded accordingly. High ground temperatures at the natural site (e.g. days 190 and 217) corresponded with the highest respiration where lower temperature days (e.g. 140 and 212) had decreased respiration. At the experimental site, increased respiration also occurred during high temperatures (e.g. days 182 and 209) and lower flux during low temperatures (e.g. days 175 and 205). Peak respiration at the natural site occurred during the late-summer (days 190-200) whereas the experimental site peak respiration occurred from mid-late summer (days 180-210). Furthermore, water table corresponded more strongly with respiration at the experimental site where wetter plots had an observed increase in respiration as water table position decreased (Figure 4.3b).

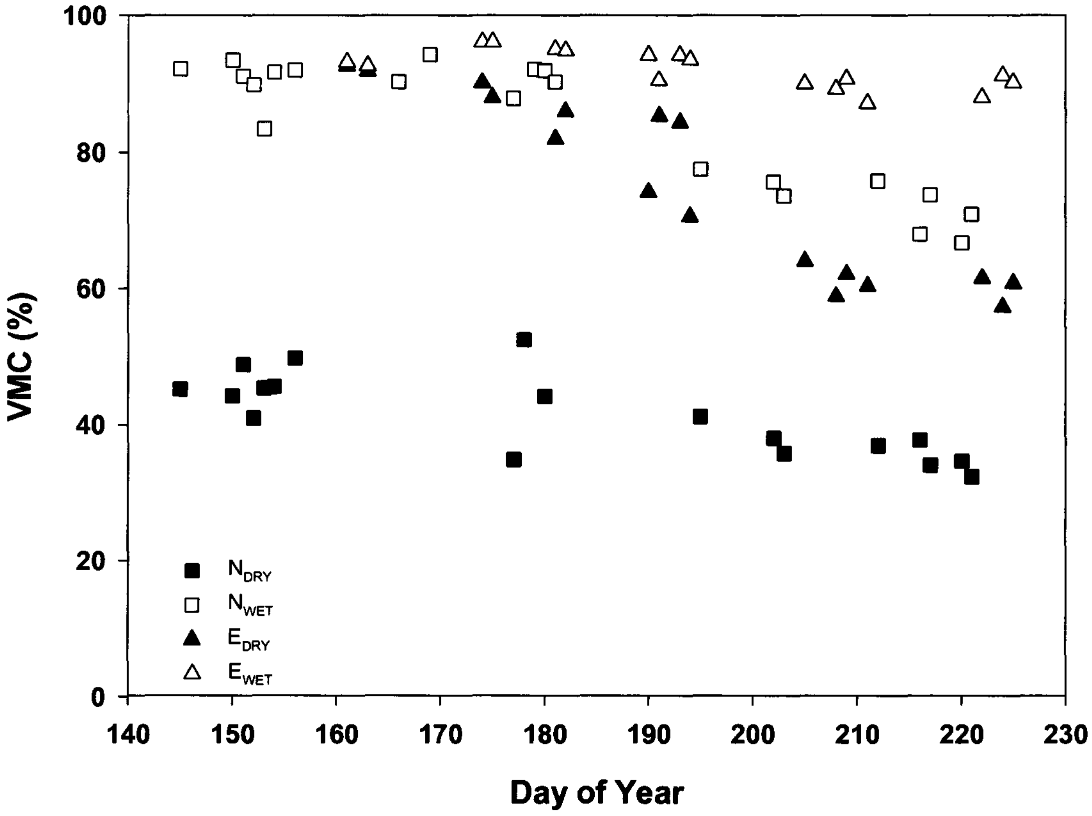

Figure 4.1: 5 cm VMC (θ_5) for wet and dry plots at the natural and experimental sites exhibiting the differences in moisture both within and between sites.

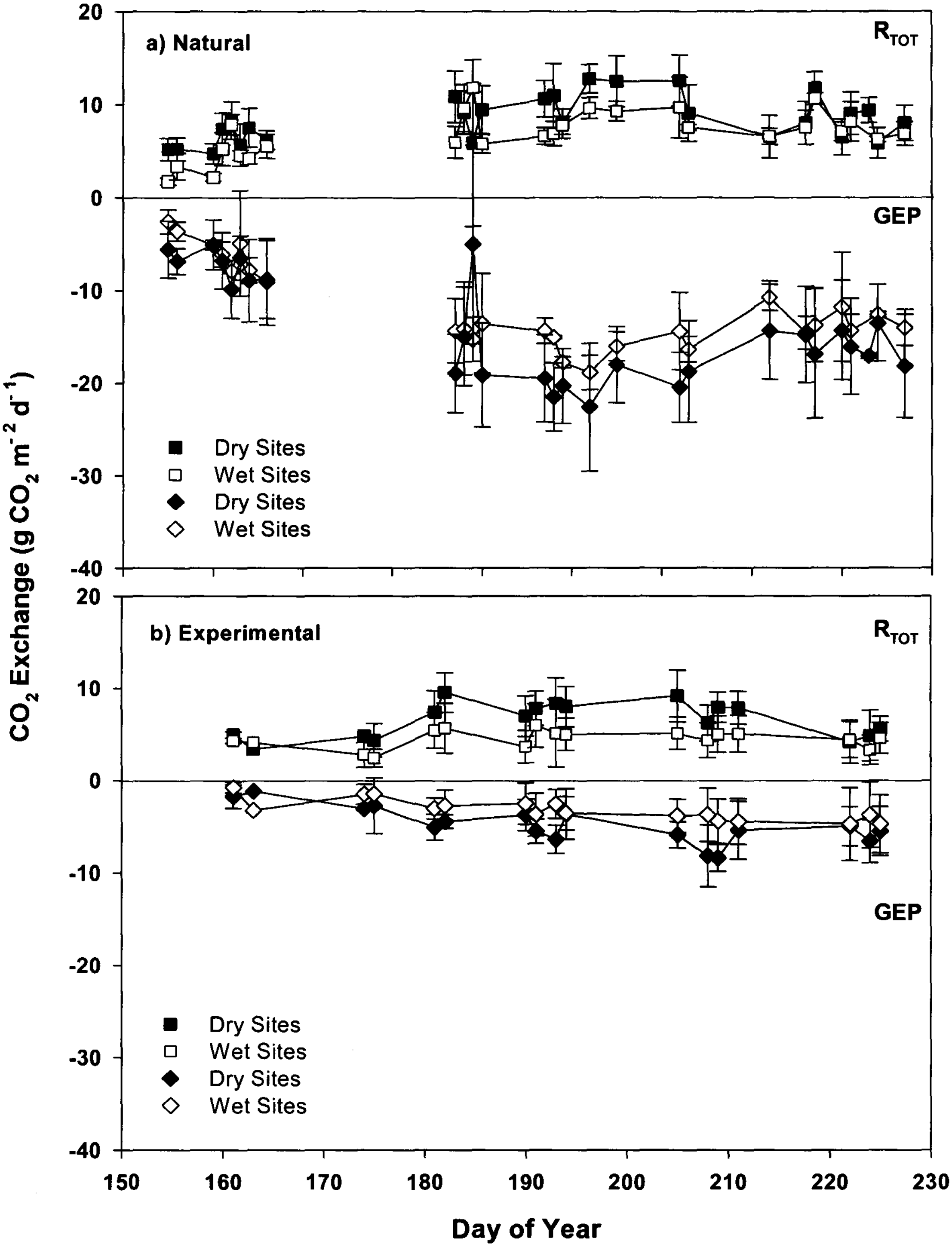

Figure 4.2: Measured daily CO_2 exchange (R_{TOT} and GEP) at wet and dry plots for a) natural and b) experimental sites over the season.

