RESTORATION AND CH_4 DYNAMICS IN A CUTOVER PEATLAND

RESTORATION AND ITS IMPACT ON METHANE DYNAMICS IN A CUTOVER PEATLAND

By

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ABSTRACT

Peatlands cover 3% of the earth's surface, with approximately 110 to 130 million hectares in Canada and are important in terms of the long-term sequestration of atmospheric carbon. In contrast to their removal of CO_2 from the atmosphere, peatlands represent 15 to 30% of the total methane emissions to the atmosphere with Canadian wetlands emitting approximately 0.1 to 1×10^{10} g yr^{-1}. Drainage and harvesting of peatlands generally reduces CH_4 emissions to the atmosphere and increases CO_2 emissions by up to 400%. However, recent studies have suggested that drained peatlands may represent a larger source of atmospheric CH_4 than undisturbed peatlands.

In the first part of this study, potential CH_4 production and oxidation was determined from natural, harvested and recently restored peat. Total depth integrated CH_4 production decreased with time post harvest where CH_4 production at 2-yr > 7-yr > 20-yr cutover peat. This decrease in CH_4 production was a result of a decreased source of labile carbon, a decrease in the methanogenic population, and an increase in the concentration of alternative electron acceptors. Restoration has altered CH_4 production processes so that total depth integrated CH_4 production was 2-yr > 7-yr > RESTORED > 20-yr cutover peat. Depth dependent trends in potential CH_4 oxidation and production from each peat were dependent on the water table position while substrate quality was the main difference production values between the Lac St. Jean and Bois-des-Bel peat.

Comparison of CH_4 fluxes over the four field seasons showed restored site bare peat and mosses did not play a significant role in CH_4 emissions from the peatland. However, the overall CH_4 function of the peatland was directly related to the increase in

CH_4 emissions from vascular vegetation, remnant ditches and newly constructed ponds which were directly attributed to an increase in labile carbon for methanogenesis provided by vegetation. CH_4 fluxes from ditches and ponds suggest that these features are the largest sources of CH_4 from the peatland. However, when weighting the fluxes to the areal extent of each feature, ditches become secondary to vascular vegetation in total CH_4 emissions while the ponds had a minimal impact on the amount of CH_4 emitted from the peatland. Furthermore, ebullition from ditches and ponds was insignificant in comparison to the diffusive fluxes.

When comparing CH_4 emissions from this site to natural peatland systems (~10 g CH_4 m^{-2} a^{-1}), it is evident that the site is still a much smaller source of CH_4 and that the carbon and CH_4 process are still changing as the pool of labile carbon increases (develops). Vegetation succession is still occurring and more time and monitoring is needed in order to determine if this site will return to similar CH_4 functions as natural peatlands.

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CHAPTER 1

INTRODUCTION

1.1 Introduction

Peatlands cover 3% of the earth's surface (Clymo 1984), with approximately 110 to 130 million hectares in Canada (Zoltai 1988, National Wetlands Working Group 1988). Northern and temperate peatlands accumulate between ~20 g C m^{-2} yr^{-1} (Gorham 1991, Clymo et al. 1998, Vitt et al. 2000) and 50 g C m^{-2} yr^{-1} (Armentano & Menges 1986) respectively, and therefore are important in terms of the long-term sequestration of atmospheric carbon dioxide (CO_2) (Gorham 1995). In contrast to their removal of CO_2 from the atmosphere, peatlands represent 15 to 30% of the total methane (CH_4) emissions to the atmosphere (Matthews & Fung 1987, Cicerone & Oremland 1988, Bartlett & Harriss 1993), with Canadian wetlands emitting approximately 0.1 to 1 x 10^{10} g yr^{-1} (Moore & Knowles 1987).

In southern Quebec and Ontario, 20 to 50% of the wetlands have been drained for agricultural and horticultural purposes (National Wetlands Working Group 1988), generally reducing the emissions of CH_4 to the atmosphere (Roulet et al. 1993, Glenn et al. 1993, Roulet & Moore 1995, Waddington & Price 2000, Sundh et al. 2000) and increasing CO_2 emissions by up to 400% (Nykänen et al. 1995, 1997, Waddington et al. 2002). However, recent studies have suggested that drained peatlands may represent a larger source of atmospheric CH_4 than undisturbed peatlands (Roulet & Moore 1995, Minkkinen et al. 1997). The drainage ditches in these drained peatlands represent areas with high CH_4 fluxes due to their frequently saturated conditions, warm temperatures and supply of labile carbon (Roulet & Moore 1995, Sundh et al. 2000). Moreover, if the ditch area is large then the total CH_4 flux to the atmosphere can be significant (Roulet & Moore 1995). In restored peatlands where drainage ditches are blocked, CH_4 production and emissions may be enhanced by increasing stagnant, anaerobic conditions and growth of vegetation (Waddington & Price 2000).

Implementation of the Kyoto Protocol and increasing public interest in peatland conservation has created a greater demand for peatland restoration since restoration of these systems is significant in terms of reverting these ecosystems back to net carbon sinks. However, the impact of peatland restoration at a large scale on CH_4 fluxes and processes has not been undertaken. Consequently, the goal of this thesis is to determine the effect of restoration on CH_4 dynamics in a cutover peatland.

1.2 Peatland Ecosystems

Peatlands make up 85% of Canada's wetlands (Roulet et al. 1993) and are a contemporary and long-term sink of atmospheric carbon (Gorham 1991) storing 23 g C m^{-2} yr^{-1} (Gorham 1995). The relative strength of these source/sink functions depends, in part, on the type of peatland ecosystem and its chemical and physical properties which are controlled mainly by the hydrological conditions of the wetland (e.g. Devito & Dillon 1993, Waddington & Roulet 1996). Peatlands are transitional zones between terrestrial and aquatic ecosystems and are defined as lands where the water table is close to or at the surface, causing the formation of hydric soils and the dominance of hydrophytic plants (Tarnocai 1988) and possess a peat layer exceeding 40 cm (Zoltai 1988). They are further classified by the Canadian Wetlands Classification System based on vegetation, hydrology and water chemistry into swamps, fens and bogs (Tarnocai 1988).

Bogs, the focus of this study, are defined as rain-fed, or ombrotrophic, peatlands having low nutrient levels, a high water table and are isolated from regional groundwater. The bog surface may be raised or level with the surrounding terrain, may be treed, and is predominantly covered with *Sphagnum* mosses (Zoltai 1988, Clymo & Hayward 1989). The peat layer in bogs is often divided into two distinct sections: the acrotelm and the catotelm. The acrotelm is the upper section and is composed of living, dead and poorly decomposed mosses typically 0-50 cm thick (Ingram 1992). The acrotelm encompasses the full range of water table fluctuations and is also characterized by high porosity and low bulk density (Schouwenaars 1993) resulting in a relatively high hydraulic conductivity that decreases with depth (Boelter 1965). High specific yields in the acrotelm can range from 0.5 to 0.1 over 50 cm (Price 1992) maintaining a high water table (Price et al. 2003). This zone also accumulates labile carbon from vegetation through root exudates and senescence (Waddington & Price 2000). Aerobic conditions found within this layer enhance decomposition and CO_2 production while reducing CH_4 emissions through the oxidation of CH_4 to CO_2. Conversely, the catotelm is a layer of more decomposed peat. This zone is permanently saturated with a lower porosity and a higher bulk density due to shrinkage and compression (Price 1996, Price & Whitehead 2001). It has less variation in hydraulic conductivity with depth; with hydraulic conductivity three to four orders of magnitude lower compared to the acrotelm as a result of the increased friction in the smaller pores (Waddington & Price 2000, Price et al.

2003). Generally, this zone possesses much more recalcitrant carbon than the acrotelm due to the mineralization of the labile carbon in the acrotelm. As a consequence of the saturated conditions, anaerobic decomposition and methanogenesis are the dominant processes in the catotelm (Clymo, 1984).

1.3 Peatland Carbon Cycling

1.3.1 Carbon Balance

The carbon balance of a peatland (ΔC) is represented as:

$$\Delta C = CO_{2\,(GEP)} - CO_{2\,(NER)} - CH_4 - DOC \qquad (1)$$

where $CO_{2\,(GEP)}$ and $CO_{2\,(NER)}$ refer to the gross ecosystem production and net ecosystem respiration of CO_2, respectively. CH_4 refers to methane emission, while DOC is the water borne loss of dissolved organic carbon. The amount of CO_2 fixed by plants through photosynthesis to form organic carbon is a measure of the gross ecosystem production (GEP). GEP is dependent on the amount of photosynthetically active radiation (PAR) (Frohlking et al. 1998, Schlesinger 1997, Joabsson et al. 1999a), temperature (Waddington & Roulet 1996), nutrient supply (Shaver et al. 1998) and plant type and growth (Griffis et al. 2000) where increases in the first three variables generally increase GEP. Mean GEP for wetlands is ~1300 g C m^{-2} yr^{-1}, accumulating 3.8 x 10^{15} g yr^{-1} (Schlesinger 1997). However, bogs are known to be less productive systems than other types of wetlands and have a lower GEP. For example, GEP in a *Sphagnum* bog in Ontario was 30 to 32 g C m^{-2} yr^{-1} (Belyea & Warner 1996) while *Sphagnum* moss productivity in a forested bog in northern Minnesota was 320 to 380 g C m^{-2} yr^{-1} (Grigal 1985).

Net ecosystem respiration (NER) is the amount of CO_2 released to the atmosphere from plant, root and soil respiration. Respiration is dependent on peat volumetric moisture content (VMC) (Moore & Knowles 1989), the pool of labile carbon available for decomposition (Valentine et al. 1994) and peat temperature (Moore & Dalva 1993). It is estimated that NER represents 50% of gross CO_2 fixation by photosynthesis (Schlesinger 1997) with respiration from live roots accounting for 35-45% of this total (Silvola et al. 1996).

Generally, net ecosystem exchange (NEE) is measured directly and is the sum of GEP and NER. NEE is most sensitive to the pattern and timing of weather events (Griffis et al. 2000). Peatlands act as CO_2 sinks when the beginning of the growing season experiences frequent rain events, high water table positions and warm temperatures which result in early plant leafing whereas net CO_2 source years are experienced when dry conditions occur in early spring (Griffis et al. 2000). This NEE interannual variability is most pronounced during pre-green and post-green periods due to the growth stage and phenology of wetland vegetation (Griffis et al. 2000). Summer NEE values have been found to range from -2 to -12 g CO_2 m^{-2} d^{-1}, where a negative flux indicates an uptake of CO_2 to the plant and removal from the atmosphere (Bellisario 1995, Ball 1996, Carroll & Crill 1997, Griffis et al. 2000).

Peatlands are a large source of CH_4, releasing approximately 4.0 g C m^{-2} yr^{-1} globally (Gorham 1991) representing 15 to 30% of the total atmospheric burden of CH_4 (Matthews & Fung 1987, Cicerone & Oremland 1988, Bartlett & Harriss 1993). The net flux of CH_4 to the atmosphere is dependent on the extent of the aerobic and anaerobic zones with the water table generally representing the division between these two zones. However, the saturated (and therefore generally anoxic) conditions of the capillary fringe can also be significant in extent above the water table within peat. For example, Whitehead (1999) found that the capillary fringe extended ~30 cm above the water table in moderately decomposed peat. Therefore, using the water table position as an indicator between the zones of CH_4 production and consumption may underestimate total CH_4 production and overestimate total consumption of CH_4, possibly attributing to the variability seen when correlating CH_4 flux to the water table. Consequently, it may be important to determine the extent of the capillary fringe at a site to determine its areal significance and importance to potential CH_4 production. Nevertheless, in general as the water table increases CH_4 production increases while CH_4 oxidation decreases. The opposite is true for water table declines. CH_4 emissions are also dependent on temperature (Dise et al. 1993, Moore & Dalva 1993, Moore et al. 1994) and carbon quality (Crill et al. 1988, Valentine et al. 1994, Chanton et al. 1995). In some vegetative communities, CH_4 flux increases with an increase in NEP (Whiting & Chanton 1992, 1993, Chanton et al. 1993, Bellisario 1995, Waddington & Roulet 1996). Findings from Whiting & Chanton (1993) and King et al. (2002) estimate that approximately 1-5% of GEP is emitted back to the atmosphere as CH_4.

Dissolved organic carbon (DOC) is produced through the decomposition of plant tissues and soil organic matter. DOC in rainwater is generally <2 mg L^{-1} (Dalva & Moore 1991) whereas concentrations in stream water from natural peatlands range between 20 to 30 mg L^{-1} (Moore et al. 1998). Moore et al. (1998) estimates that DOC export from peatlands ranges from 5 to 40 g DOC m^{-2} yr^{-1}. DOC concentrations follow a seasonal trend where concentrations are highest in the summer due to low flow periods while decreases are seen during high flow periods in the spring and autumn (Bourbonniere 1989, Waddington & Roulet 1996, Tóth 2002). Studies have shown that DOC production is not significantly affected by changes in temperature (Moore et al. 1998, Tóth 2002), however DOC was shown to be released during water table fluctuations or flushing episodes (Moore et al. 1998). As a result, potential global warming causing lower water table levels and higher soil temperature will be unlikely to affect DOC production, although it may influence the export pathways and flux. DOC leached from increased plant production may result in higher porewater DOC concentrations (Moore et al. 1998).