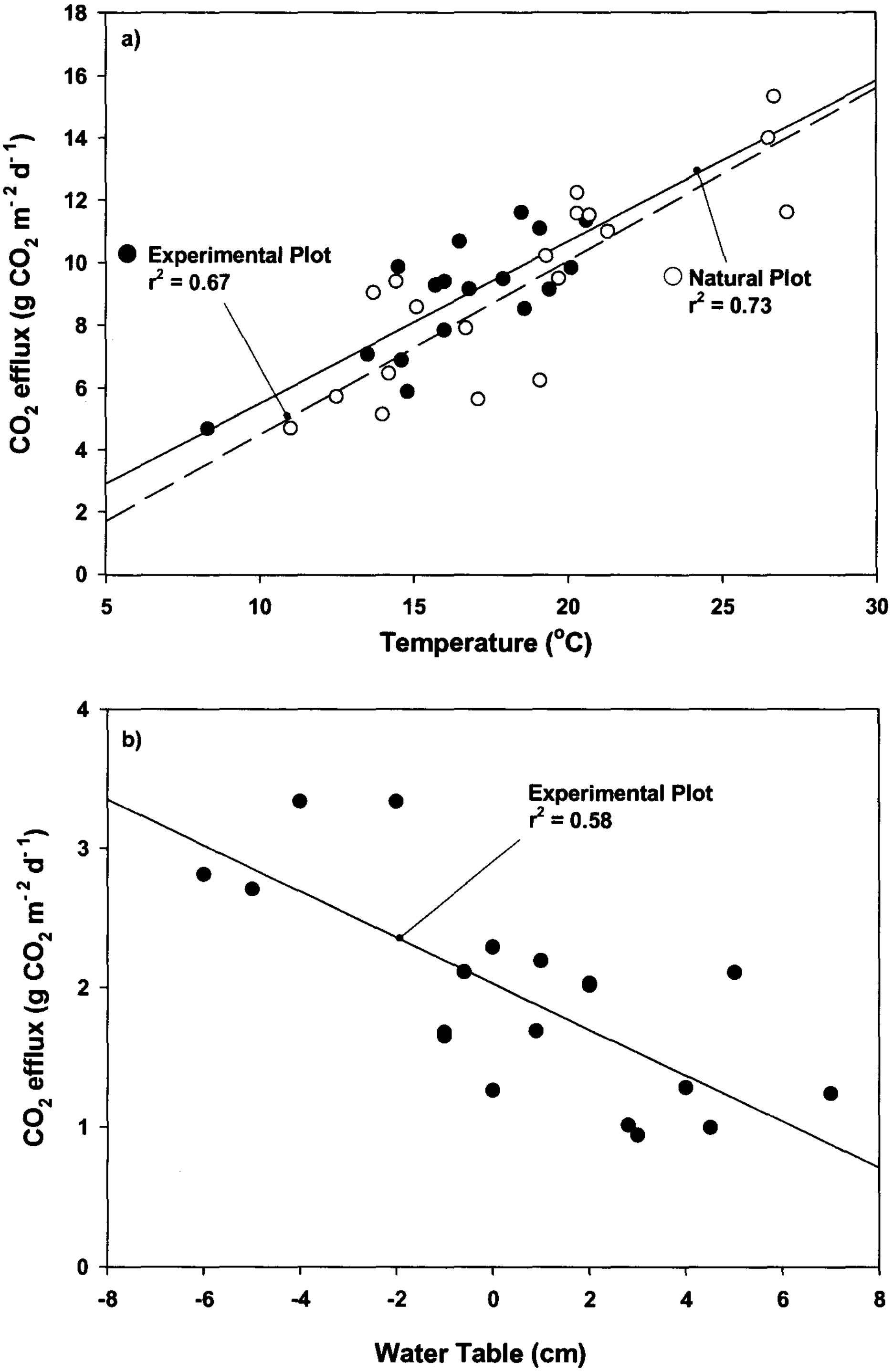

Figure 4.3: Respiration relationships with ground temperature at a a) natural (black circles) and experimental (open circles) plot (5 cm at natural and 10 cm at experimental) and water table at an b) experimental plot

4.5 Measured Seasonal CO_2 Exchange

Differences were observed in measured seasonal average CO_2 exchange at both sites where R_{TOT} at N_{WET} and N_{DRY} was 7.4 ± 2.6 and 8.7 ± 3.3 g CO_2 m^{-2} d^{-1} and 4.5 ± 2.5 and 6.68 ± 2.23 g CO_2 m^{-2} d^{-1} at E_{WET} and E_{DRY} respectively (Figure 4.4). R_{TOT} was significantly higher ($p<0.05$) at the natural site however N_{WET} and E_{DRY} plots were not significantly different from each other. Within groups R_{TOT} at the dry plots were significantly higher ($p<0.05$) than wet plots.

Seasonal averages of GEP at N_{WET} and N_{DRY} was -12.6 ± 5.0 and -14.6 ± 7.1 g CO_2 m^{-2} d^{-1} where experimental was -3.4 and -5.2 g CO_2 m^{-2} d^{-1} respectively (Figure 4.4). Overall, the natural site GEP was statistically higher ($p<0.05$) than the experimental site. Moreover, E_{DRY} plots were significantly higher than E_{WET} plots; however there was no significant difference between N_{DRY} and N_{WET} plots.

Lastly, NEE at N_{WET} and N_{DRY} plots was -5.2 ± 4.0 and -5.9 ± 5.4 g CO_2 m^{-2} d^{-1} and 1.1 ± 3.0 and 1.5 ± 2.4 g CO_2 m^{-2} d^{-1} for E_{WET} and E_{DRY}. NEE was significantly higher ($p<0.05$) at the natural site than the experimental site although no significant differences existed between the wet and dry plots at each site.

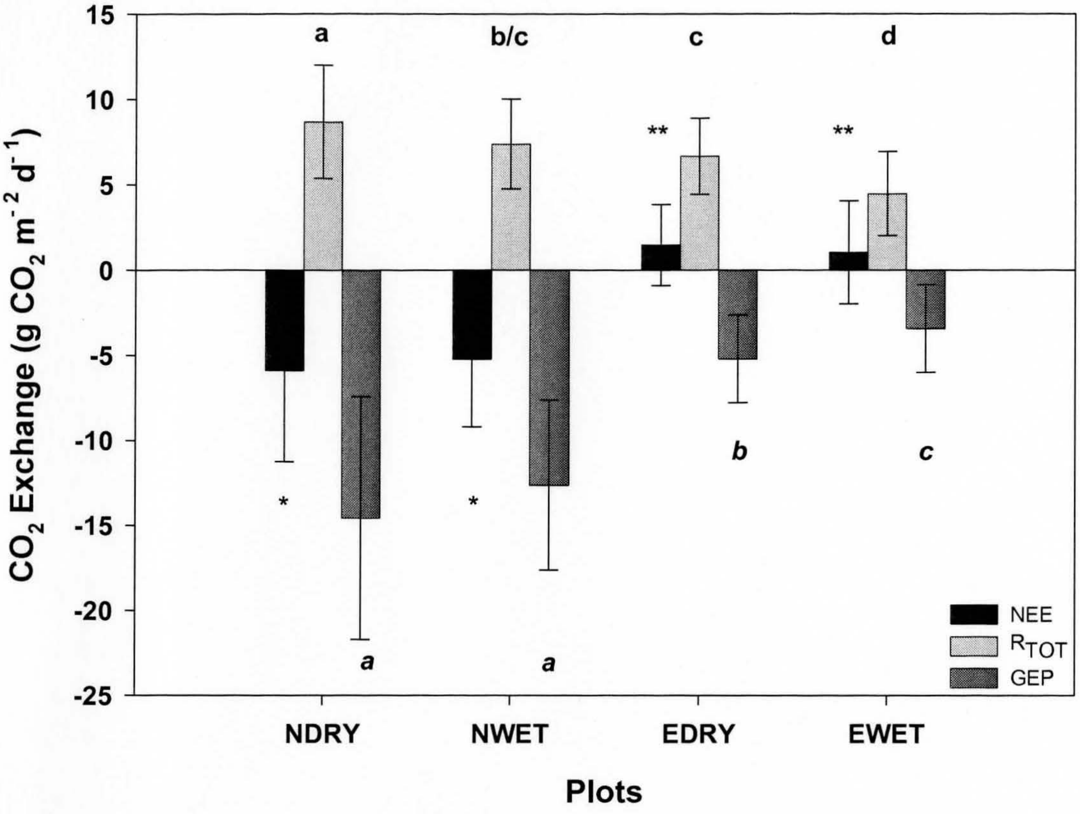

Figure 4.4: Measured average seasonal CO$_2$ exchange (NEE, GEP and R$_{TOT}$) at the natural and experimental sites for wet and dry plots. Significant differences ($p<0.05$) existed between and within sites and are denoted by bold letters (**a-d**) for R$_{TOT}$, italic letters (*a-c*) for GEP and asterisks (*) for NEE.

4.6 Modeled CO_2 Exchange

The natural site modeled R_{TOT} averaged 8.3 and 5.9 g CO_2 m^{-2} d^{-1} for dry and wet plots respectively. Conversely, E_{DRY} and E_{WET} averaged 4.5 g CO_2 m^{-2} d^{-1} each respectively. GEP at N_{DRY} and N_{WET} averaged -7.3 and -6.6 g CO_2 m^{-2} d^{-1}, however the experimental site GEP was much lower, averaging -2.2 and -1.4 g CO_2 m^{-2} d^{-1} for dry and wet respectively. Overall, NEE at N_{DRY} and N_{WET} was 0.93 and -0.72 g CO_2 m^{-2} d^{-1} and at E_{DRY} and E_{WET} 2.3 and 3.2 g CO_2 m^{-2} d^{-1} (Figure 4.6). In general, respiration was highest at the natural site compared to the experimental site. Similarly, GEP was greater at the natural site suggesting greater productivity in the vegetative composition compared to the experimental site. Due to the differences in production and respiration at each site, the overall NEE indicates that the natural site was not significantly different from zero ($p<0.05$); however the experimental site was a moderate source of CO_2 to the atmosphere over the season.

4.7 Ecophysiological Parameters

Light response curves for the median plot at both the natural and experimental sites illustrate the differences in productivity over the season (Figure 4.5). Generally the modeled curves at the natural site maintained robust well-fitted (r^2 value) curves over the three periods (r^2 values: early 0.71, mid 0.90, late 0.96) and variability in GEP around the curves was minimal with high GP_{MAX} values. However, the experimental plot experienced greater variability in GEP with weaker fits around the curves (r^2 values: early 0.26, mid 0.68, late 0.22) with greatly reduced GP_{MAX} values. The median GP_{MAX}

at the natural plot ranged from 8.8 to 19.9 g CO_2 m^{-2} d^{-1} over the three periods whereas the median GP_{MAX} at the experimental plot ranged from 2.2 to 6.6 g CO_2 m^{-2} d^{-1}. Furthermore, GP_{MAX} values at the natural site were generally the greatest during the mid-period (July), whereas the experimental site had maximum productivity over the late period (August).

4.8 Physiological Conditions of Vegetation

Vegetation coverage at the natural site ranged between 20-90% for mosses and 5-50% for shrubs. Conversely, the relative coverage of mosses and shrubs at the experimental site was moderately higher ranging from 40-95% and 5-60% respectively (Figure 4.7). Mosses and shrubs at the natural site were undisturbed and the vegetation was generally healthy through most of the season experiencing moderate desiccation at a number of plots, particularly the hummock microforms over the latter half of the season (mid-July to August). At the experimental site the plots were installed into vegetation that had experienced disturbance from the extraction-restoration process. Consequently, the plots at the experimental site visually had varying degrees of disturbance ranging from compaction to highly stressed desiccated moss and shrub covers relative to the undisturbed natural site. Moreover, a number of plots (E3-E4, E6-E7) had highly disturbed moss and shrub vegetation with relatively low living biomass. These disturbances can affect the overall productivity of the plots due to the relative amounts of living and dead vegetation present. Measured maximum GEP from daily measurements (where PAR>1000) over the season revealed that GEP at a moderately disturbed plot generally had higher GEP than a highly disturbed plot at the experimental site (Figure 4.8). Maximum GEP at a highly disturbed plot was 4.2 g CO_2 m^{-2} d^{-1} whereas a moderately disturbed plot had a considerably higher maximum GEP of 10.9 g CO_2 m^{-2} d^{-1}. Furthermore, the variability in maximum GEP over the season was greatest at the highly disturbed plot where the moderately disturbed plot had a moderately steady increase in maximum GEP over the season.

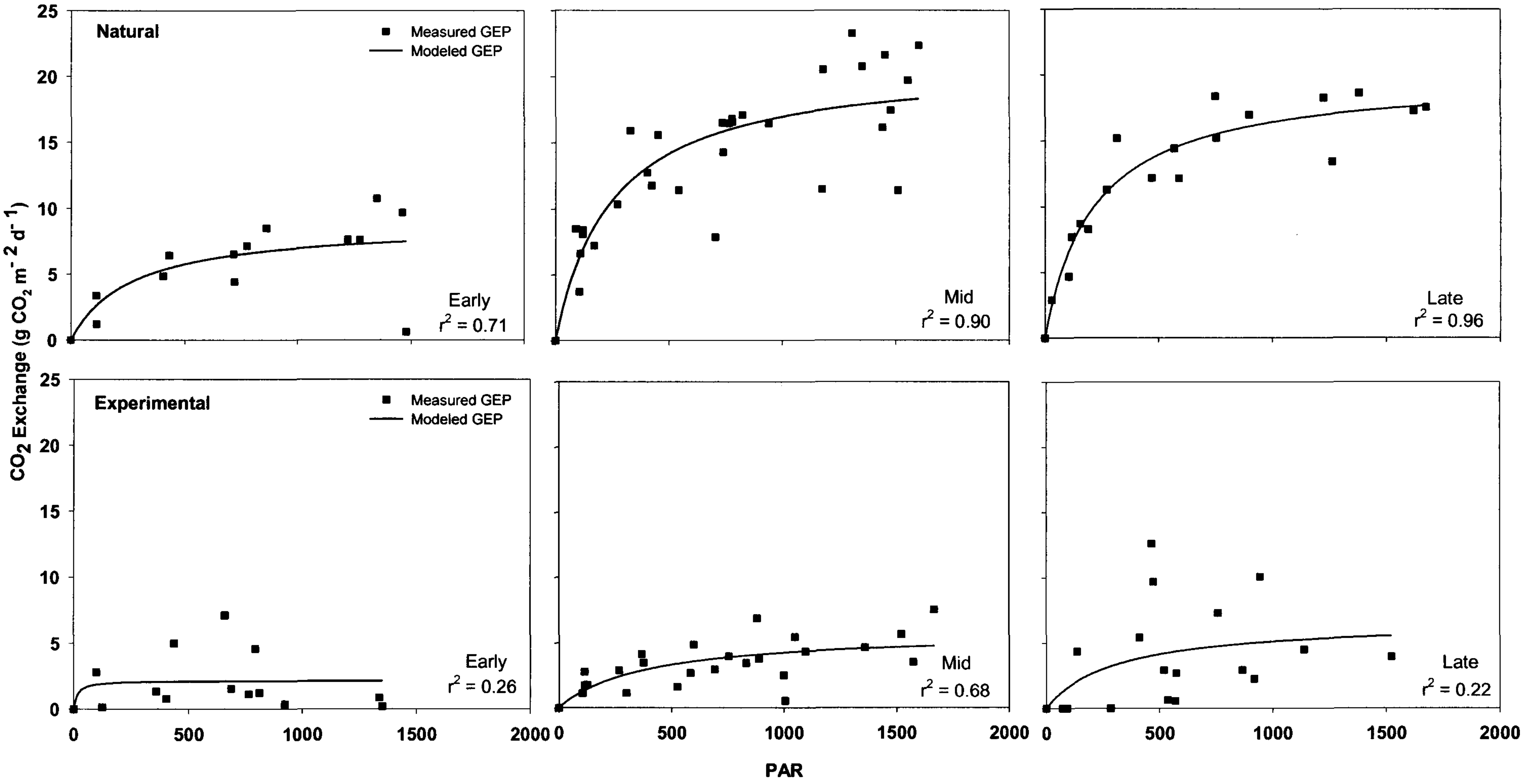

Figure 4.5: Modeled light response curves for a natural and experimental plot showing the differences in GEP_{MAX} at a) early (June) b) mid (July) c) late periods (August).

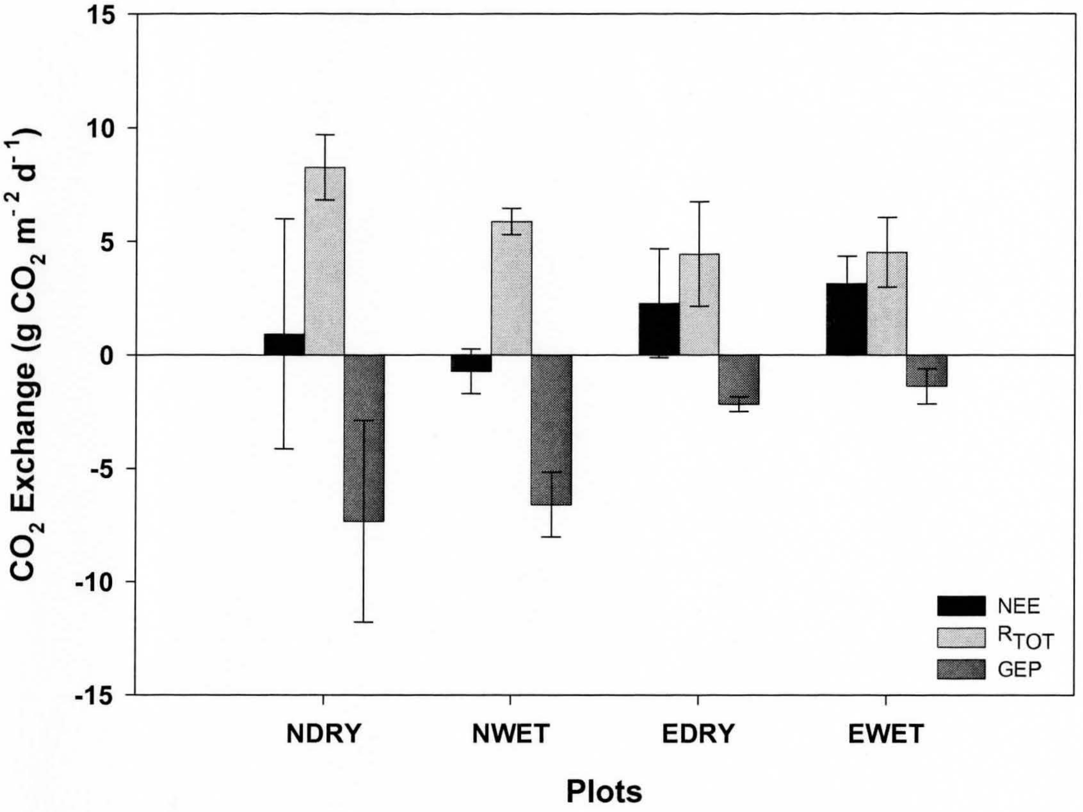

Figure 4.6: Modeled CO_2 averages for the natural and experimental sites at both wet and dry plots.