1.3.2 Controls on CH_4 Emissions

Studies have determined the flux of CH_4 from a wide range of bog sites. Values have been found to range from <1 mg CH_4 m^{-2} d^{-1} to over 1300 mg CH_4 m^{-2} d^{-1} (Crill et al. 1988, Moore & Knowles 1990, Roulet et al. 1992, Roulet et al. 1994, Waddington & Roulet 1996, Granberg et al. 1997, Hargreaves & Fowler 1998, Bellisario et al. 1999, Fiedler & Sommer 2000). CH_4 efflux is extremely variable, both spatially and temporally, due to the multiple factors controlling CH_4 production, oxidation and transport. This variability has prevented comparisons between sites as well as causing difficulties when attempting to upscale fluxes from vegetation communities to the landscape scale (Bubier & Moore 1994). This section provides a review of the controls of temperature, water table, carbon quality and vegetation on CH_4 emissions.

Temperature is known to control the rate of decomposition, thereby controlling the rate of supply of carbon to methanogens for CH_4 production (Valentine et al. 1994, Updegraff et al. 1998). Some authors suggest that temperature is the main control for CH_4 fluxes (Hargreaves & Fowler 1998, Updegraff et al 1998); however other authors suggest that temperature becomes the main control of CH_4 flux only when the site is flooded or the water table level is near the surface, thereby eliminating the oxidation of CH_4 (Bubier & Moore 1994, Nykänen et al. 1998). Laboratory studies show an important but weak relationship between temperature and CH_4 flux. Temperature and CH_4 flux relationships in the field also indicate seasonal patterns linked to the thermal regime (Moore & Knowles 1987, Windsor et al. 1992). Crill et al. (1988) found that CH_4 flux increased over 70 fold with a 3 fold increase in soil temperature. However, the strength of the relationships determined in the field are not as strong as those determined in the laboratory due to the in situ variability and complexity of the processes (Segers 1998).

Changes in temperature cause concomitant changes in the rates of CH_4 production and oxidation, however, methanogens have been shown to be more temperature-dependent than methanotrophs (Moore & Dalva 1993, Dunfield et al. 1993, Bubier & Moore 1994, Valentine et al. 1994, Updegraff et al. 1995, Van Hulzen et al. 1999) where Q_{10} values range from 1 to 28 (Dunfield et al. 1993, Moore & Dalva 1993, Dise et al. 1993, Valentine et al. 1994, Mikkela et al. 1995, Updegraff et al. 1995, Segers 1998, Daulat & Clymo 1998, Van Hulzen et al. 1999) and from 1.2 to 2.1 (Dunfield et al. 1993, Moore & Dalva 1993) for CH_4 production and oxidation, respectively.

CH_4 emissions are best explained by water table position rather than temperature (Moore & Knowles 1989, Moore & Dalva 1993, MacDonald et al. 1998, Waddington & Price 2000) as the water table position controls the extent of the zones of CH_4 production and oxidation. Field and laboratory studies have also determined relationships between CH_4 flux and water table position (Sundh et al. 1995, 1995, MacDonald et al. 1998, Hargreaves & Fowler 1998, Moore & Roulet 1993, Dise et al. 1993) but these relationships are often weak (Windsor et al. 1992). Highest CH_4 emission rates generally occur when the water table is near the vegetation surface which results in minimal CH_4 oxidation, thereby allowing more CH_4 to escape to the atmosphere (Crill et al. 1988, Sundh et al. 1995). Correspondingly, when the water table is lower more CH_4 is oxidized, resulting in a lower net CH_4 flux. Other studies found results contrary to this, where increases in CH_4 flux were found with decreases in the water table position (Moore et al. 1990, Moore & Dalva 1993, Bubier & Moore 1994). These situations are associated with episodic events where a decrease in the water table increases the total stress of the overlying peat, thereby degassing CH_4 bubbles previously trapped within the peat matrix. Conversely, Dise et al. (1993) found that CH_4 emission did not increase with an increase in the water table position, but experienced a lag time of approximately three weeks. Reasons for this lag time were not discussed however; possible explanations could be the inhibition of methanogenesis by alternative electron acceptors (such as NO_3 and SO_4) (Freeman et al. 1994, Granberg et al. 2001) and/or the recovery of the methanogenic population after exposure to oxic conditions (Segers 1998, Whalen & Reeburgh 2000).

Studies of peat CH_4 production and oxidation potentials have found that maximum rates of CH_4 production occur within 10 cm of the surface in saturated peat or below the mean water table position (Svensson & Sundh 1993, Sundh et al. 1994) while the highest CH_4 oxidation rates occur at or just above the mean water table (Sundh et al. 1994, 1995). As a result, water table reductions >20 cm can switch off the zone where most of the CH_4 is produced in the peat profile (Sundh et al. 1994).

CH_4 production also depends on the rate of supply of carbon to methanogens. The botanical composition of peatlands significantly influences decomposition rates (Nilsson & Bohlin 1993, Sundh et al. 1994) and therefore the quality of available carbon for methanogenesis. Peat containing more woody species (i.e. trees and shrubs) has a much higher lignin to nitrogen (N) ratio and a much lower C:N ratio. As lignin formation requires oxygen, lignified compounds in litter will resist anoxic degradation and are deemed recalcitrant (Svensson & Sundh 1993). The decrease in CH_4 production with depth is a direct result of the decrease in substrate quality or increase in lignin (recalcitrant) carbon content (Valentine et al. 1994). Crill et al. (1988) found that bog sites had more humified peat compared to fen sites, indicating that more recalcitrant peat was linked to a lower flux. Dise et al. (1993) noted that peat humification explained only 2% of the CH_4 flux. Additions of more easily degradable (labile) carbon has been found to increase CH_4 production (Valentine et al. 1994) and is more sensitive to changes in temperature and aeration than recalcitrant carbon (Updegraff et al. 1995). The duration in which litter is under oxic conditions will determine the extent of degradation and the quality of organic matter entering the anoxic zone (Svensson & Sundh 1993). Low water table levels accelerate the decomposition of labile carbon through aerobic respiration with less labile substrate available for methanogenesis (Chanton et al. 1995). Consequently, zones of higher CH_4 production may occur in peat profiles where more labile carbon accumulated under anoxic conditions preventing excessive aerobic decomposition (Sundh et al. 1994).

Studies have shown that vascular plants are responsible for 64 to greater than 90% of CH_4 emissions (Whiting & Chanton 1992, Shannon et al. 1996). Increases in GEP and biomass of vascular plants is directly linked to increases in CH_4 emission with 1 to 4% of GEP converted to CH_4 (Whiting & Chanton 1993, Waddington et al. 1996, Bellisario et al. 1999, King & Reeburgh 2002). Consequently, vascular plants are an important control on CH_4 emissions to the atmosphere and stimulate methanogenesis through the supply of labile carbon (e.g. root exudates and senescence) and enhance emissions by the transport of CH_4 from the soil to the atmosphere. However, plants can also dampen CH_4 emissions through oxidation of the rhizosphere.

Most of the carbon assimilated by plants is allocated to below ground tissue (Joabsson et al. 1999b). Photosynthetic products (root exudates) are secreted from roots, providing a source of labile carbon for methanogenesis (Whiting & Chanton 1993, Waddington et al. 1996, Shannon et al. 1996, Lloyd et al. 1998, Bellisario et al. 1999, Waddington & Price 2000, Joabsson & Christensen 2001). The decay of roots provides an additional source of labile carbon for CH_4 production (Shannon et al. 1996). Peatland plants have been found to have high root to shoot ratios (Joabsson et al. 1999b). Consequently, as a plant grows and increases in GEP, below ground biomass and root exudates increase concurrently, resulting in more labile carbon for methanogenesis and thereby higher CH_4 emissions (Waddington et al. 1996, Moore et al. 1998, Joabsson et al. 1999b). Waddington et al. (1996) found higher dissolved CH_4 concentrations over 24 hours at sites with fully vegetated plants compared to sites with clipped plants, suggesting that the decrease in CO_2 fixation resulted in a subsequent decrease in root exudates available for methanogenesis. Joabsson et al. (1999b) also found similar results, with dissolved CH_4 concentrations higher at control sites compared to shaded sites at the beginning of the field season. However, at the end of the season, concentrations at the shaded plots became greater than the control plots, suggesting a stronger transport of the dissolved CH_4 through the more vigorous development of the vascular root system of the control site vegetation. In addition, Joabsson et al. (1999b) found higher CH_4 emissions from control monoliths than from shaded monoliths. A decrease in CH_4 emissions was associated with a decrease in easily degradable carbon which was substantiated by lower concentrations of organic acids in the shaded monoliths. Greenup et al. (2000) found that below ground biomass was a better predictor of CH_4 flux than GEP ($R^2 = 0.93$) and that the long term control of CH_4 flux by plants was through the release of carbon substrates.

Vascular plants have large air spaces or aerenchymous tissue which can act as conduits for CH_4 transport, bypassing the oxidative zone without being oxidized to CO_2 (Whiting & Chanton 1993, Waddington et al. 1996, Daulat & Clymo 1998, Joabsson et al. 1999b, Greenup et al. 2000). Many studies have shown that vascular plants can enhance CH_4 emissions and that the conduit potential increases as the biomass increases (Whiting & Chanton 1993, Waddington et al. 1996, Shannon et al. 1996, Greenup et al.

2000, Frenzel & Karofeld 2000). Roura-Carol & Freeman (1999) found that CH_4 flux was higher from *Sphagnum* than from *Juncus*. The result was unexpected and was partially attributed to the low biomass of *Juncus* reducing the CH_4 transport capacity of the plant. Waddington et al. (1996) found that *Eriophorum* enhanced the seasonal CH_4 flux by 55 to 85%. Furthermore, Shannon et al. (1996) found that clipped plants still had the potential to transport CH_4 and showed no significant difference in flux compared to non clipped plants. Greenup et al. (2000) further supported this finding by simulating the conduit effect of vascular plants with glass tubes. Mean CH_4 flux values from *Sphagnum* areas was 0.1 ± 0.1 mg CH_4 m^{-2} d^{-1} while emissions from *Sphagnum* areas with glass tubes was significantly higher (2.7 ± 1.3 mg CH_4 m^{-2} d^{-1}) (Greenup et al. 2000). Conversely, Frenzel & Karofeld (2000) found that CH_4 emissions ceased after plants were clipped below the water table preventing CH_4 to escape to the atmosphere. Greenup et al. (2000) concluded that the conduit mechanism for CH_4 emissions of vascular plants was only a short term processes compared to the supply of labile carbon substrates. The degree in which vascular plants can enhance CH_4 dynamics likely changes throughout the season and is correlated to the water table position (Waddington et al. 1996). Higher water table levels increase the percent of roots within the saturated zone and the amount of CH_4 the plant is able to transport. In addition, it has been shown that, generally, stomatal activity has little effect on CH_4 emissions (Whiting & Chanton 1993, Shannon et al. 1996, Joabsson et al. 1999b, Greenup et al. 2000).

Diffusion gradients of O_2 from the atmosphere to the peat soil results in the transport of O_2 through the aerenchyma into the rhizosphere, enlarging the oxic zone around roots (Chanton et al. 1992, Lloyd et al. 1998). The enhanced oxidation of previously saturated conditions may decrease CH_4 emissions through the stimulation of methanotrophs converting CH_4 to CO_2 (Chanton et al. 1992, Christenson et al. 1994). However, Frenzel & Rudolph (1998) found very low rates of CH_4 oxidation associated with *Eriophorum*. As *Eriophorum* is highly aerenchymateous, this was unexpected. The authors suggest an extremely low pH within the rhizosphere (due to naturally low pH conditions plus H^+ ions released by the roots) may inhibit methanotrophic bacteria thereby preventing CH_4 oxidation from occurring within this zone. In addition, Roura-Carol & Freeman (1999) found that CH_4 fluxes from *Sphagnum* were unusually higher compared to *Juncus*. The authors speculated that the absence of roots for *Sphagnum* prevented any O_2 to enter the rhizome therefore eliminating any CH_4 oxidation whereas the opposite was true for *Juncus*. However, the consensus is that the enhanced transport and stimulation of CH_4 by plants is greater than the enhanced oxidation by roots (Gerard & Chanton 1993, Joabsson et al. 1999). Chanton et al. (1992) suggest that the lower importance of enhanced oxidation by plants may be a result of limitations imposed by competition between root respiration, aerobic microbial metabolism and ferrous iron oxidation.

1.4 Peatland Exploitation

The growing demand for horticultural and specialty peat products has led to the growth of the peat industry in Canada, generating $187 million annually (Bergeron 1994). Approximately 12 400 ha of peatlands were actively extracted in 2000 in Canada (Cleary 2003) with harvesting in Québec representing 29% of Canadian extraction

(Cleary pers. comm.). Over 70% of the peatlands lost have been harvested in the same regions of Québec (Lavoie & Rochefort 1996). The dominant method used for peat extraction in North America is the vacuum harvesting technique. This method begins with the creation of drainage ditches, typically 30 m apart, to lower the water table in order to allow heavy machinery to access the site. The parallel drainage ditches separate individual peat fields. The fields are convex in shape in order to facilitate drainage into the ditches (Rochefort et al. 2003). The surface vegetation is removed and the underlying peat is milled to enhance drying. The surface peat fragments are then vacuumed from the surface using specialized machinery. When the fibrous nature of the peat is no longer suitable, or when the mineral substrate is approached the cutover peatlands are then abandoned (Waddington & Price 2000).

1.4.1 Impacts to Hydrology

The primary impact of peatland drainage and harvesting is a lowering of the water table position from just below the surface to greater than 60 cm (Price 1996, Vompersky & Sirin 1997, Van Seters & Price 2001). Schouwennars (1988) suggests that a mean water table position exceeding 40 cm below the surface is detrimental to the recolonization of *Sphagnum* species. This is supported by the lack of recolonization of *Sphagnum* in vacuum harvested sites (Lavoie & Rochefort 1996, Ferland & Rochefort 1997). The lowering of the water table can also result in subsidence of the peat surface through oxidation and shrinkage of the peat above the water table and compression below (Schothorst 1982).

Removal of the acrotelm exposes the more decomposed peat of the catotelm at the surface of the peatland. The higher bulk density of this peat results in a decreased mean saturated hydraulic conductivity and lower specific yield (Sy) as a result of the smaller pores (Price et al. 2003). Van Seters & Price (2002) found saturated hydraulic conductivity to change from 4.1 x 10^{-5} to 1.3 x 10^{-5} cm s^{-1} and Sy to change by 50% from 0.14 to 0.07. Price (1997) also found a decrease in Sy of 25 to 33%. As a result of this change in Sy, only a small amount of water needs to be drained to cause a large lowering of the water table and the water table to fluctuate significantly (Price 1996, 1997). Subsidence compounds this effect by further decreasing pore sizes (Price et al. 2003). For example, Van Seters & Price (2002) found that a subsidence of 80 cm resulted in a 67% increase in water table fluctuations.

Drained harvested peatlands experience low evaporative losses due to lower ground temperatures and heat flux resulting in less energy available for convective fluxes (Price 1996, Price et al. 1998, Petrone et al. 2001, Price et al. 2003). In addition, once the water table becomes >50 cm below the surface, groundwater becomes disconnected from the evaporative process, further decreasing evaporative losses, and causing soil moisture to be depleted instead, increasing water tension (Price 1996, Price et al. 1998, 2003). It has been suggested by Price (1996) that water in the unsaturated zone is more relevant to *Sphagnum* survival than the level of the water table and supports the soil water tension threshold of –100 mb proposed by Hayward and Clymo (1982). In fact, harvested peatlands had no *Sphagnum* recolonization in areas where water tensions ranged from -156 to -355 mb (Price 1997, Price & Whitehead 2001, Price et al. 2003).

1.4.2 Carbon Cycling Impacts

It has been well documented that peatlands become substantial sources of CO_2 to the atmosphere, increasing up to 400%, after drainage and harvesting due to increased respiration and the destruction of carbon fixing vegetation (Silvola 1986, Nykänen et al. 1995, 1997, Minkkinen et al. 1997, Minkkinen & Laine 1998, Warner 1999, Waddington & Warner 2000, Sundh et al. 2000, Waddington et al. 2002, Waddington & McNeil 2002). Total ecosystem respiration is dependent on the water table position for this controls the extent of the oxic zone. However, when water table positions are high, respiration becomes dependent on temperature and substrate quality (Waddington et al. 2002). Waddington & Warner (2001) found that CO_2 emissions increased with time post harvest as a result of older sites experiencing drier (lower soil moisture) conditions thereby increasing rates of respiration. Values from Waddington et al. (2002) support this as a 2-year cutover site released 363 g CO_2-C m^{-2} compared to the 7-year site of 399 g CO_2-C m^{-2}. In addition, Waddington & McNeil (2002) found that peat oxidation rates remained high even after two decades of post extraction abandonment. However, Minkkinen & Laine (1998) found that a 34 year drained site lost ~164 to ~218 g CO_2-C m^{-2}, lower than 2-year and 7-year values reported by Waddington et al. (2002). Gorham (1991) estimates that oxidation of peat on account of long term drainage operations results in a net flux of 8.5 Tg CO_2 yr^{-1} to the atmosphere.

Peatland drainage and harvesting can decrease or stop CH_4 emissions with values ranging from -0.4 to 33 mg CH_4 m^{-2} d^{-1} (Roulet et al. 1993, Roulet & Moore 1995, Minkkinen et al. 1997, Minkkinen & Laine 1998, Komulainen et al. 1998, Alm et al.

1999, Sundh et al. 2000, Freeman et al. 2002). In fact, nutrient rich fens with high CH_4 fluxes can experience large reductions (80 to 90%) in CH_4 emissions after drainage (Sundh et al. 2000). Komulainen et al. (1998) list several reasons for this decrease in CH_4 production: 1) only recalcitrant lignified carbon remains for microbes, thereby limiting production, 2) CH_4 is being oxidized in the large oxic zone within the peat profile, and 3) successional change in vegetation towards forest species alters the substrate quality of the litter entering the system and decreases vascular transport of CH_4 by shading out ground species coverage. Despite this, drained and cutover peatlands can still act as weak sources of CH_4 during periods of high water, increasing CH_4 production and limiting CH_4 oxidation (Alm et al. 1999). Roulet et al. (1993) and Roulet & Moore (1995) suggest that there is a critical water table level, 20 to 40 cm, in which peatlands convert from a source (0 to 15 mg m^{-2} d^{-1}) to net sinks (-0.4 to 0 mg m^{-2} d^{-1}) of CH_4. However, when considering emissions from harvested peatlands, values from the drainage ditches themselves need to be included. Peatland drainage has the opposite effect on ditches, with CH_4 flux increasing (<5 to 595 mg CH_4 m^{-2} d^{-1}) post drainage (Roulet & Moore 1995, Minkkinen et al. 1997, Sundh et al. 2000). Inclusion of ditch flux values did not significantly change previous estimates of bog emissions determined by Minkkinen et al. (1997) because the proportional area of ditches was small compared to the rest of the peatland. In addition, if CH_4 fluxes from a peatland prior to drainage were initially low, then the relative impact of the ditches on CH_4 emissions post drainage would be much greater. A model developed by Roulet & Moore (1995) determined that forested bogs with ditches closer than 38 m would experience a net increase in CH_4

emissions due to the combination of low antecedent CH_4 fluxes from the undrained peatland and moderate fluxes from the ditches.

DOC concentrations from harvested sites have been shown to range from 40 to 625 mg C L^{-1} (Glatzel et al. 2003, Tóth 2002). Concentrations were found to increase immediately during harvesting (up to 188 mg C L-1) then decrease due to low dissolved organic matter source remaining (Glatzel et al. 2003). Tóth (2002) found that DOC concentrations and export from a cutover peatland were higher than from a nearby natural site.

1.5 Peatland Restoration

In Canada, some peatlands have not been recolonized by *Sphagna*, even after 30 years of natural succession (Rochefort et al. 2003). As a result, considerable research has focused on the processes of restoration. However, only 2.4% of Canadian cutover peatlands are being actively restored (Cleary 2003). Restoration practices differ between North America and Europe due to the difference in land uses of peatlands, peat extraction methods, and goals for restoring regional biodiversity (Rochefort et al. 2003). The primary long term goal of restoration in Canada is the return to a functional peat accumulating ecosystem within 20 to 30 years. However, the short term goal is to establish a plant cover composed of peat bog species, in particular *Sphagnum*, and to restore hydrological conditions similar to natural bogs (Rochefort et al. 2003). This process can be significantly accelerated through managed rewetting, introduction of plant species, fertilization and mulching (Rochefort et al. 2003).

The first step requires prohibiting drainage and to provide wet conditions suitable for the establishment of *Sphagnum* and other plants. This is completed by the blocking of drainage ditches, construction of dykes, and the creation of open water reservoirs. Diasporas collected from natural bog sites are then reintroduced to the harvested site. Rochefort et al. (2003) suggest that the most successful density of plant reintroduction is 1 ha of diasporas for every 10 ha of harvested peatland. Straw mulch is then applied to reduce harsh microclimatic conditions at a density of 3000 kg ha^{-1} in order to maximize the success of plant establishment (Rochefort et al. 2003). Finally, phosphate rock fertilizer is added to the restored peat surface. The purpose of this is to increase the establishment of companion species that would in turn facilitate the survival of *Sphagnum* through modification of the microclimate (Tuittila et al. 2000a, Rochefort et al. 2003).

1.5.1 Impacts to Hydrology

An increase in the mean water table position is the dominant change caused by blocking drainage ditches. The construction of dykes also retains water during snowmelt and autumn and early spring rain events which also results in a higher water table position (Price et al. 2003). Moreover, Price et al. (1998) found that water table levels were higher under straw mulch compared to sites with only bare peat. In fact, the water table was greater than 40 cm below the surface 40% of the time under straw mulch and 60% of the time under bare peat. Shantz (2003) also found an increase in water table levels at a recently restored peatland, however the fluctuations in the water table position were still large. The creation of open water reservoirs is often used to increase passive lateral seepage, limiting the degree of water table fluctuations and improving moisture conditions at the surface through the increase in bulk specific yield (Schlotzhauer & Price 1999).

A straw mulch cover also alters the microclimate to conditions more suitable for *Sphagnum* recolonization, as a result of its effects on the energy balance. Several studies found a decrease in net radiation and evaporation due to the change in albedo (Hares & Novak 1992, Price et al. 1998, Petrone et al. 2001), thus causing the soil to remain cool during the day and warm at night (McDonald & Helgerson 1990). As a result, water tension decreased to levels accessible for *Sphagnum* and increased relative humidity at the soil surface (Price et al. 1998). In fact, Price (1997) found that water tension was between 0 and -100 mb 97% of the time after restoration compared to a drained peatland which experienced water tension less than -100 mb 82% of the time. However, the growth of vascular plants may increase evaptransperation, negatively impacting the restoration process by lowering water table levels (Ingram 1987, Heathwaite 1994, Petrone et al. 2003).

1.5.2 Carbon Cycling Impacts

Generally, studies have shown that net CO_2 losses decreased with restoration as increased water table levels limited the zone for aerobic decomposition (Tuittila et al. 1999, Komulainen et al. 1999, Waddington & Warner 2001). Waddington & Warner (2001) found the following trend in respiration: cutover (398 g C m^{-2}) > restored (169 g C m^{-2}) > natural (138 g C m^{-2}). In addition to lower total ecosystem respiration, increases in gross photosynthesis resulted in more CO_2 being stored within the ecosystem (Tuittila et al. 1999, Komulainen et al. 1999) and accounted for 70% of the net CO_2 decrease. Tuittila et al. (1999) found that the seasonal CO_2 balance for a rewetted cutover peatland became a net sink after two years (9.1 g CO_2-C m^{-2}) and still greater net sink in the third year (64.5 g CO_2-C m^{-2}) due to a dense *Eriophorum* cover sequestering more CO_2 than was respired while Komulainen et al. (1999) found the CO_2 balance was two times lower at a drained site compared to rewetted sites which ranged from 54 to 101 g C m^{-2}.

Nevertheless, Komulainen et al. (1999), Waddington & Warner (2001) and Petrone et al. (2001) found that restored sites were still a net source of CO_2 to the atmosphere. In the studies by Waddington & Warner (2001) and Komulainen et al. (1999), *Sphagnum* was the dominant plant species which sequestered much lower rates, 2.6 to 5.1 g CO_2 m^{-2} d^{-1} (Waddington et al. 2003), of CO_2 compared to *Eriophorum*, 58.8 g CO_2 m^{-2} d^{-1} the dominant plant species in the Tuittila et al. (1999) study. As fens consist of more vascular plants they may restore faster than bogs which are dominated by bryophytes (Komulainen et al. 1999). In the studies by Waddington & Warner (2001) and Petrone et al. (2001), the seasonal CO_2 balance was determined one year post restoration compared to two and three years in Komulainen et al. (1999) and Tuittila et al. (1999) respectively. In addition, mulch (not used in the other studies) decomposition further enhanced total respiration (Waddington et al. 2003).

Contrary to CO_2, studies have found that CH_4 flux increases after restoration as a result of a higher water table limiting the amount of CH_4 that is oxidized (Komulainen et al. 1998, Tuittila et al. 2000b). Komulainen et al. (1998) found emissions from a bog in southern Finland to increase 5 fold (0.8 to 4.6 g CH_4 m^{-2} yr^{-1}) after rewetting. Both

Komulainen et al. (1998) and Tuittila et al. (2000b) found an increase in *Eriophorum* (> 1% to 20-70%) after rewetting and that CH_4 fluxes were larger at rewetted sites with *Eriophorum* vegetation than rewetted sites without any vegetation, emphasizing the importance of plant species composition on CH_4 emissions. Restored bog CH_4 emissions became significantly higher than the drained bog two years post restoration while fen CH_4 flux experienced a significant increase after only one year post restoration, again suggesting that fens restore faster than bogs (Komulainen et al. 1998). Seasonal CH_4 flux was higher after rewetting, however values were lower than emissions from natural peatlands (Tuittila et al. 2000b). The lower values may be attributed to the reduction of the methanogenic population due to persistent aerobic conditions (Segers 1998, Whalen & Reeburgh 2000). In fact, Shannon & White (1994) determined that more than one year was needed to restore CH_4 fluxes following drought conditions in a natural peatland. Therefore, the extreme length of aerobiosis at cutover sites may significantly increase the time post restoration for methanogens to recolonize and grow (Tuittila et al. 2000b).

Similar to DOC concentrations after harvesting, DOC has also been found to increase after restoration with concentrations ranging from 30 to 191 mg L^{-1} (Fenner et al. 2001, Glatzel et al. 2003, Tóth 2002). The increase in concentration is a result of the higher water table levels and soil moisture in the unsaturated zone mobilizing and transporting the carbon from oxidized peat and can be influenced by drying and wetting cycles (Glatzel et al. 2003, Tóth 2002). Tóth (2002) found that DOC export from a restored site was lower than an adjacent cutover site, due to changes in the hydrologic conditions, however, DOC concentrations increased each year post restoration and became higher than the cutover site. Contrary to DOC concentration under harvesting, DOC concentrations during restoration were more strongly related to soil moisture and water table position than peat temperature (Tóth 2002). Tóth (2002) noted that old ditches in the restored peatland had high amounts of hydrophilic DOC indicating a higher carbon quality. This higher carbon quality may lead to greater methanogenesis.