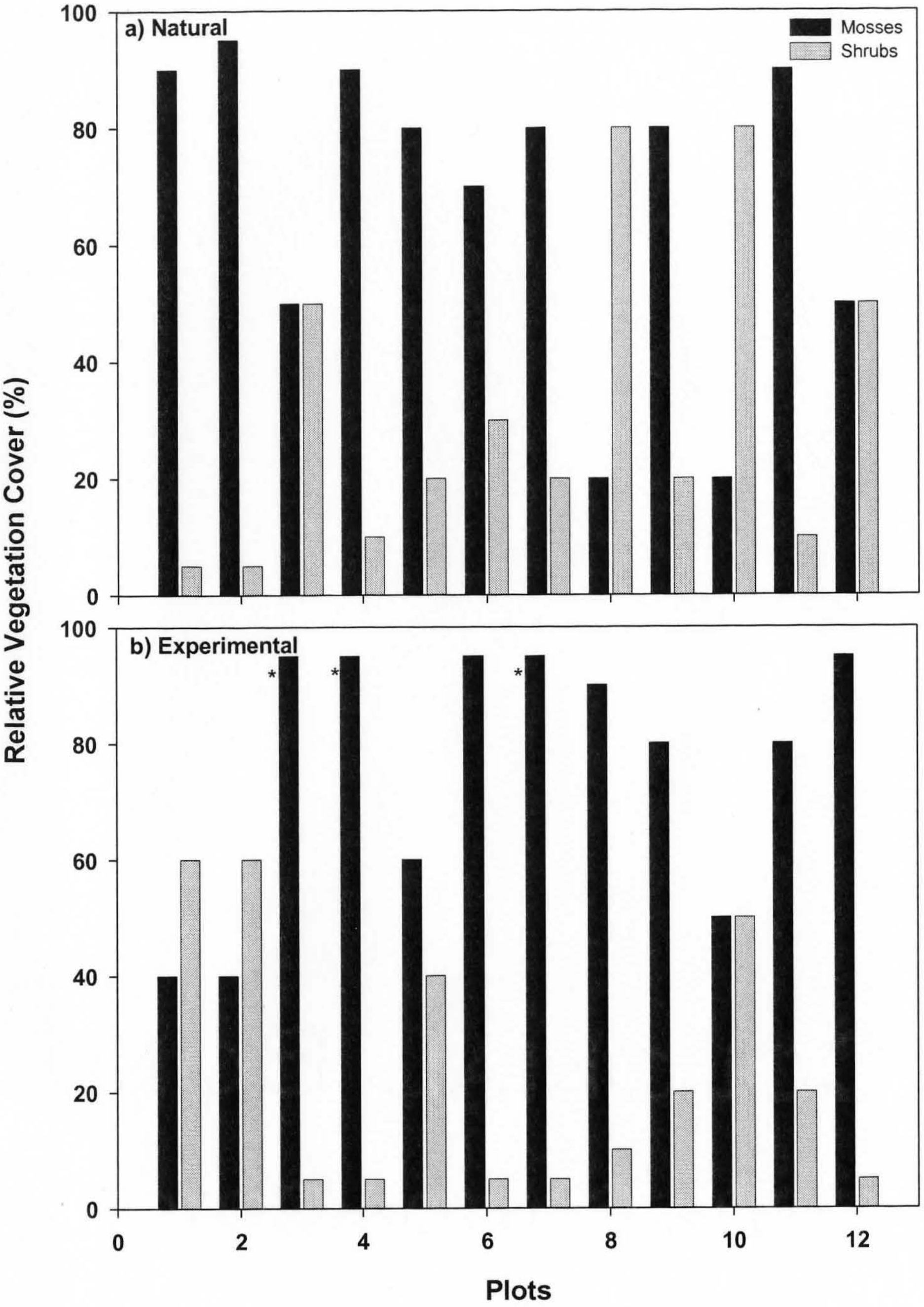

Figure 4.7: Relative Vegetation Cover for plots at the a) natural and b) experimental sites (* denotes a visually highly disturbed moss layer)

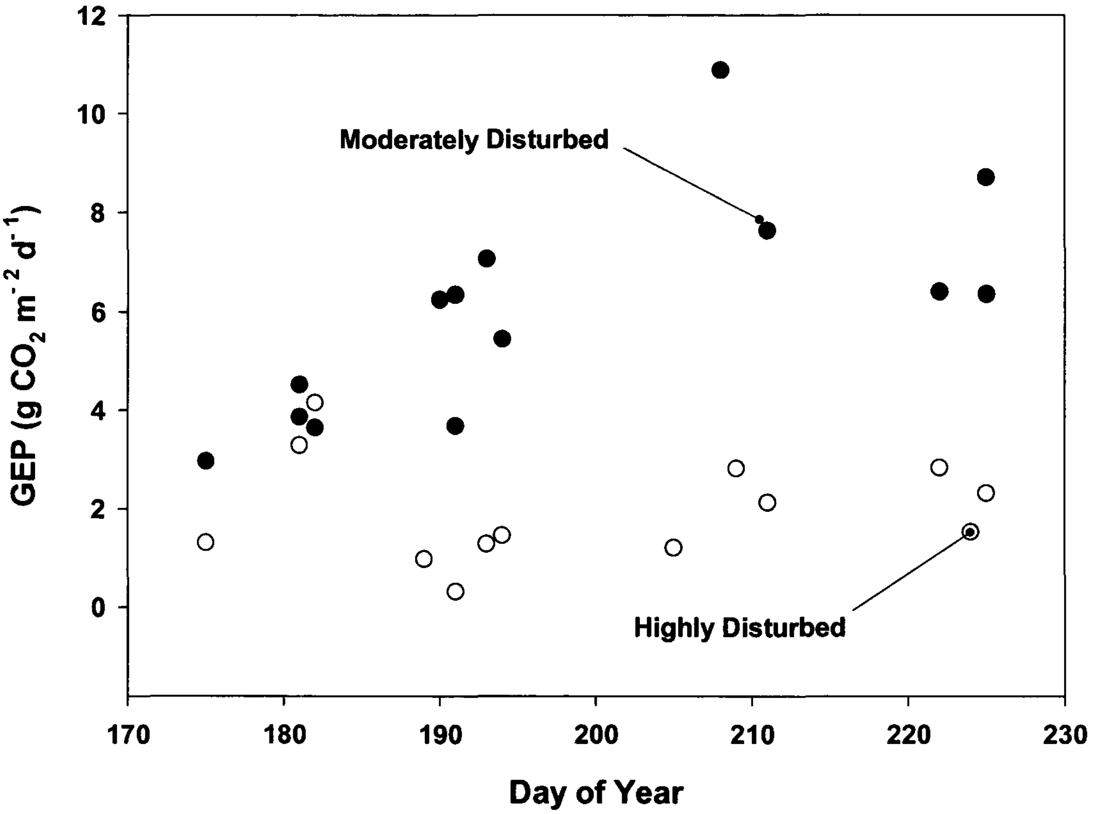

Figure 4.8: Maximum GEP (PAR>1000) at a moderately disturbed (dark circles) and highly disturbed (open circles) plot at the experimental site