1.6 Objectives

While few studies have shown the effects of harvesting on CH_4 flux (e.g. Glenn et al. 1993, Roulet et al. 1993, Roulet & Moore 1995, Minkkinen et al. 1997, Waddington & Price 2000, Sundh et al. 2000) even fewer have looked at the effects of restoration on CH_4 flux (Komulainen et al. 1998, Tuittila et al. 2000b). The majority of these studies present data from a single field season, discussing the annual variability without considering how the flux changes over a longer (i.e. multi year) time frame. Previous studies have also failed to compare CH_4 processes from a restored site to cutover and natural CH_4 processes and link CO_2 and DOC dynamics. Therefore, the main focus of this research is to determine the effect of peatland restoration on ecosystem scale CH_4 emissions over multiple years. More specifically, the objectives of this research are to (1) determine the impacts of harvesting and restoration on CH_4 production and oxidation rates, (2) determine how water table position in harvested and restored sites affects net CH_4 production and oxidation, (3) determine the impact of restoration on CH_4 fluxes in relation to environmental variables such as water table position, soil temperature and gross ecosystem production, and its influence on changes in subsurface CH_4 storage, and

(4) determine the importance of ditches, pools and ebullition to the flux of CH_4 from cutover and recently restored peatlands.

CHAPTER 2

STUDY AREA

To determine the impacts of harvesting and restoration on CH_4 production and oxidation rates and on predicting changes in CH_4 production and oxidation based on changes to the water table (see Chapter 3), peat cores were collected from the Bois-des-Bel (BDB) and St. Marguerite Marie (LSJ) peatland. The impact of restoration on CH_4 fluxes in relation to environmental variables and its influence on changes in subsurface storage and the importance of ditches, pools and ebullition to the flux of CH_4 (see Chapter 4) were tested only at the BDB peatland.

The Bois-des-Bel peatland is located in the Bas-St Laurent region of Québec, approximately 14 km from Rivière-du-Loup (47°58'N, 69°25'W), while the Sainte-Marguerite-Marie peatland is situated in the Lac Saint-Jean region of Québec (48°47'N, 72°10'W). At BDB, the mean annual temperature is 3°C and the mean temperature for the months of January and July are -12°C and 18°C respectively (Environment Canada 1993). The mean annual precipitation is 924 mm, of which 27% falls as snow (Environment Canada 1993). The LSJ peatland experiences a mean annual temperature of 2.2°C and the mean temperature for January and July are -17.1°C and 17.3°C respectively (Environment Canada 1993). The mean annual precipitation is 909 mm, of which 32% falls as snow (Environment Canada 1993).

The BDB peatland is an ~200 ha treed bog of which 11.5 ha was drained in 1972, harvested from 1973-1980 and then abandoned (Figure 2.1). Peat harvesting was completed using the vacuum harvest method. The top layer of *Sphagnum* moss and ~80 cm of underlying peat were removed. The older peat was not harvested due to its large wood content, making it inadequate for commercial purposes (Campeau & Rochefort 1996). The 11.5 ha cutover portion of the peatland was divided into eleven 30 m x 300 m fields, separated by drainage ditches running from north to south. The drainage ditches increased runoff from the site through the main southern drainage ditch (Figure 2.1). Restoration of the bog (see Rochefort 2000) occurred in the autumn of 1999 for zones 2 to 4 and in the autumn of 2000 for zone 1 (hereafter referred to as the recently restored site) (Figure 2.1). Fields 10 and 11 (hereafter referred to as the 20 year cutover site) were left untouched in order to compare the effects of harvesting to the effects of restoration while field 9 acted as a buffer zone between the cutover and restored sites (Figure 2.1). The average peat depths of the restored and abandoned sites are 1.5 and 1.6 m, respectively. The dominant species found throughout the site are *Polytricum* spp., *Ericaceous* shrubs, *Eriophorum vaginatum*, and *Typha latifolia*. *Sphagnum* spp. are present at the restored site while *Picea mariana* and *Betula* spp. are present at the abandoned site. *Eriophorum*, *Typha latifolia* and *Betula* spp. are invasive species that appeared after harvesting. The natural site, within the same 200 ha treed bog and located ~2 km NW from the restored and cutover sites, has no surface outflow. The peat depth ranges from 2.1 to 2.4 m (Pellerin & Lavoie 2000). The dominant species at this site consisted of *Picea mariana*, *Larix laricinia*, *Sphagnum* spp., mosses, *Ericaceous* shrub, *Ledum groenlandicum*, *Chamaedaphne calyculata*,

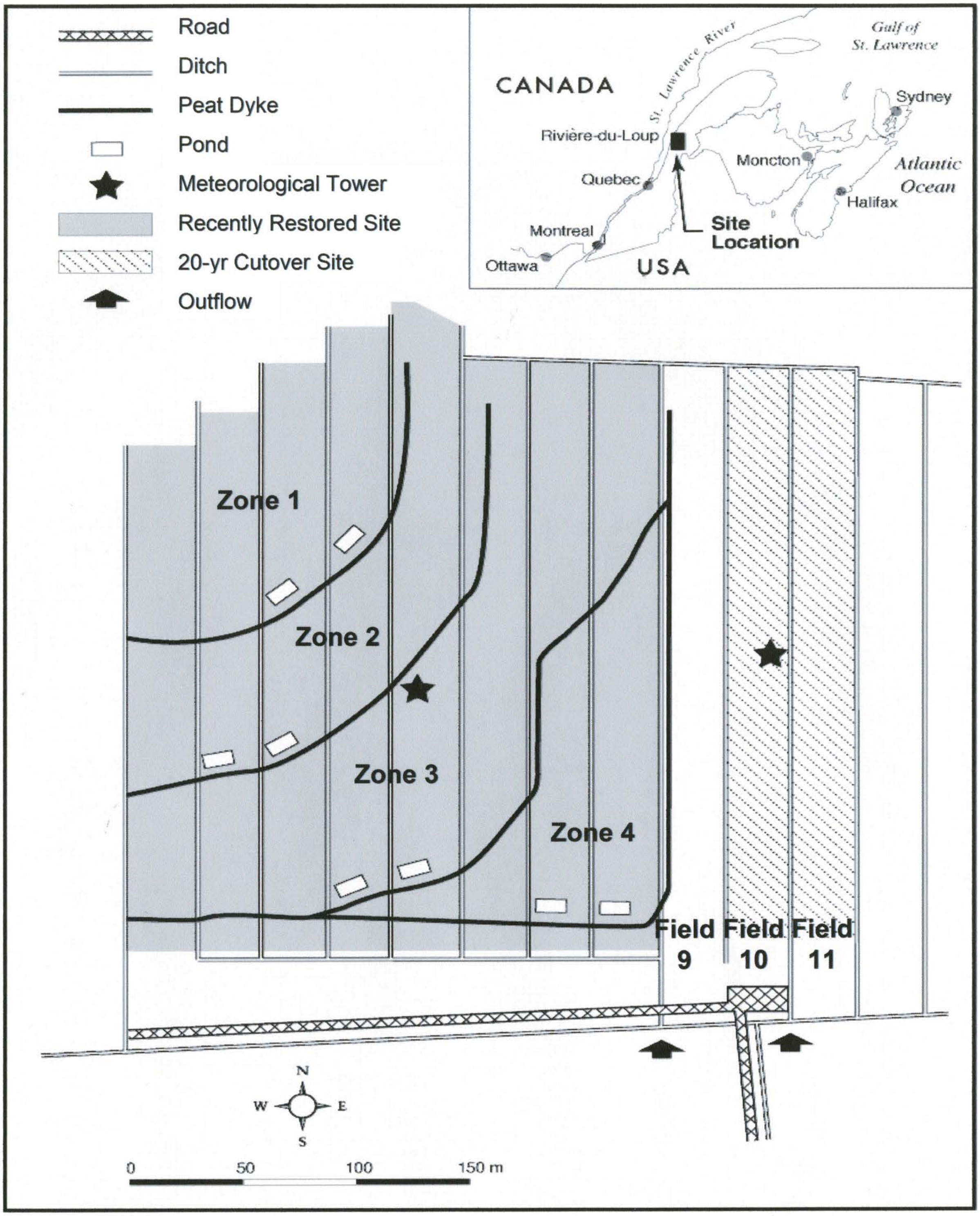


Figure 2.1 Location of Bois-des-Bel (BDB) research site in Québec (shown in top insert map), and location of the recently restored and 20-yr cutover sites within the peatland.

Kalmia angustifolia, and *Vaccinium angustifolium* (Pellerin & Lavoie 2000). The mean summer water table position in 2001 for the natural, 20 year cutover and recently restored sites were -22.7, -41.7, and -34.1, respectively (Tóth 2002).

The Lac St. Jean peatland is an ~4315 ha bog-poor fen complex classified as a plateau bog (National Wetlands Working Group 1997) (Figure 2.2). The site overlies a terrace of deltaic sands and iron pan (Price 1996) preventing water drainage and resulting in a high water table. The first site was drained in 1990 and harvested during 1991 with drainage ditches blocked in the spring of 1992 in order to rewet the site. The site was sampled in 1998, seven years after harvesting and is hereafter referred to as the 7-year cutover site. An additional site was drained in 1996 with approximately 80 cm of peat cut before drainage ditches were incompletely filled with peat in 1997. This site was also sampled in 1998, two years after harvesting and is hereafter referred to as the 2-year cutover site. Both the 2-year and 7-year cutover sites were essentially devoid of vegetation (Price 1997). A natural site was also sampled and was dominated by *Sphagnum fuscum*, *S. angustifolium*, *S. magellanicum* and *S. capillifolium* (Campeau & Rochefort 1996). The mean summer water table in 1998 for the natural, 2 year cutover and 7 year cutover sites were -11.7, -30.6 and -35.1 cm, respectively (Waddington et al. 2002).

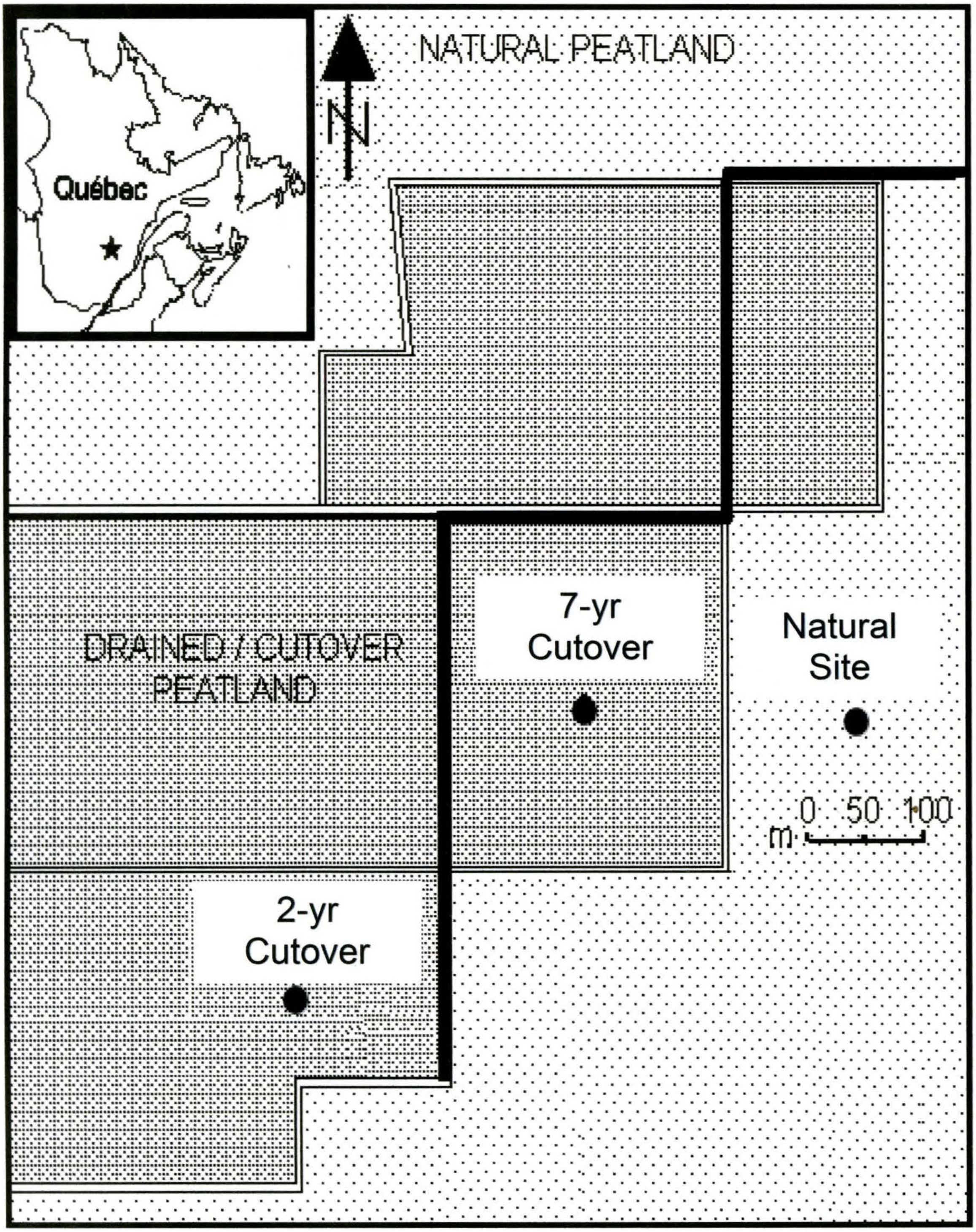


Figure 2.2 Location of Lac St. Jean (LSJ) research site in Québec (shown in top insert map), and location of the natural, 2-yr and 7-yr cutover sites within the peatland.