4.9 Discussion

As mentioned earlier, natural peatlands are a net long-term sink of atmospheric CO_2, however, cutover peatlands represent a persistent source of atmospheric CO_2 with carbon loss estimated at 300 to 400 g C m^{-2} y^{-1} (Waddington and Price, 2000; Waddington and McNeil 2002; Petrone et al. 2003) due to enhanced peat oxidation (Greenwood, 2005). While Schothorst (1977) suggested that oxidation should decrease with time since abandonment due to a decrease in substrate quality most measurements of CO_2 exchange in cutover peatlands suggests otherwise. For example, Warner (1999) found that older cutover peatlands lost more carbon than recent cutover sites and Greenwood (2005) demonstrated that a cutover peatland was still a large source of CO_2 over 20 years post abandonment releasing between 83 and 136.8 g C m^{-2} over a 2-year period. Hence, the longer a cutover peatland remains in an unrestored state the greater the release of CO_2 to the atmosphere. Waddington and McNeil (2002) estimated that an 11.5 ha peatland lost 730 t C due to peat oxidation in the first 19 years post extraction because of enhanced decomposition from a low water table and low VMC (Waddington et al., 2002). Komulainen et al. (1999) showed that CO_2 efflux from peatlands can decrease when plots are rewetted. Consequently, it was hypothesized that acrotelm transplanting would result in a decrease in respiration due to wetter conditions and the removal of the high quality peat in the lower acrotelm and upper catotelm. Indeed, respiration at the natural site was considerably higher than the experimental site with CO_2 emissions totaling 144.8 and 203.7 g C m^{-2} (wet and dry plots) however; the experimental site emitted only 110.5 g C m^{-2} representing a large reduction (50-80%) in emissions compared to the natural site over the season. This suggests that transplanting of the acrotelm on the cutover surface immediately after extraction may directly benefit restoration through an immediate reduction in respiration. The decrease in respiration at the experimental site can be partly explained by changes in peat VMC dynamics (Chapter 3) as VMC of the acrotelm has a major control on the gas exchange process (e.g. McNeil and Waddington, 2003; Silvola, 1986, 1990; Komulainen et al., 1999). The experimental site maintained a moderately higher water table over the season and generally wetter surface moisture conditions than the natural site post restoration (Chapter 3). CO_2 efflux at the experimental site was predominately subject to moisture controls particularly water table depth with temperature as a secondary control. As water table position decreased at plots with high VMC (i.e., lawns), CO_2 efflux increased with drawdown revealing moderately strong negative relationships with plots having r^2 values ranging from 0.48 – 0.78. Drier plots (i.e. hummocks) were mainly controlled by moderately strong positive correlations to temperature (r^2 = 0.59 - 0.67,) indicating increased efflux with higher temperatures. Lafleur et al. (2005) found that a dry peatland was strongly correlated to peat temperature however their results suggest that wetter peatlands may have stronger respiration controls with water table depth.

The extraction-restoration process likely influences reduced respiration at the experimental site since a preserved portion of the acrotelm is replaced directly on the cutover surface immediately after extraction. Price and Whitehead (2004) showed that VMC under *Sphagnum* cushions were generally 5-14% greater than on adjacent bare cutover peat which suggests that mosses can regulate local substrate water storage and therefore aid in retaining moisture in peat. Warner and Waddington (2001) noticed a reduction in peat respiration from peat with *Sphagnum* cover versus cutover bare peat indicating that the differences in CO_2 efflux from the sites are potentially due to moisture dynamics between cutover and natural sites.

Increasing VMC on cutover peatlands is particularly important for *Sphagnum* moss regeneration and productivity as can both increase with high water levels (Campeau and Rochefort, 1996). As such, it was hypothesized that GEP would be higher at the experimental site and higher than recently restored peatlands. However, the experimental site experienced considerably lower production over the season. Moreover, the differences in GEP accounted for the greatest influence on the overall net CO_2 exchange between the natural and experimental site. Over the study season the natural site (wet and dry) had an overall uptake of -179.2 and -162.0 g C m^{-2} compared to -54.0 and -34.4 g C m^{-2} at the experimental plots (wet and dry) representing a reduction of 20-30% in total productivity. The low productivity at the site (despite the reduction in respiration) shifted the site towards a net source of CO_2 over the season. Consequently, the net carbon flux over the season at the experimental site (wet and dry) emitted 78.5 and 56.5 g C m^{-2} with the natural plots (wet and dry) storing -17.6 and -22.8 g C m^{-2} respectively.

The productivity and growth of *Sphagnum* in cutover peatlands is not only limited by water availability but also by drying and wetting cycles (McNeil and Waddington, 2003). Large variability in VMC in the capitula and acrotelm (Chapter 3) likely contributed to the low (and variable) GEP at the experimental site due to large changes in moisture, which can suppress photosynthesis and enhance respiration. The diurnal variation in surface moisture (θ_c) was especially high at the experimental plots with observed wetting and drying cycles of up to 30% in change of moisture (~10 mm) on a daily basis (Chapter 3). Consequently, the variability in GEP observed at the experimental site may have been related to the diurnal cycles at the peat surface. Indeed the scatter in experimental site light response curves was much greater than the natural site where moisture conditions were much more stable (Chapter 3). Photosynthetic rates of *Sphagnum* mosses can increase with higher water contents (Rydin and McDonald, 1985) suggesting that water availability is important for moss growth and productivity. However, McNeil and Waddington (2003) showed that drying and wetting cycles could negatively affect *Sphagnum* primary production and consequently net ecosystem CO_2 exchange. The drying and subsequent rewetting of the peat can produce an immediate increase of respiration but more importantly shut down photosynthesis for a prolonged period of time (20-days) (McNeil and Waddington, 2003). As a result, the diurnal wetting and drying at the experimental plots may have suppressed the photosynthetic ability (i.e. GEP) of *Sphagnum* for the majority of the season in turn affecting the carbon balance through enhanced respiration. Conversely, more stable θ_c at the natural site were observed over the season where less variability and consistently higher production occurred suggesting that stable moisture is needed for *Sphagnum* growth and productivity. Furthermore, McNeil and Waddington (2003) suggest that carbon cycling will not be restored until a suitable moss layer accumulates (i.e. acrotelm) to stabilize the water table. Results indicate that the transplanted acrotelm is sufficient in stabilizing the water table therefore provides improved moisture supply for photosynthesis and subsequent suppression of respiration. As was suggested in Chapter 3, as the acrotelm further resettles post disturbance (i.e. new growth of vegetation) at the experimental site, it may be possible to further stabilize the variability in surface moisture conditions thereby increasing productivity over time.

Due to peatland extraction, removal of the acrotelm exposes the older and highly degraded catotelm peat (Ingram 1978), which can undergo a number of structural changes (Chapter 3) creating a variable water and more importantly lower soil-water tension (Price, 1996). Consequently this can limit water availability to plants, particularly non-vascular *Sphagnum* mosses (Price and Whitehead, 2004) where soil-water tension below -100 mb (cm), impedes the ability of the mosses to extract moisture from the surface (Price, 1997) leading to desiccation and eventual death of the mosses if soil-water tension remains low (i.e. more negative). As such, it was hypothesized that the retention of the acrotelm would aid in maintaining low soil-water tension found in natural peatlands therefore increase *Sphagnum* survival post restoration. Results indicated that soil-water retention curves and peat properties (i.e. porosity and bulk density) at the experimental site were not significantly different ($p<0.05$) from the natural site suggesting no apparent structural change occurred to the peat to impede water movement (Chapter 3). Indeed the experimental θ_c was variable over the season, however spatial moisture surveys showed that the average moisture was between 90-93% over the season therefore never reached the critical 33% (-100 mb) soil-water tension threshold described by the laboratory derived curves (Chapter 3). Therefore soil-water tensions at the surface were low since the experimental site was wet suggesting that water availability to the surface was ample to supply *Sphagnum* with moisture for photosynthesis and growth, however this implies that moisture was not the only control on productivity at the site. Diurnal variations in moisture as discussed above likely caused reductions in GEP despite the wetter conditions at the surface.

While moisture is generally the main control of gas exchange, the disturbance of the vegetation with the transplanting process likely had a considerable effect (and possibly the greatest effect) on productivity. The cutting and transplanting of the acrotelm can cause disturbance to the vegetative structure causing death and desiccation, especially to *Sphagnum* mosses. This in turn can lower GEP considerably due to the lack of photosynthesis thereby shifting the experimental site towards a net source of CO_2. Vegetation at both the natural and experimental site were both comparable in terms of moss and shrub communities however the physiological 'health' of the vegetation, in particular the disturbance to the vegetative structure, may have had a considerable affect on photosynthesis. As the vegetation is initially removed and subsequently replaced over the cutover surface, the vegetation can be compressed, cracked (macropores and fissures), and even replaced on its side or upside down. As a result, the vegetation became stressed due to changes in the acrotelm structure where the disturbance caused some of the vegetation to desiccate and eventually die out. This is reflected in the productivity where results for maximum GEP (PAR>1000) at a highly disturbed moss dominated plot (4.2 g CO_2 m^{-2} d^{-1}) represented a 40% decrease in maximum productivity than a moderately disturbed moss dominated plot (10.9 g CO_2 m^{-2} d^{-1}). The percentage of living and dead vegetation at the plots controlled productivity where plots with more living vegetation had higher overall productivity. Therefore, the generally low productivity of the plots was offset by higher respiration shifting the site towards a source of atmospheric CO_2. Interestingly, the greatest productivity was observed during the latter part of the season corresponding to the growth of new capitula of *Sphagnum* moss. Regeneration of mosses post-disturbance appears to increase productivity and it is expected as the vegetation resettles post disturbance, productivity at the site should increase due to the growth and regeneration of both new and old vegetation. As in traditional restoration, reestablishment and survival of key vegetative species such as *Sphagnum* (main peat forming vegetation) will be the indicator in measuring successful restoration and on going vegetation surveys by other researchers will be able to confirm this hypothesis in the near future.

Traditional restoration efforts have shown that GP_{MAX} can increase post-restoration where Waddington and Warner (2001) showed that a restored peatland at a plot scale (-17.5 g CO_2 m^{-2} d^{-1}) had two times greater maximum production than a natural site (-8.2 g CO_2 m^{-2} d^{-1}) and almost three times that of naturally regenerated cutover peatland (-6.5 g CO_2 m^{-2} d^{-1}). Similarly Greenwood (2005) found that the GP_{MAX} had an increasing trend over a 3-year period (-7.9 to -35.5 g CO_2 m^{-2} d^{-1}) at the ecosystem restoration scale. Furthermore, modeled GP_{MAX} for natural northern boreal peatlands have shown to range from 4.1 ± 0.1 to 7.1 ± 0.5 with an average of 5.2 ± 0.1 (Frolking et al., 1998). Results from this study suggest that while experimental GP_{MAX} was considerably lower on average than standard restored sites, it was comparable to the mean maximum for natural northern boreal peatlands. However, GP_{MAX} is likely enhanced at standard restored sites because of the changing and emerging vegetation. Herbaceous vegetation can colonize rapidly after restoration and are pioneer species prior to *Sphagnum* moss reestablishment (Lavoie et al., 2003). As such, the herbaceous vegetation have higher photosynthetic rate compared to moss species such as *Sphagnum* (Griffis et al., 2000), which can account for the large differences in GP_{MAX} between natural and standard restored peatlands.

Conclusions and implications for restoration

Waddington and Price (2000) suggest that it is important to restore an extracted peatland as soon as possible post abandonment to reduce total carbon losses (Waddington and McNeil, 2002) and limit the irreversible changes to the peat structure (Price, 1996, 1997; Schlotzhauer and Price, 1999). Reestablishment of key vegetative species such as *Sphagnum* have been indicators in measuring successful restoration and it is expected that the new extraction-restoration technique should substantially improve the ability for the ecosystem to return to a natural carbon accumulating systems due to the immediate presence of the acrotelm and vegetation structure. The acrotelm transplant onto cutover peat approach adopted at the experimental site was successful in maintaining moisture conditions similar to the natural site (Chapter 3) but it was still a moderate source of CO_2 to the atmosphere with the natural site being a slight sink, however not significantly different from zero flux.

The acrotelm approach emitted 110.5 g C m^{-2} representing a three to four times decrease in respiration than the estimated emissions from abandoned cutover sites (300 to 400 g C m^{-2} y^{-1}) (Waddington and Price, 2000; Waddington and McNeil 2002; Petrone et al. 2003). Restored peatlands have also shown a significant increase in CO_2 efflux post-restoration with fluxes approximately double the rate of pre-restoration (Petrone et al., 2003). In comparison total NEE at the experimental site was a combined (wet and dry plots) 135 g C m^{-2} representing only 25% of the emissions of a standard restored site. Greenwood (2005) determined that 2-years post restoration a restored peatland actually stored between -13.5 and -20.2 g C m^{-2}. However, the ability of the experimental site in this study to maintain carbon-accumulating processes as the natural or a standard restored site was not observed post-disturbance due to differences in productivity. Nevertheless, the experimental site did maintain limited productivity post-harvest indicating that the carbon cycling of the system was still functional post disturbance suggesting that the acrotelm restoration technique can potentially return the ecosystem towards a natural sink of atmospheric CO_2 over a longer period time.

CHAPTER 5: SUMMARY

5.1 Conclusions

Natural peatlands are an important component of the global carbon cycle contributing to a net long term sink of ~23-28 g C m^{-2} y^{-1} of atmospheric carbon dioxide (CO_2) (Gorham, 1991). The natural carbon storage function of these ecosystems can be severely impacted due to peatland drainage and peat extraction and are generally left abandoned for many years before any type of restoration occurs. Consequently, this can lead to large and persistent sources of atmospheric CO_2 following abandonment due to the decomposing peat and the unvegetated surface at the abandoned cutover site. Moreover, the cutover peatland is left hydrologically variable at the surface where low water table position and soil moisture conditions lead to increased soil-water tension at the surface. Consequently, this creates harsh ecological and microclimatic conditions for vegetation reestablishment, particularly peat-forming *Sphagnum* moss. Standard restoration techniques aim to restore the peatland to a carbon accumulating system through various water management techniques by improving hydrological conditions and reintroducing *Sphagnum* at the surface. However, restoring the hydrology of peatlands can be expensive due to the cost of implementing the various restoration techniques. The goal of this study was to determine from a hydrological and carbon cycling perspective if a new peatland extraction-restoration technique, where the acrotelm is preserved and replaced on the cutover peat, could be a feasible restoration option. Results presented in this thesis presents evidence that this acrotelm transplant technique can provide favourable moisture conditions aiding in the survival and reestablishment of *Sphagnum* moss thereby potentially returning the ecosystem to a net sink of atmospheric CO_2 sooner than standard restoration techniques.

Hydrologically, the extraction-restoration technique provided conditions which prevented low moisture and high soil-water tension conditions at the surface over the summer season. The transplanted acrotelm maintained both a high water table and moisture conditions providing sufficient water transport to the surface for *Sphagnum* moss. Furthermore, high moisture conditions decreased soil-water tension considerably compared to the natural site where moisture was maintained well above the measured critical *Sphagnum* threshold of 33% (-100 mb) VMC further providing favourable conditions for *Sphagnum* moss survival and growth. VMC variability at the experimental site was high suggesting that a possible disturbance occurred during the extraction-restoration process however, soil-water retention analysis and physical peat properties were not significantly different indicating that no apparent change in the peat matrix structure occurred.

Peat respiration at the experimental (110.5 g C m^{-2}) restored acrotelm surface decreased significantly compared the natural peatland (144.8 and 203.7 g C m^{-2}). Increased water table led to wetter conditions at the experimental site and likely contributed to the reduced total respiration. However, gross ecosystem production (GEP) at the experimental site (-54.0 and -34.4 g C m^{-2}) was significantly reduced compared the natural site (-179.2 and -162.0 g C m^{-2}). Consequently this resulted in a shift towards a net source of CO_2 to the atmosphere over the season at the experimental site (78.5 and 56.5 g C m^{-2}) and a sink of CO_2 at the natural site (-17.6 and -22.8 g C m^{-2}). While significant differences existed in respiration at each site, the overall net ecosystem exchange (NEE) at both sites was determined largely by the variation in productivity (GEP) particularly at the experimental site.

Light response curves showing the relationship between GEP and photosynthetically active radiation (PAR) indeed indicated that maximum GEP was considerably different from the natural site, however it also suggests that the experimental site was still productive post-disturbance. Moreover, it is likely that the percentage of living and dead vegetation at the plots post restoration had a large control on productivity where it was evident that plots with more living vegetation had higher overall productivity (GEP). Furthermore, the variability of moisture at the surface consequently lead to large diurnal variations in moisture (~30%) at the experimental site. But as suggested above there were no significant differences in peat structure between the sites. It is theorized that a change in volume in the capitula may enhance wetting and drying cycles. Lateral expansion/contraction within the peat matrix may occur due spaces (gaps/fissures) left from the extraction-restoration process promoting large moisture changes thereby potentially affecting the gas exchange process. Large changes in moisture have been seen to affect productivity leading to variable GEP and enhanced respiration (i.e. McNeil and Waddington, 2003), making it important to limit the moisture variability at the surface from a carbon cycling perspective. Therefore a combination of both physiological health of the vegetation and wetting/drying cycles contributed to lower GEP, suggesting the importance of limiting disturbance at the surface during the extraction and restoration process.