CHAPTER 3

CH_4 PRODUCTION AND OXIDATION IN CUTOVER AND RESTORED PEATLANDS

3.1 Introduction

The emission of methane (CH_4) to the atmosphere from natural peatlands has been estimated at 115 Tg yr^{-1}, representing ~20% of global CH_4 emissions (Matthews & Fung 1987, Cicerone & Oremland 1988). Canada is covered by 110 to 115 million ha of peatlands, with the majority located in the boreal zone. Relatively few peatlands are located in the temperate regions of southern Ontario and Québec (National Wetlands Working Group 1988). However, in this temperate region more peatlands have been impacted (such as harvesting and drainage for horticultural purposes) (Rochefort 2000). For example, the St. Lawrence Lowlands of southern Québec have experienced peatland losses of ~70% (Lavoie & Rochefort 1996). Drainage and harvesting reduces CH_4 emissions to the atmosphere (Waddington & Price 2000, Sundh et al. 2000) and increases CO_2 emissions up to 400% (Nykänen et al. 1995, Waddington et al. 2002), due to a lowering of the water table and an increase in the zone of aerobic decomposition and CH_4 oxidation. As a result, active restoration efforts are being undertaken to return the natural carbon sink function of cutover peatlands.

Changes in water table position alter the extent of the oxic and anoxic zones and therefore the rates of CH_4 production and oxidation (Sundh et al. 1993, 1994, 1995). Anoxic conditions, or a redox potential below -240 mV, are necessary for the production of CH_4. Low redox conditions may have slow rates of decomposition (Valentine et al.

1994) due to the dependence of methanogens on other bacteria to supply them with carbon substrates (such as acetate, CO_2, H_2, and methyl compounds) needed for CH_4 production (Sundh et al. 1994). Whalen & Reeburgh (2000) found that methanogens exposed to oxic conditions were unable to produce CH_4 after 48 hours under anoxic conditions, whereas methanotrophs exposed to anoxic conditions, oxidized CH_4 within 20 hours after a return to oxic conditions. Bacterial biomass (Sundh et al. 1994), alternative electron acceptors (Van Hulzen et al. 1999), and pH (Dunfield et al. 1993, Valentine et al. 1994) can also affect rates of CH_4 production.

Because the distributions of methanotrophic bacteria are dependent upon supplies of CH_4 and O_2, they are most abundant at the zone just above the mean seasonal water table position (Sundh et al. 1994, Granberg et al. 1997). Moreover, because a large proportion of methanotrophic bacteria are attached to peat particles (Sundh et al. 1995) water table position will control the biomass of methanotrophs available to oxidize diffusing CH_4. Studies estimate that 80 to 90% of CH_4 can be oxidized before reaching the peat surface (Oremland & Culbertson 1992, Bubier et al. 1993, Frenzel & Karofeld 2000). Consequently, the oxic layer acts as a strong control on the amount of CH_4 actually emitted to the atmosphere.

Peatland drainage, harvesting and restoration activities result in dramatic changes in the water table position. Harvesting and the subsequent enhanced peat oxidation lowers the quality of carbon in the surface of peatlands (Waddington et al. 2001). Conversely, peatland restoration can increase surface peat quality (Gruneir, 2003). Consequently, changes in potential peat CH_4 production and oxidation are expected, which will lead to changes in the flux of CH_4. However, no studies have investigated potential CH_4 production and oxidation rates from restored cutover peatlands. The objective of this chapter is to determine in the laboratory under controlled conditions the potential rates of CH_4 production and oxidation in peat from natural, harvested and recently restored peatlands.

3.2 Methodology

Cores were removed from the recently restored, 20-year cutover and natural peats at the BDB peatland and from the 2-year cutover, 7-year cutover and natural peats at the LSJ peatland using a Wardenaar peat corer. All cores were wrapped in plastic and returned immediately to the McMaster Ecohydrology Laboratory where they were frozen until analyzed. Samples from the BDB peat were concentrated near the seasonal mean 2001 water table position. This resulted in 7 depths for the 20-year cutover (centered at 10, 25, 32.5, 37.5, 42.5, 47.5, 65 cm) and natural peats (centered at 5, 15, 22.5, 27.5, 35, 45, 65 cm) and 9 depths (centered at 5, 15, 22.5, 27.5, 32.5, 37.5, 45, 55, 70 cm) for the recently restored peat (due to the larger variance between maximum and minimum water table values). LSJ peat cores were subdivided into 5 cm sections at depths (centered at 2.5, 7.5, 12.5, 22.5, 32.5, 52.5, 77.5 cm) with the exception of the 30 cm section at the natural peat (Waddington et al. 2001).

The experiment was completed under aerobic and anaerobic conditions for the BDB peat and only under anaerobic conditions for the LSJ peat. For the aerobic experiment, approximately ~10 to 20 g wet weight of BDB peat was placed in 250 mL incubation jars and spiked with ~20 mL of a 53 ppmv CH_4 standard. For the anaerobic experiment, peat slurries of approximately ~15 g wet weight of BDB peat or ~35 g wet weight of LSJ peat were made in 250 mL incubation jars by the addition of distilled water. For the anaerobic experiment, the jars were then flushed with N_2 for 15 minutes to displace air and sealed. Aerobic and anaerobic samples were incubated at 4 and 20°C inside a dark Conviron growth chamber and were sampled initially, then every 12 hours over a 48 hour period. Anaerobic samples were mechanically agitated for 20 minutes prior to sampling to mix the gases within the peat pore spaces and the jar headspace. 3 mL gas samples were collected from the headspace with an equal amount of N_2 backfilled into the jar to ensure constant air volume/pressure.

Gas samples were analyzed using a Varian 3800 gas chromatograph equipped with a flame ionization detector (FID) and Porapak N column to analyze CH_4 concentration. A CH_4 standard gas was used for calibration and analyzed after every 6 to 12 samples.

The mean of three samples was used to calculate concentration values and were corrected for standard pressure and temperature by multiplying by the corrected headspace volume and adjusting for dilution. CH_4 production and oxidation were calculated by dividing the CH_4 flux by the final dry peat weight (g), determined by oven drying the sample at 55°C for 24 to 48 hours at the end of the experiment. Total CH_4 production and oxidation were determined by summing the areal estimates of CH_4 production/oxidation (determined by multiplying the depth-integrated mean CH_4 production/oxidation by the bulk density determined for each depth). The rate of change in CH_4 production and oxidation over a 10°C temperature range (Q_{10} values) were then calculated for 4 to 20°C. Statistical analyses were completed for depth integrated CH_4 production and oxidation and Q_{10} values using two sample student's t-test assuming equal variance with $\alpha = 0.05$.

3.3 Results

3.3.1 Potential CH_4 Production

The average BDB potential CH_4 production varied between 0.005 ± 0.004 and 0.048 ± 0.028 μg CH_4 g^{-1} dry peat d^{-1}, and between 0.026 ± 0.014 and 0.046 ± 0.060 μg CH_4 g^{-1} dry peat d^{-1} for LSJ peat. Generally, potential CH_4 production rates at all temperatures were greatest at the LSJ natural peat followed by the 2- and 7-yr cutover peat, the BDB natural peat, and then the recently restored and 20-yr cutover peat (Figure 3.1 and 3.2). However there are exceptions at 20°C, where the recently restored peat was higher than the 7- and 20-yr cutover peat.

Potential CH_4 production rates at the natural peat increased with depth at all temperatures until reaching a maximum, at 7.5 and 22.5 to 35 cm for LSJ and BDB respectively, then decreased with depth to reach a minimum in the deeper peat. The 2-yr cutover peat also showed the same pattern, however the depth of maximum production occurred at 32.5 cm. Conversely, both the 7- and 20-yr cutover peat experienced no significant depth dependent trend at 4°C. At 20°C, surface peaks occurred at 2.5 and 10 cm, for the 7- and 20-yr cutover peat, with secondary peaks at 52.5 and 37.5 cm respectively, followed by a decrease in potential CH_4 production rates with depth. The potential CH_4 production rate vs. depth pattern for the recently restored peat is similar to the natural peat, where potential CH_4 production increased with depth to maxima at 32.5

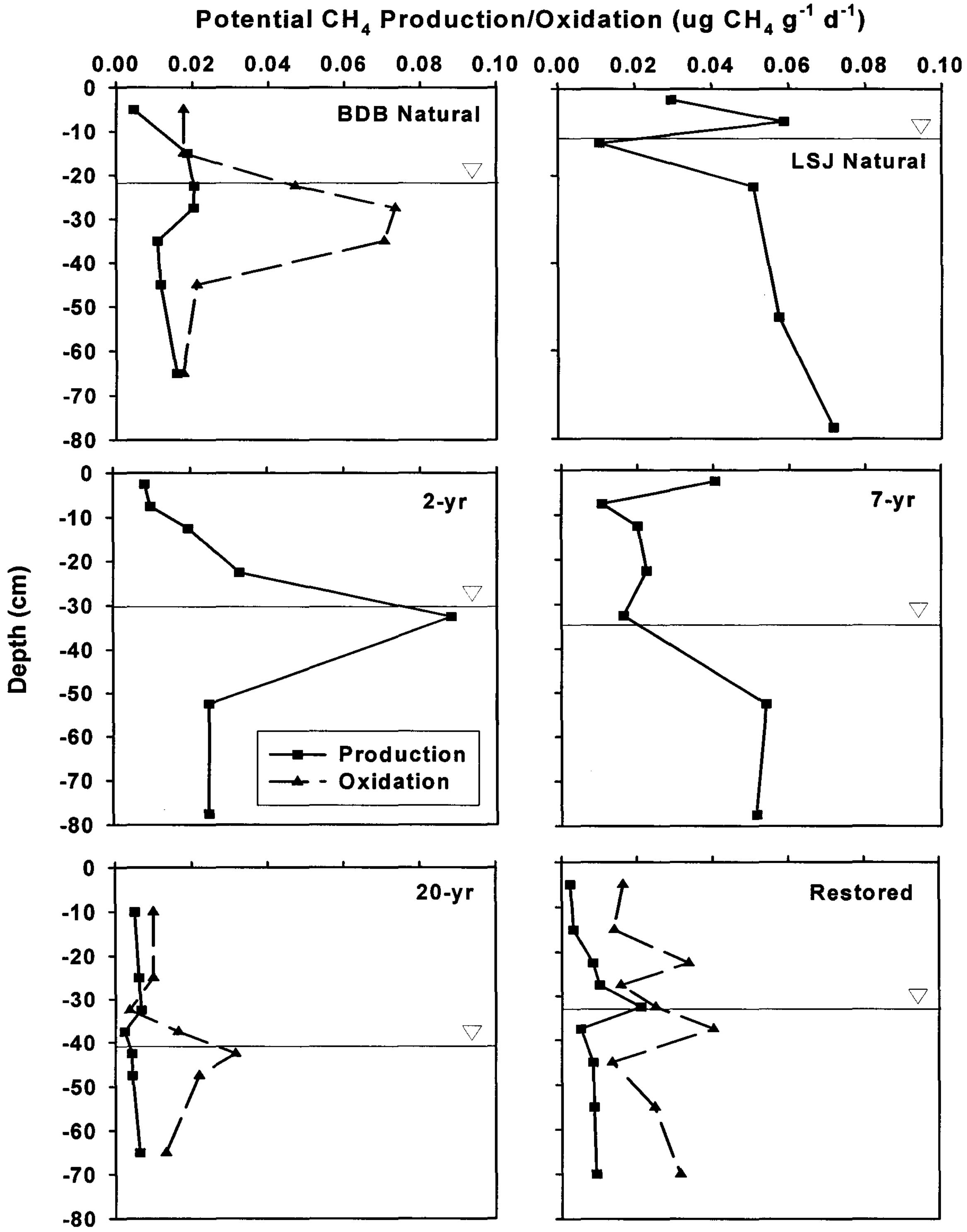


Figure 3.1 Potential CH_4 production and oxidation (ug CH_4 g^{-1} d^{-1}) at 4°C at the BDB and LSJ natural peat, 2-yr, 7-yr, 20-yr cutover peat and recently restored peat.

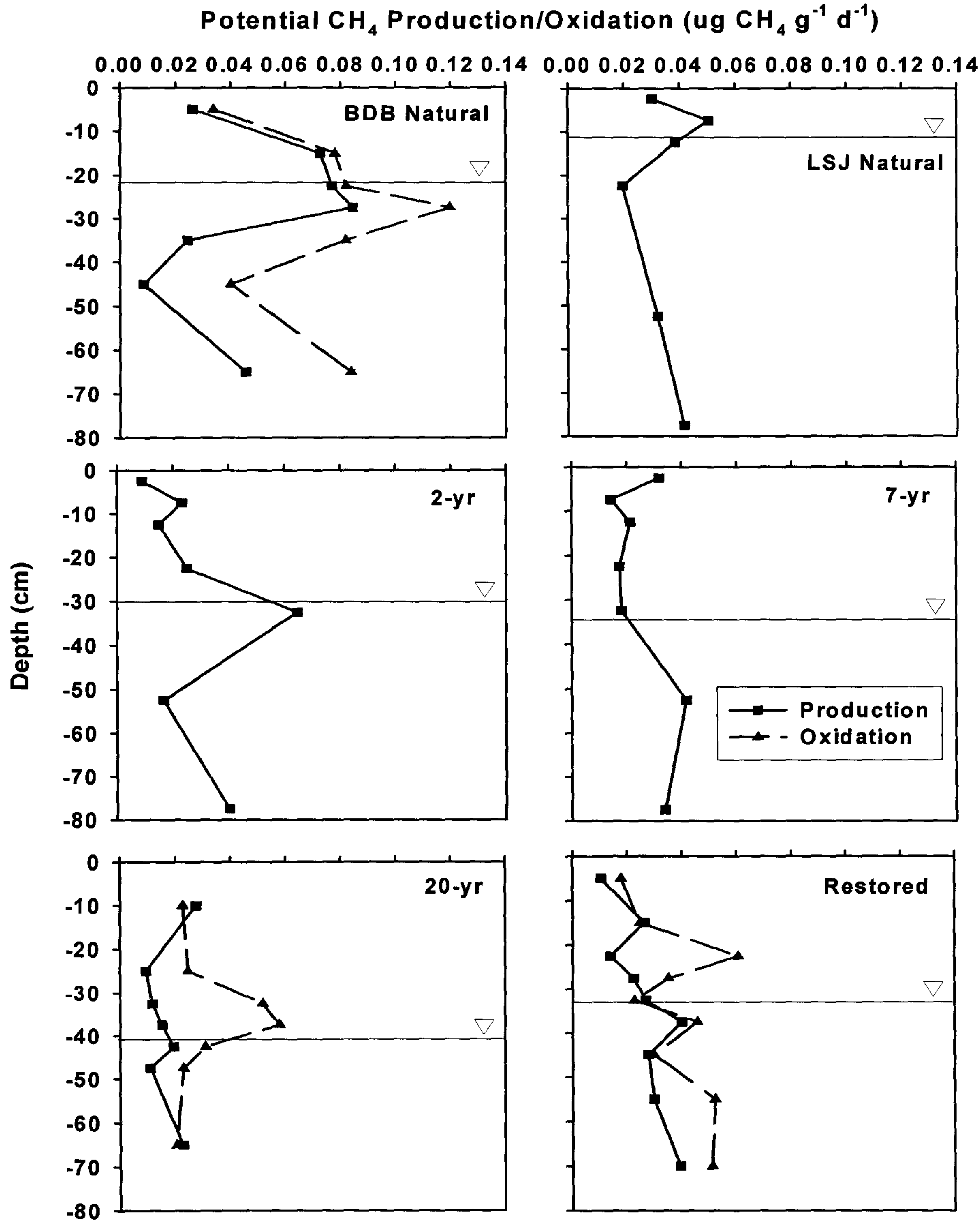


Figure 3.2 Potential CH_4 production and oxidation (ug CH_4 g^{-1} d^{-1}) at 20°C at the BDB and LSJ natural peat, 2-yr, 7-yr, 20-yr cutover peat and recently restored peat.

to 37.5 cm then decreased with depth to a minimum in the deeper peat. However at 20°C, the pattern is more similar to the 7- and 20-yr cutover peat at 20°C with the presence of two peaks in production located at 15 to 22.5 and 37.5cm. The highest potential CH_4 production rates were measured at 20°C for all peat with production increasing with temperature.

All peats experienced highest Q_{10} CH_4 production values at the surface followed by lowest values at 20-30 cm and then increased with depth (Table 3.1). The BDB natural, 20-yr and recently restored peat Q_{10} values (mean 2.01 to 2.36) were high compared to the LSJ natural, 2- and 7-yr peat (mean 0.44 to 0.70). Recently restored peat Q_{10} values were significantly higher ($p < 0.05$) than the 2- and 7-yr cutover peat at most depths (Table 3.1), but only significantly higher ($p < 0.05$) than the LSJ natural peat at the 0-20 and 40-80 cm depths. The BDB natural, 20-yr cutover and recently restored peat experienced greater temperature dependence than the LSJ natural, 2- and 7-yr cutover peat. Q_{10} production values followed the trend: restored > 20-yr > BDB natural > 7-yr > 2-yr > LSJ natural.

Total depth integrated CH_4 production for the upper 80 cm followed the general trend: 2-yr > LSJ natural > 7-yr > restored > BDB natural > 20-yr at 4°C, with 2-yr and LSJ natural peat values being significantly higher ($p < 0.05$) than recently restored peat values (Figure 3.3). At 20°C, the trend switches to 2-yr > restored > 20-yr > LSJ natural > 7-yr > BDB natural with only the LSJ natural and 7-yr cutover peat significantly different than the recently restored peat. The total depth integrated production at the LSJ natural peat was always significantly greater ($p < 0.05$) than the BDB natural peat except

Table 3.1 Q_{10} ratios for CH_4 production between 4 and 20°C for the BDB and LSJ natural peat, 2-yr, 7-yr and 20-yr cutover peat, and the recently restored peat.

Depth (cm)	BDB Natural	LSJ Natural	2-Yr Cutover	7-Yr Cutover	20-Yr Cutover	Recently Restored
0-20	2.6	0.8*	0.6*§†	0.6*§†	3.4	4.2
20-30	2.5	0.3§	0.5§	0.5§	1.0	1.2
30-40	1.4	0.3	0.5*	0.8*	1.88	1.5
40-80	1.5	0.4*	0.5*	0.8*	2.2	2.4
Mean	**2.0**	**0.4**	**0.5**	**0.7**	**2.1**	**2.4**

*Recently restored value significantly higher at α=0.05
†20-yr cutover value significantly higher at α=0.05
§BDB natural value significantly higher at α=0.05

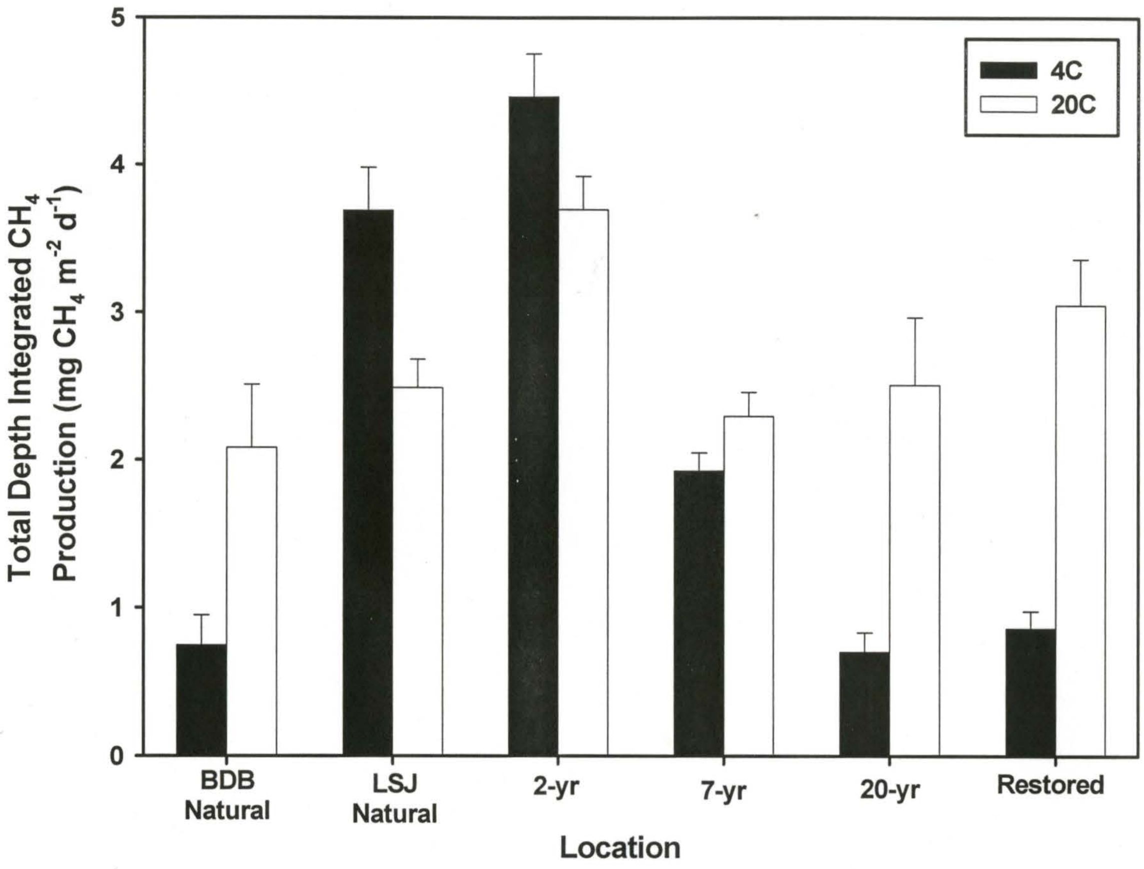


Figure 3.3 Total depth integrated CH_4 production rates over 80 cm at 4 and 20°C at the BDB and LSJ natural peat, 2-yr, 7-yr, 20-yr cutover peat and recently restored peat.

at 20°C, while the BDB natural peat, 20-yr cutover and recently restored peat were not significantly different at any temperature.

3.3.2 Potential CH_4 Oxidation

Average potential CH_4 oxidation varied between 0.015 ± 0.008 and 0.074 ± 0.034 $\mu g\ CH_4\ g^{-1}$ dry peat d^{-1} for all peats and depths. All peats exhibited the trend of an increasing potential CH_4 oxidation with depth to a maximum that varied between the peat, followed by a decrease in the deeper layers (Figure 3.1 and 3.2). The BDB natural peat potential CH_4 oxidation peaked at a depth of 27 cm and increased with an increase in temperature. The 20-yr cutover and recently restored peat peaks also increased with an increase in temperature. The maximum potential CH_4 oxidation at the 20-yr cutover peat occurred at 37 and 42 cm depth while the maximum peaks at the recently restored peat occurred at 22.5 and 37.5 cm. The recently restored peat also experienced secondary peaks in oxidation at 4 and 20°C, similar to the pattern with potential CH_4 production. The highest oxidation rates were measured at 20°C for the BDB natural peat with oxidation increasing with an increase in temperature.

Q_{10} values were also calculated for CH_4 oxidation (Table 3.2). Each peat experienced different trends where the BDB natural peat Q_{10} ratios decreased with depth until a maximum occurred at 40-80 cm. The 20-yr cutover peat experienced the opposite trend with Q_{10} ratios increasing with depth until a minimum at 40-80 cm. The recently restored peat did not exhibit any significant depth dependent trends. Overall, the 20-yr cutover peat experienced higher Q_{10} ratios (mean 1.7) and a greater temperature dependence than the other two peats. The BDB natural and recently restored peat were

Table 3.2 Q_{10} ratios for CH_4 oxidation between 4 and 20°C at the BDB natural peat, 20-yr cutover peat, and the recently restored peat.

Depth (cm)	BDB Natural	20-Yr Cutover	Recently Restored
0-20	2.0	1.4	0.9
20-30	1.1	1.6	1.2
30-40	0.7	3.0	0.7†
40-80	2.0	0.7§*	1.2
Mean	**1.4**	**1.7**	**1.0**

*Recently restored value significantly higher at $\alpha=0.05$
†20-yr cutover value significantly higher at $\alpha=0.05$
§BDB natural value significantly higher at $\alpha=0.05$

significantly higher than the 20-yr cutover peat at the 40-80 cm depth whereas the 20-yr cutover peat was significantly higher than the recently restored peat at the 30-40 cm depth.

Total depth integrated CH_4 oxidation also showed the trend of increasing with an increase in temperature for the BDB natural peat (Figure 3.4). The 20-yr cutover and recently restored peat also increased with temperature from 4 to 20°C. Generally, restored > 20-yr cutover > BDB natural peat, with the exception at 20°C where the BDB natural peat became larger than the 20-yr cutover peat. However, differences between peats were not significant ($p < 0.05$).

3.4 Discussion

3.4.1 Potential CH_4 Production

Potential CH_4 production rates for the natural peats were up to three orders of magnitude smaller than values reported for other undisturbed peatlands (range from 0 to 35 $\mu g\ CH_4\ g^{-1}\ d^{-1}$) (Moore & Knowles 1990, Roulet et al. 1993, Moore & Dalva 1993, Sundh et al. 1993, 1994, Valentine et al. 1994). However, values were similar to those reported by Whalen & Reeburgh (2000) for a temporarily saturated peat (mean < 0.048 $\mu g\ CH_4\ g^{-1}\ d^{-1}$) and a permanently saturated peat (maximum 0.139 $\mu g\ CH_4\ g^{-1}\ d^{-1}$) within a boreal bog.

The cutover and recently restored peat results coincided with those found for other harvested peat, specifically from old harvested peat (0.008 to 0.018 $\mu g\ CH_4\ g^{-1}\ d^{-1}$) and newly harvested peat (0 to 0.11 $\mu g\ CH_4\ g^{-1}\ d^{-1}$) (Sundh et al. 2000). Conversely,

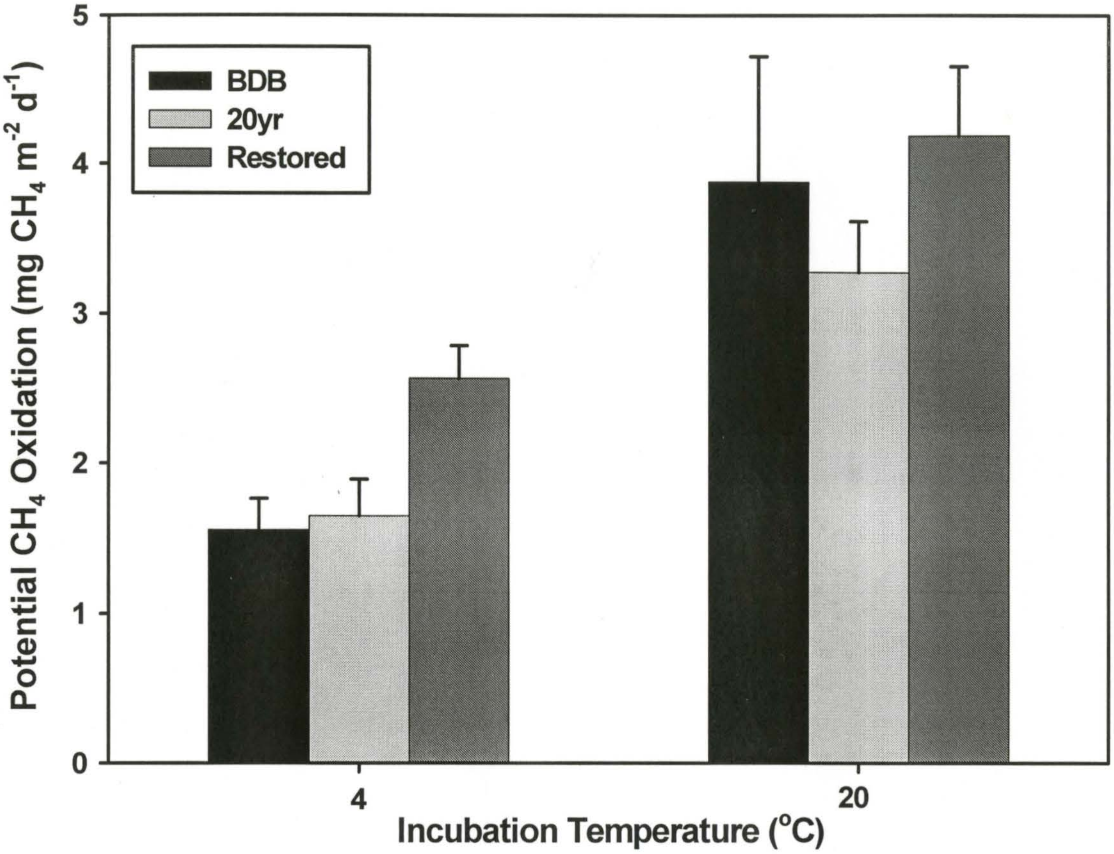


Figure 3.4 Total depth integrated potential CH_4 oxidation rates over 80 cm at 4 and 20°C at the BDB natural peat, 20-yr cutover peat and recently restored peat.