The new extraction-restoration technique has potential to return a peatland to both near-natural hydrological conditions and towards a net sink of atmospheric CO_2. The replaced acrotelm on the cutover surface aided in maintaining adequate moisture conditions thereby provided favourable conditions for *Sphagnum* survival and reestablishment. However, the ability of the system to remain a net sink of CO_2 as observed at the natural site was not observed post-disturbance due to differences in productivity. Both variability in surface soil moisture and disturbance to the surface vegetation may have had a great impact on overall productivity. Therefore it is suggested that the extraction-restoration process use more care in both the removal and replacement of the acrotelm on the cutover surface. By limiting surface damage (e.g. compression) and spaces (gaps/fissures) between the transplanted acrotelm blocks, this may potentially limit moisture variability by decreasing lateral expansion and increase survival to the vegetation (i.e. *Sphagnum* moss) thereby increasing overall productivity. Nevertheless, this process (extraction and restoration) is potentially improved over standard extraction where productivity of the cutover site is completely removed due to the lack of vegetation after extraction. Consequently, complete restoration to the surface is needed to return carbon cycling process to the system through the regeneration of new vegetation. However, the acrotelm restoration maintains the vegetative structure and while the process did maintain limited productivity post-extraction, this indicates that the carbon dynamics of the ecosystem was maintained due to this process potentially returning the ecosystem towards a natural sink of atmospheric CO_2 sooner than standard restoration.

REFERENCES

Alm, J., Schulman, L., Walden, J., Nykanen, H., Martikainen, P.J, & Silvola, J. 1999. Carbon balance of a boreal bog during a year with an exceptionally dry summer. *Ecology*, 80, 161-174.

Bartlett, K.B., Crill, P.M., Sass, R.L., Harriss, R.C. and Dise, N.B. 1992. Methane emissions from tundra environments in the Yukon-Kuskikwim delta, Alaska. *Journal of Geophysical Research*, Vol. 97, 16656-16660.

Boelter, D.H. 1965. Hydraulic conductivity of peats. *Soil Science*, 100: 227-231

Boelter, D.H. 1968. Important physical properties of peat. *In*: *Proceedings, 3rd International Peat Congress*, Quebec City, 1967; 150-156.

Campeau, S., and Rochefort, L. 1996. *Sphagnum* regeneration on bare peat surfaces: field and green house experiments. *Journal of Applied Ecology* 33: 509-608.

Cleary, J., Roulet, N.T., & Moore, T.R. 2005. Greenhouse Gas Emissions from Canadian Peat Extraction, 1990-2000: A Life-cycle Analysis. *Ambio*, Vol. 34, No.6.

Clymo, R.S. (1983) Peat. *In*: Gore, A.J.P. (Ed.), *Mires: Swamp, Bog, Fen and Moor*, Elsevier Scientific, New York, pp. 159-224.

Dane, J.H., and Hopmans, J.W. 2002. Pressure Plate Extractor *In*: *Methods of Soil Analysis Part 4 – Physical Methods* Dane, J.H., and Topp, G.C. (eds). Soil Science of America Book Series, SSSA, Madison Wisconsin.

Day, S. 2003. Restoration and its Impact on Methane Dynamics in a Cutover Peatland, M.Sc. Thesis, McMaster University, Hamilton, Ontario, Canada.

Eggelsmann, R. 1988. Rewetting for protection and renaturation/regeneration of peatlands after or without peat winning. *In*: *Proceedings of the 8th International Peat Congress*, Leningrad, Russia, p. 251-260.

Eggelsmann, R., and Blankenburg, J. 1993 Moor und wasser – Leegmoorprojekt, Naturschutz Landschaftpfl. *Niedersachs*, Heft 29: 19-48

Environment Canada. 2006. *Canadian Climate Normal, 1971-2000.* Quebec. Atmospheric Environmental Service, Canadian Climate Program, Environment Canada, Ottawa.

Ferland C., and Rochefort, L. 1997. Restoration techniques for *Sphagnum*-dominated peatlands. *Canadian Journal of Botany*, 75: 1110-1118

Foster, D.R., King, P., and Glaser, P.H. 1983. Origin of string patterns in boreal peatlands. *Nature*, Vol. 306, 256-258.

Freeman, C., Lock, M.A., and Neal, C. 1993. Fluxes of CO_2, CH_4, and N_2O for a Welsh peatland following simulation of water table draw-down: Potential feedback to climatic change. *Biogeochemistry*, 19: 51-60.

Gillham, R.W. 1984. The capillary fringe and its effect on water-table response. *Journal of Hydrology*, 67, 307-324

Girard M, Lavoie C, Thériault M. 2002. The regeneration of a highly disturbed ecosystem: a mined peatland in southern Québec. *Ecosystems*, 5: 274-288.

Gorham, E. 1991. Northern peatlands: role in the carbon cycle and probable response to climatic warming. *Ecological Applications*. 1: 182-195.

Gorham, E. 1995. Biogeochemistry of northern peatlands. *In*: *Biotic Feedbacks in Global Climatic Systems*, pp. 169-187

Gorham, E., & Rochefort, L. 2003. Peatland restoration: A brief assessment with special reference to *Sphagnum* bogs. *Wetlands Ecology and Management*, 11:109-119.

Greenwood, M.J. 2005. The effects of restoration on CO_2 exchange in a cutover peatland. M.Sc. Thesis, McMaster Univeristy, Hamilton, Ontario, Canada.

Griffis, T.J., Rouse, W.R., and Waddington, J.M. 2000. Interannual variability of net ecosystem CO_2 exchange at a subarctic fen. *Global Biogeochemical Cycles*, 14: 1109-1121.

Hayward, P.M., and Clymo, R.S. 1982. Profiles of water content and pore size in Sphagnum and peat, and their relation to peat bog ecology. *Proc. R. Society Lond.* B, 215, 299-325.

Heathwaite ,A.L., and Gottlich, K.H. (eds). 1993. *Mires: Process, Exploitation and Conservation*, Chichester: John Wiley & Sons. pp 506.

Ingram, H.A.P. 1978. Soil layers in mires: functions and terminology. *Journal of Soil Science,* 29: 224-227.

Ingram, H.A.P. 1983. Hydrology. *In*: *Ecosystems of the World*, Volume 4A, *Mires: Swamp, Bog, Fen and Moor, General Studies*, Gore AJP (ed). Elsevier: New York; 67-158.

Ingram, H.A.P. 1992. Introduction to the ecohydrology of mires in the context of cultural perturbation. *In*: *Peatland Ecosystem and Man: An Impact Assessment*, Bragg, O.M. Hulme, P.D., Ingram, H.A.P. (Tr.) Academic Press, London, p. 276.

International Panel on Climate Change (IPCC). 2001. Climate Change 2001: *The Scientific Basis*. Houghton, J.T., Ding, Y., Griggs, D.J., Nouger, P., van der Linden, J., and Xiaosu, D. (Eds). Cambridge University Press, UK. pp 944

Kellner, E., and Halldin, S. 2002. Water budget and surface-layer water storage in a Sphagnum bog in central Sweden. *Hydrological Processes*, 16 (1): 87-103.

Kennedy, G.W., and Price, J.S. 2005. A conceptual model of volume-change controls on the hydrology of cutover peats. *Journal of Hydrology*, 302 (1-4): 13-27.

Kettridge, N. University of Sheffield. Personal Communication. Nov. 2005.

Klute, A. 1986. Water Retention: Laboratory Methods. Pressure Plate Extractor *In*: *Methods of Soil Analysis Part 1 – Physical and Mineralogical Methods Second Edition* Klute, A. (ed). Soil Science of America Book Series, SSSA, Madison Wisconsin.

Komulainen, V-M., Tuittilia, E-S., Vasander, H., and Laine, J. 1999. Restoration of drained peatlands in southern Finland: Initial effects on vegetation change and CO_2 balance. *Journal of Applied Ecology*, Vol. 36, 36, 634-648.

Lafleur, P.M., Moore, T.R., Roulet, N.T., and Frolking, S. 2005. Ecosystem Respiration in a Cool Temperate Bog Depends on Peat Temperature But Not Water Table. *Ecosystems,* 8: 619-629.

Landriault, L.E. 2004. Moisture Dynamics Within Naturally Regenerating Sphagnum capillifolium Cushions Found in an Abandoned Block-cut Bog, Quebec. M.ES. Thesis, University of Waterloo, Waterloo, Ontario, Canada.

LaRose, S., Price, J.S., and Rochefort, L. 1997. Rewetting of a cutover peatland: Hydrologic assessment. *Wetlands*, 17(3), 416-423.

Lavoie, C., and Rochefort, L. 1996. The natural re-vegetation of a harvested peatland in southern Quebec: a spatial and dendroecological analysis. *Ecoscience*, 3, 101-111.

Lavoie, C., Grosverner, P., Girard, M. and Marcoux, K. 2003. Spontaneous revegetation of mined peatlands: an useful restoration tool? *Wetlands Ecology and Management*, 11: 97-107.

McNeil, P. 2001. Limits to *Sphagnum* growth in an abandoned mined peatland. M.Sc. Thesis, School of Geography and Geology, McMaster University, Ontario, Canada.

McNeil, P. and Waddington, J.M. 2003. Moisture controls on *Sphagnum* growth and CO_2 exchange on a cutover bog. *Journal of Applied Ecology*. 40, 354-367.

Moore, T.R., 1987. Patterns of Dissolved Organic Matter in Sub-Arctic Peatlands. *Earth Surfaces Processes and Landforms*, 12(4): 387-397.

Moore, T.R., and Dalva, M. 1993. The influence of temperature and water table position on carbon dioxide and methane emissions from laboratory columns of peatland soils. *Journal of Soil Science*, 44: 651-664.

Moore, T.R., and Knowles, R. 1989. Methane and carbon-dioxide Evolution from sub-arctic fens. *Canadian Journal of Soil Science*, 67 (1): 77-81.

Moore, T.R., Bubier, J., Lafleur, P., Frolking, S., and Roulet, N.T. 2002. Plant biomass, production and CO_2 exchange on a cutover bog. *Journal of Applied Ecology*, 90: 25-36.

Okruszko, H. 1995. Influence of hydrological differentiation of fens on their transformation after dehydration and on possibilities for restoration. *In* Wheeler, B.D. Shaw, S.C. Fojt, W., and Robertson, R.A. (eds), *Restoration of Temperate Wetlands*, pp. 113-120, John Wiley & Sons, Chichester.

Petrone, R.M. and Waddington, J.M. 2001. Ecosystem scale evaporation and net CO_2 exchange from a restored peatland. *Hydrological Processes*, 15 (14): 2839-2845.

Petrone, R.M., Price, J.S., Waddington, J.M., and von Waldow, H. 2004. Surface moisture and energy exchange from a restored peatland, Quebec, Canada. *Journal of Hydrology*, 295, 198-210

Petrone, R.M., Waddington, J.M., and Price, J.S. 2003. Ecosystem-scale flux for CO_2 from a restored vacuum harvested peatland. *Wetland Ecology and Management*, 11: 419-432.

Price, J.S. 1996. Hydrology and mircoclimate of a partly restored cutover bog, Quebec. *Hydrological Processes*, 1263-1272.

Price, J.S. 1997. Soil moisture, water tension and water table relationships in a managed cutover bog. *Journal of Hydrology*, 202: 21-32

Price, J.S. 1998 Method for restoration of a cutover peatland, Quebec, Canada. In: *Proceedings, Peatland Restoration and Reclamation: Techniques and Regulatory Considerations*, (eds) T.J. Malterer, K. Johnson, and J. Stewart. International Peat Society, International Peat Symposium, Duluth, Minnesota, USA, p. 149-154.

Price, J.S. 2003. Role and character of seasonal peat soil deformation on the hydrology of undisturbed and cutover peatlands. *Water Resources Research*, Vol. 39, No. 9, 1241.

Price, J.S. and Whitehead, G.S. 2001. Developing hydrological thresholds for *Sphagnum* recolonization on an abandoned cutover bog. *Wetlands*, 21: 32-42

Price, J.S. and Whitehead, G.S. 2004. The influence of past and present hydrological conditions on *Sphagnum* recolonization and succession in a block-cut bog, Quebec. *Hydrological Processes*, 18, 315-328.

Price, J.S., Heathwaite, A.L., and Baird, A. 2003. Hydrological processes in abandoned and restored peatlands. *Wetlands and Ecological Management*, 11: 65-83.

Price, J.S., Rochefort, L., and Quinty, F. 1998. Energy and moisture considerations on cutover peatlands: surface microtopography, mulch cover and *Sphagnum* regeneration. *Ecological Engineering*, 10: 293-312

Quinty, F., and Rochefort L. 1996. Plant re-introduction on a harvested peat bog, *In*: *Northern Forested Wetlands: Ecology and Management*, pp. 133-145, CRC/Lewis Publishers, Boca Raton, Fla.

Robert, C., Rochefort, L., and Garneau, M. 1999. Natural revegetation of two block-cut mined peatlands in eastern Canada. *Can. J. Bot.*, 77: 447-459.

Romanov, V.V. 1968. Hydrophysics of Bogs. Israel Programs for Scientific Translations, Jerusalem, p. 299.

Roulet, NT. 1991. Surface level and water-table fluctuations in a sub-arctic fen. *Arctic and Alpine Research*, 23 (3); 303-310.

Rydin, H., and McDonald, A.J.S. 1985. Tolerance of Sphagnum to water level. *J. Bryol.* 13, 571-578.

Sagot, C., and Rochefort, L. 1996. Sphagnum desiccation tolerance. *Cryptogamie Bryologie Lichenologie*, 17 (3): 171-183.

Schlotzhauer, S.M. and J.S. Price. 1999. Soil water flow dynamics in a managed cutover peat field, Quebec: Field and Laboratory investigations. *Water Resources Research* 35, 3675-3683.

Schothorst, C.J. 1977. Subsidence of low moor peat in the western Netherlands, *Geoderma*, 17, 265-291.

Schouwenaars, J.M. 1988. Hydrological differences between bogs and bog relicts and consequences for restoration. *Hydrobiologia*, 264, 217-224

Schouwenaars, J.M. 1998. The impact of water management on ground fluctuations in a disturbed bog relict. *Agric. Water Manag.*, 14: 439-449.

Shantz, M., and Price, J.S. 2005. Characterization of surface storage and runoff patterns following peatland restoration, Quebec, Canada. *Hydrological Processes*, In press, DOI 10.1002/hyp.6140

Silvola, J. 1986. Carbon dioxide dynamics in mires reclaimed for forestry in eastern Finland. *Annals Bot. Fennici*, Vol. 23, 59-67.

Silvola, J. 1990. Combined effects of varying water content and CO_2 concentration on photosynthesis in *Sphagnum* fucsum. *Holarct. Ecol.,* 13(3) 224-228

Skempton, A.W. and Patley, D.J. 1970. Ignition loss and other properties of peats and clays from Avonmouth, King's Lynn and Cranberry Moss. *Geotechnique*, 20:334-356

Toth, K. 2002. Dissolved organic carbon dynamics in a cutover and restored peatland. M.Sc. Thesis, McMaster University, Hamilton, Ontario, Canada.

Tuittilia, E-S., Komulainen, V-M., Vasander, H. and Laine, J. 1999. Restored cut-away peatland as a sink for atmospheric CO_2. *Oecologia*, 120: 563-574.

Van Seters, T.E. and Price, J.S. 2001. The impact of peat harvesting and natural regeneration on the water balance of an abandoned cutover bog, Quebec. *Hydrological Processes*, 15: 233-248.

Van Seters, T.E., Price, J.S. 2002. Towards a conceptual model of hydrological change on an abandoned cutover bog, Quebec. *Hydrological Processes*, 16; 1965-1981

Waddington J.M., and Roulet, N.T. 1996. Atmosphere-wetland carbon exchanges: Scale dependency of CO_2 and CH_4 exchange on the developmental topography of a peatland. *Global Biogeochemical Cycles*, 10(2): 233-245

Waddington, J.M. and Price, J.S. 2000. Effect of peatland drainage, harvesting, and restoration on atmospheric water and carbon exchange. *Physical Geography*, 21(5): 433-451.

Waddington, J.M. and Roulet, N.T. 1997. Ground flow and dissolved carbon movement in a boreal peatland. *Journal of Hydrology*, 191 (1-4): 122-138.

Waddington, J.M. and Roulet, N.T. 2000. Carbon balance of a boreal patterned peatland. *Global Change Biology*. 6(1): 87-97

Waddington, J.M. and Warner, K.D. 2001. Atmospheric CO_2 sequestration in restored mined peatlands. *Ecoscience*, 8(3): 359-368

Waddington, J.M., & McNeil, P. 2002. Peat oxidation in an abandoned cutover peatland. *Canadian Journal of Soil Science*, 82, 3:279-286

Waddington, J.M., Rochefort, L., Campeau, S. 2003. *Sphagnum* production and decomposition in a restored cutover peatland. *Wetlands Ecology and Management*. 11: 85-95

Waddington, J.M., Warner, K.D. and Kennedy, G.W. 2002. Cutover peatlands: A consistent source of CO_2. *Global Biogeochemical Cycles*, 10.1029/2001GB001398

Warner, K. 1999. Net ecosystem CO_2 exchange in natural, cutover and partly restored peatlands. M.Sc. Thesis. School of Geography and Geology, McMaster University, Hamilton, Ontario, Canada.

Whitehead, G.S. 1999. The hydrological processes influencing the natural regeneration of Sphagnum in a cutover bog after 25 years of abandonment, Quebec. M.ES. Thesis, Department of Geography, University of Waterloo, Waterloo, Ontario.