Roulet et al. (1993) found no production of CH_4, over a 45 cm depth, from a drained peat while Shannon et al. (1993) determined potential CH_4 values one to two orders of magnitude smaller than those determined in this study.

Production was not determined beneath ditches. However, Sundh et al. (2000) found potential CH_4 production ditch values of 0.1 to 1.2 and 0.2 to 0.9 $\mu g\ CH_4\ g^{-1}\ d^{-1}$ at a new and old harvested peat, respectively. Dissolved CH_4 concentrations (see Chapter 4) from both the recently restored and 20-yr cutover peat were significantly higher below the ditches compared to where the cores for the experiment were removed. This suggests that potential CH_4 production data could, in accordance with Sundh et al. (2000), be higher in peat beneath the ditches. The possibility of a higher potential CH_4 production for ditch peat was further substantiated by the significant presence of vascular plants within these ditches which were sources of readily available labile carbon for methanogens. Tóth (2002) found DOC consisted predominantly (31 to 78%) of hydrophilic carbon (highly labile carbon generally produced by fresh vegetation) within the ditches.

Some studies have found highest rates of potential CH_4 production in surface layers (0 to 25 cm) of peat compared to intermediate and deeper zones (Moore & Knowles 1990, Shannon et al. 1993, Valentine et al. 1994). Results from this study do not support this and are more similar to the CH_4 production/oxidation with depth patterns shown by Roulet et al. (1993), Sundh et al. (1993, 1994, 1995), Frenzel & Karofeld (2000), and Whalen & Reeburgh (2000). These studies determined that the highest rates of CH_4 production and oxidation were closely linked to the level of the average water table position (Roulet et al. 1993, Sundh et al. 1993, 1994, 1995, Whalen & Reeburgh 2000). Sites with low water table levels (i.e. harvested sites) have lower potential CH_4 production (as suggested by Figure 3.1 and 3.2) as higher oxidation of organic matter results in less substrate available for methanogens. Conversely, wet sites with high water table levels have limited aerobic degradation, therefore the quantity and quality of substrate matter is much higher (Sundh et al. 1994). Sundh et al. (1994) suggested that a permanent decrease in the water table position of 20 cm is sufficient to switch off most of the CH_4 production in the peat profile.

Sundh et al. (1993) found that only a small fraction of CH_4 production occurred above the water table while Sundh et al. (1994) found that maximum CH_4 production depth was positively correlated to the average water table position ($R^2 = 0.77$) and was generally 10 cm below the average water table position. Results from this study show that the maximum CH_4 production was found in peat just above and below the average water table position (Figure 3.1, 3.2) with the average depth of maximum CH_4 production at BDB (all peats) of 3.7 to 7.8 cm above the average water table position while LSJ (all peats) was 5.0 to 15.1 cm below the average water table position at 4 and 20°C respectively. Maximum CH_4 production occurring higher than the average water table position at BDB may be a result of the greater duration of peat oxidation occurring at the peat compared to LSJ. Oxidation would cause the pores to decrease significantly in size, enlarging the capillary fringe above the water table. Therefore, the depths of maximum CH_4 production could still be located within saturated peat despite being higher than the position of the average water table.

Potential CH_4 production generally decreased with depth and is attributed to the recalcitrant nature of deeper peat which have been anaerobically degraded over a long period of time, depleting the pool of labile carbon for methanogens (Sundh et al. 1993, 1994, Valentine et al. 1994, Sundh et al. 2000). As a result, the rate of degradation of this recalcitrant organic matter takes much longer, thereby reducing the amount of CH_4 that can be produced over a short time frame (Sundh et al. 1994). However, these layers can act as long term contributors to dissolved CH_4 and episodic CH_4 releases (Valentine et al. 1994).

Higher potential CH_4 production from the LSJ peat compared to the BDB peat may also be a function of the botanical community composition. Studies have shown that woody plant species have higher C:N and lignin:N ratios, reflecting the resistance of the organic matters to degradation (Svensson & Sundh 1993, Sundh et al. 1994, Valentine et al. 1994). As many of the species at the BDB site are trees/shrubs (e.g. *Picea mariiana*, *Larix larcinia*, *Ledum groenlandicum*, *Chamaedaphne calcyculata*, *Kalmia angustifolia*, *Vaccinium angustifolium*) the peat composition may be very recalcitrant to begin with despite the presence of *Sphagnum* species. Conversely, the LSJ site is dominated by bryophyte species such as *Sphagnum* spp., therefore the peat would likely have lower C:N and lignin:N ratios suggesting that the carbon is more available for methanogenesis. The difference in potential CH_4 production between BDB and LSJ peats can also be attributed to the degree of degradation that has occurred at the sites. Rotenberg (1999) found that CO_2 production for peat cores decreased with time post-harvesting (2-yr cutover peat 1.66 $\mu g\ CO_2\ m^{-2}\ d^{-1}$ and 7-yr cutover peat 1.28 $\mu g\ CO_2\ m^{-2}\ d^{-1}$) suggesting that substrate quality had decreased. Gruneir (2003) found that the 20-yr cutover peat produced even less CO_2 (0.94 μg CO_2 m^{-2} d^{-1}) while the recently restored peat had increased CO_2 production (1.22 μg CO_2 m^{-2} d^{-1}) indicating that peat substrate quality has increased post restoration.

3.3.2 Potential CH_4 Oxidation

Potential CH_4 oxidation rates for the BDB natural peat were up to four orders of magnitude smaller than values reported for other undisturbed peatlands (range from 0 to 112 μg CH_4 g^{-1} d^{-1}) (Moore & Dalva 1993, Shannon et al. 1993, Roulet et al. 1993, Sundh et al. 1993, 1994, 1995). However, values were similar to those reported by Whalen and Reeburgh (2000) of 0.220 to 0.233 μg CH_4 g^{-1} d^{-1} for a temporarily saturated peat and 0.498 to 0.650 μg CH_4 g^{-1} d^{-1} for permanently saturated peat within a boreal bog. The 20-yr cutover and recently restored peat results are still significantly lower than those determined for other harvested peats where Roulet et al. (1993) found oxidation ranging from 0 to 13 μg CH_4 g^{-1} d^{-1} while Shannon et al. (1993) found slightly lower values of 0 to 1 μg CH_4 g^{-1} d^{-1} from drained peat.

The highest rate of oxidation occurred close to the average water table position (as in Roulet et al. 1993, Sundh et al. 1993, 1994, 1995, Frenzel & Karofeld 2000, Whalen & Reeburgh 2000) where there is both a source of O_2 and CH_4. Sundh et al. (1994) discovered that aerated peats experienced low oxidation activity from 0 to 5 cm. Potential CH_4 oxidation for the 2-yr, 7-yr, 20-yr cutover and recently restored peat also showed low oxidative activity near the surface. As methanotrophs require CH_4, the highest biomass of methanotrophs is located near a supply of CH_4 (i.e. near the water table) (Sundh et al. 1994, Granberg et al. 1997), therefore the low activity in the surface layers could be representative of the low methanotrophic population. Sundh et al. (1995) established that drier peats have higher potential CH_4 oxidation contrary to the results here which found that the wettest peat (BDB natural) had the highest potential CH_4 oxidation while the driest peat (20-yr cutover) had the lowest potential CH_4 oxidation. This also can be attributed to the small supply of CH_4 from the 20-yr cutover peat limiting the methanotrophic population.

The recently restored peat experienced two peaks in CH_4 production and oxidation at generally 22.5 and 37.5 cm depths, contrary to the other peats which had only one maximum close to the average water table position. The CH_4 production/oxidation maximum at 37.5 cm coincides with the average water table position and was expected based on the results from other studies. However, the production peak that occurred at 22.5 cm was unexpected. Field observations noted a high *Eriophorum* root density from the surface to ~35 cm depth. Joabsson & Christensen (2001) also noted that potential CH_4 production peaked at the same depth as the maximum root density of 5 to 15 cm. Perhaps, the highest density of vascular vegetation roots occurred within the 22.5 cm area, acting as a source zone of labile carbon. However, this peak occurred in the aerobic zone based on the position of the average water table and methanogens have been found to be inhibited under oxic conditions (Whalen & Reeburgh 2000). Because of the highly variable nature of the water table at the restored peat, it is possible that the methanogens have developed a tolerance to brief oxic conditions (Segers 1998) and thereby a more bimodal distribution around this secondary zone of labile carbon. In addition, it may also be possible that this 22.5 cm depth may be saturated as Whitehead (1999) found that the capillary fringe could extend up to 30 cm above the water table in moderately decomposed peat. However, we have no data to confirm or deny this possibility. Therefore, the main peak in production and oxidation at 37.5 cm is a result of the bacterial biomass while the secondary peak at 22.5 cm is more likely a function of substrate quality.

As the position of the water table is one of the major controls on CH_4 production and oxidation, understanding the seasonal movement, and thus the probability of the water table occurring at each depth in the soil profile, would assist in predicting the amount of potential CH_4 production and oxidation occurring. Water table position probability of exceedence graphs were created for the BDB natural, 20-yr cutover and recently restored sites (Figure 3.5). Water table values remain shallower for a longer period of time at the BDB natural site followed by the recently restored and 20-yr cutover sites. The depth of the water table at which net CH_4 production below exceeds the net CH_4 oxidation above was calculated from the total depth integrated CH_4 production and oxidation profiles. These depths were at approximately 25 to 30 cm for the BDB natural site and 35 to 40 cm for both the 20-yr cutover and recently restored sites (indicated by the grey line in Figure 3.6). The amount of time that the water table is at or exceeds this depth in the BDB natural peat is ~90% while it is only ~37% and ~63% at the 20-yr cutover and recently restored sites, respectively. Consequently, potential CH_4 production is greater than potential CH_4 oxidation more often from the restored peat than the 20-yr cutover peat, suggesting CH_4 fluxes are increasing from the restored peat.

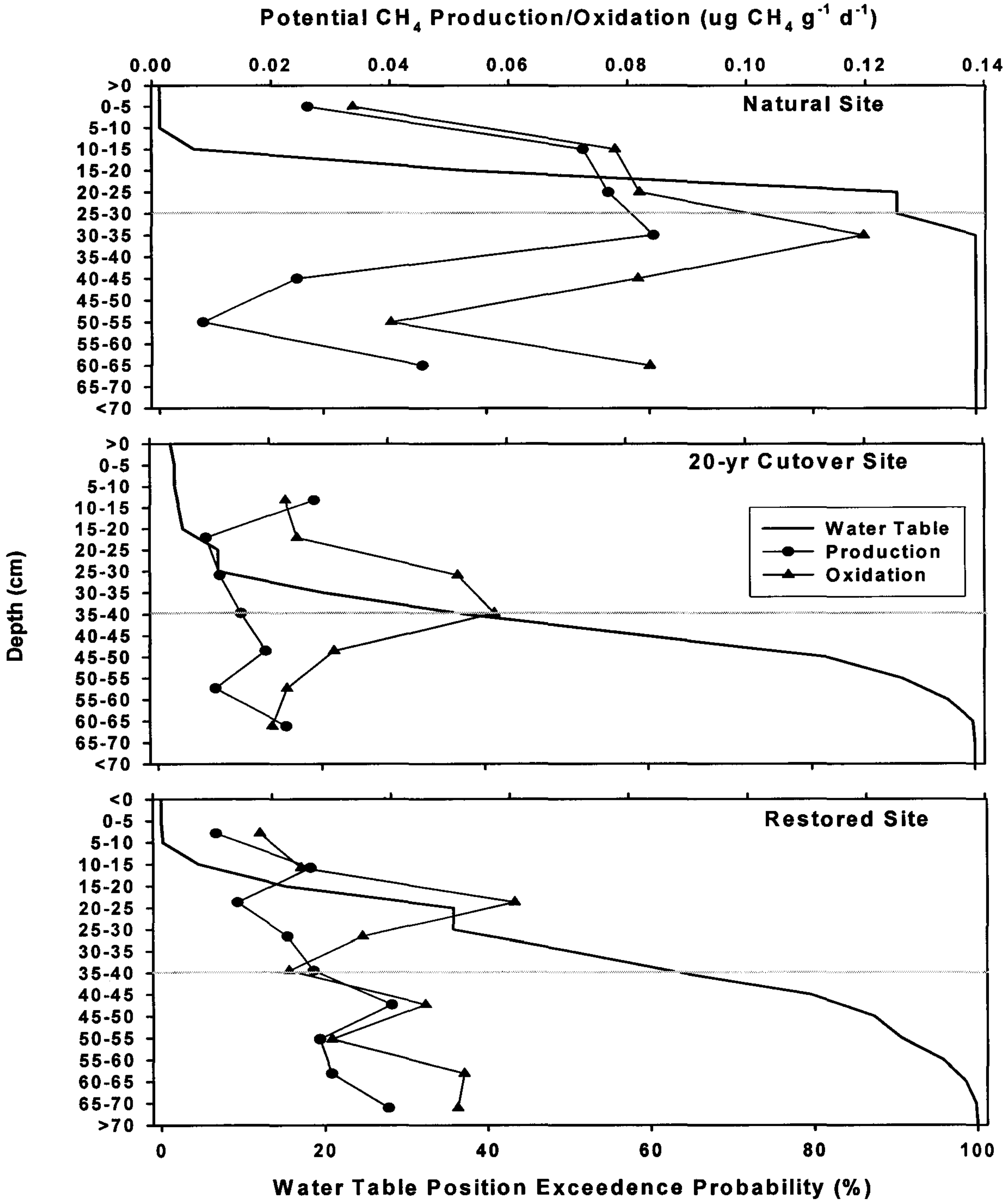


Figure 3.5 BDB potential CH_4 production and oxidation plotted with the water table position exceedence probability. Grey line indicates the depth at which the potential CH_4 production below the line is greater than the potential CH_4 oxidation above the line.

3.4.3 Q_{10} Values

Production Q_{10} values for BDB fall within the range of values found in the literature (1 to 28) (Dunfield et al. 1993, Moore & Dalva 1993, Dise et al. 1993, Valentine et al. 1994, Mikkela et al. 1995, Updegraff et al. 1995, Segers 1998, Daulat & Clymo 1998, Van Hulzen et al. 1999) however production Q_{10} values for LSJ are close to but slightly lower than literature values. A model proposed by van Hulzen et al. (1999) provides a possible reason for the difference in Q_{10} values between BDB and LSJ. Van Hulzen et al. (1999) suggest that there are three phases in which different factors control CH_4 production. During phase I, CH_4 production is suppressed by electron acceptors via competition for substrates; during phase II, CH_4 production gradually increases in time which is explained by growth of methanogenic biomass; while during phase III, CH_4 production is directly controlled by anaerobic carbon mineralization. The low sensitivity of LSJ peat to temperature effects could be a result of higher concentrations of alternative electron acceptors (i.e. NO_3^{-1}, Fe^{3+}, SO_4^{-2}). That is, unsaturated peats have higher amounts of alternative electron acceptors available than saturated peats, resulting in higher Q_{10} values (van Hulzen et al. 1999). As LSJ has been drained more recently than BDB, it is expected that more alternative electron acceptors would be available, suppressing the production of CH_4 and that an increase in temperature (increasing the mineralization rate and therefore rate of reduction of alternative electron acceptors) did not reduce all of the alternative electron acceptors available, delaying the shift from phase I/II to phase II/III. On the other hand, BDB production Q_{10} values were much higher suggesting that the reduction of the available alternative electron acceptors occurred much quicker (supported by the extremely low porewater concentrations of SO_4^{-2} determined from this peat, data not shown), resulting in a higher CH_4 production rate at higher temperature. In comparison with other studies, this experiment was run for a much shorter time scale and may also be responsible for the smaller Q_{10} values. For example, Dunfield et al. (1994), Updegraff et al. (1995) and van Hulzen et al. (1999) ran their experiments for 3 to 9 days, 98 days and 80 weeks, respectively, attaining much higher Q_{10} values (5.3 to 16, 2.9 to 3.6, 16 to 28, respectively) with CH_4 production likely controlled by anaerobic carbon mineralization.

Oxidation Q_{10} values fall within the limits determined by other studies of 1.2 to 2.1(Dunfield et al 1993, Moore & Dalva 1993). Oxidation Q_{10} values are significantly lower (less temperature sensitive) than production Q_{10} values as methanotrophs are less temperature dependent than methanogens (Moore & Dalva 1993, Dunfield et al. 1993, Bubier & Moore 1994, Valentine et al. 1994, Updegraff et al. 1995, Van Hulzen et al. 1999). This is a result of methanogens relying on the rate of carbon mineralization which is controlled by temperature, while methanotrophs rely on the rate of CH_4 supply.

3.4.4 Total Depth Integrated CH_4 Production and Oxidation

The high total depth integrated CH_4 production values for LSJ peat can be attributed to: 1) the higher substrate quality resulting in higher potential CH_4 production compared to BDB peat, 2) higher water table levels at the natural, 2-yr and 7-yr cutover sites compared to the BDB natural, and 20-yr cutover sites, and 3) both the larger supply of labile carbon and higher water table levels producing a larger methanogenic biomass.

Both the recently restored and 20-yr cutover peats have higher total depth integrated CH_4 production values than the BDB natural peat. This was unexpected as the natural peat has a much larger supply of labile carbon and higher potential CH_4 production. Bulk densities determined for the peats were used to calculate the total depth integrated CH_4 production. The greater amount of peat per m^2 over 80 cm and low potential CH_4 production resulted in more total CH_4 than the high potential CH_4 production and smaller amount of peat over 80 cm found for the BDB natural peat. Significant increases, from 4 to 20°C, in the restored and 20-yr cutover peat total depth integrated CH_4 production can be attributed to the significantly higher depth integrated CH_4 production experienced by these two peats. As discussed above, it is suggested that the higher temperature reduced more or all of the alternative electron acceptors thereby producing more CH_4. Generally, depth integrated CH_4 production decreased with time post-harvest, as would be expected, with oxidation and anaerobic respiration depleting the pools of labile carbon and reducing the methanogenic population. Furthermore, it appears that restoration has increased CH_4 production as a result of the higher water table levels and supply of labile carbon.

Unexpectedly, the recently restored peat experienced the greatest total depth integrated CH_4 oxidation compared to the 20-yr cutover and BDB natural peats. It was expected that a higher water table level would result in a smaller oxic zone and thus a smaller methanotrophic population. Whalen & Reebugh (2000) found that methanotrophs were not as sensitive to adverse O_2 conditions, compared to methanogens, therefore it is possible that the highly fluctuating water table at the recently restored peat may not significantly affect the activity of the methanotrophs. Moreover, the recently restored peat was a larger source of CH_4, therefore a larger biomass of methanotrophs would be able to develop. Conversely, the low production of CH_4 from the 20-yr cutover peat, could limit the growth of methanotrophs despite the highly oxic conditions, thereby reducing the potential of the peat to oxidize CH_4. The BDB natural peat had essentially the same total depth integrated CH_4 oxidation as the 20-yr cutover peat at 4°C however it was greater than the 20-yr cutover peat at 20°C. Again, the larger source of CH_4 available from the BDB natural peat compared to the 20-yr cutover peat could result in the larger biomass of methanotrophs, accounting for its larger depth integrated CH_4 oxidation.

3.5 Restoration Implications

Potential CH_4 production and oxidation values were similar to values reported for other harvested peats however the natural peats were significantly smaller. The trends in potential CH_4 oxidation and production for each peat were dependent on the water table position. That is, the water table position controlled the distribution of the methanogens (just below the average water table) and methanotrophs (just above the average water table) and peaks in CH_4 production and oxidation followed the same trends respectively. The increase in vegetative cover and fluctuating water table has lead to unique CH_4 production and oxidation profiles for the restored peat with two peaks in production due to biomass and a zone of labile carbon and two peaks in oxidation which coincide with the peaks in CH_4 production. Substrate quality was the main difference in production values between the LSJ and BDB peats as the LSJ peat was composed of more cellulose based vegetation while BDB peat was dominated by woody plant species.

Total depth integrated CH_4 production decreased with time post harvest where CH_4 production at 2-yr > 7-yr > 20-yr cutover peat. This decrease in CH_4 production was a result of a decreased source of labile carbon, a decrease in the methanogenic population, and an increase in the concentration of alternative electron acceptors. Restoration of a portion of the 20-yr cutover peat has altered CH_4 production processes, moving this recently restored peat in the opposite direction so that the CH_4 production was 2-yr > 7-yr > RESTORED > 20-yr cutover peat. Three years post-restoration has only returned the recently restored peat to a condition in which CH_4 production is greater than the 20-yr but less than the 7-yr cutover peat. Therefore, it can be expected that the sooner restoration occurs after harvesting, the sooner the CH_4 processes of the carbon cycle will return to that of a natural system.

Restoration has increased the average water table position as well as the substrate quality with the growth of both bryophyte and vascular vegetation. This has resulted in higher potential CH_4 production and the amount of time in which total CH_4 production is greater than total CH_4 oxidation. However, it is expected that CH_4 production will be even higher at "hot spot" areas (saturated and vegetated) such as the ditches and ponds and that initially CH_4 production will be the dominant process in CH_4 emissions but the continually changing conditions of the peat will alter the CH_4 processes controlling CH_4 emissions. In conclusion, this study has found that restoration has increased CH_4

production but to what extent, i.e. of lower, equal or greater magnitude than natural peatlands, is still uncertain.

CHAPTER 4

CHANGES IN CH_4 STORAGE AND FLUX FROM A RESTORED PEATLAND

4.1 Introduction

Peatlands, covering 3% of the earth's surface (Clymo 1984) with approximately 110-130 million hectares in Canada (Zoltai 1988), are carbon sinks under natural conditions storing approximately 455 Pg carbon (C) but are converted to significant sources of CO_2 through the processes of drainage and harvesting (Nykänen et al. 1995, 1997, Minkkinen et al. 1997, Minkkinen & Laine 1998, Waddington & Warner 2000, Sundh et al. 2000, Waddington et al. 2002). With the implementation of the Kyoto Protocol, more peat industry companies are interested in and attempting to develop methods to reduce their carbon emissions. The expanding knowledge on peatland restoration practices has encouraged the peat horticultural industry, in particular, to restore long abandoned sites which are significant sources of CO_2 and sinks of CH_4 (Roulet et al. 1993, Roulet & Moore 1995, Minkkinen et al. 1997, Komulainen et al. 1998, Minkkinen & Laine 1998, Alm et al. 1999, Sundh et al. 2000, Freeman et al. 2002).

The process of restoration involves blocking drainage ditches in order to raise the position of the water table, increasing saturated conditions. CO_2 emissions decrease post-restoration as an increased water table level limits the depth of the zone of aerobic decomposition (Tuittila et al. 1999, Komulainen et al. 1999, Waddington & Warner 2001). Conversely, CH_4 flux increases post-restoration as a higher water table limits the amount of CH_4 that is oxidized (Komulainen et al. 1998, Tuittila et al. 2000b).

Komulainen et al. (1998) found that emissions increased five fold (2.2 to 12.6 mg CH_4 m^{-2} d^{-1}) after rewetting but remained below levels typical of natural wetlands (e.g. Waddington & Roulet 1996). The lower than natural site CH_4 flux may be due to the incomplete vegetation succession, as vegetation can have a significant impact on carbon dynamics. While CO_2 stored within the new vegetative cover through photosynthesis offsets ecosystem respiration (Tuittila et al. 1999, Komulainen et al. 1999), an increase in vascular vegetation has the opposite effect on CH_4. Both Komulainen et al. (1998) and Tuittila et al. (2000b) found an increase in the coverage of the vascular plant species *Eriophorum* (from 1% to 20-70%) at rewetted sites and that these *Eriophorum* sites had higher CH_4 fluxes compared to rewetted sites without vegetation. Vascular vegetation can enhance CH_4 emissions through the transport and supply of labile carbon (Waddington et al. 1996). Seasonal CH_4 flux was higher after rewetting, however values were lower than emissions from natural peatlands (Tuittila et al. 2000b). These lower values, therefore are likely attributed to the reduction of the methanogenic population due to many years of persistent aerobic conditions prior to restoration (Segers 1998, Whalen & Reeburgh 2000, Chapter 3).

Because CH_4 is 21 times stronger as a greenhouse gas than is CO_2 (IPCC, 1996), the increase in emissions from restored peatlands may be of concern for addressing the overall change in global warming potential. Since the long term effects of restoration have yet to be studied, it is expected that the system will become a source of CH_4 to the atmosphere of the same magnitude as natural systems, less than 10 g CH_4 m^{-2} yr^{-1} (Minkkinen et al. 1997). However, the rate at which this occurs and the processes that control the storage and flux of CH_4 post peatland restoration remains unknown. Moreover, no studies have examined the processes controlling the flux of CH_4 (diffusion and ebullition) from open water features (e.g. ditches and pools) of restored peatlands. Therefore, the objectives of this research are to (1) determine the impact of restoration on CH_4 fluxes in the first three years post-restoration, (2) determine the processes controlling changes in CH_4 flux and subsurface storage, and (3) determine the importance of ditches, pools and ebullition to the overall flux of CH_4 from cutover and recently restored peatlands.

4.2 Methodology

Data were collected from May to mid October 1999, 2000, 2001, and 2002 from the restored and cutover sites at the Bois-des-Bel peatland. The study years represented a pre-restoration year (1999), and the first three years post-restoration (2000, 2001 and 2002). The 2002 field season was used to undertake experiments designed to examine the processes controlling CO_2 and CH_4 flux. Mean values were calculated from May 1 to August 31 each year to facilitate inter-year comparison.

4.2.1 Environmental Variables

Precipitation, temperature, evapotranspiration, water table position, soil moisture and photosynthetically active radiation (PAR) were measured continuously at two meteorological towers located within the restored and cutover sites (see Figure 2.1). Precipitation was measured every half-hour using a tipping bucket rain gauge connected to a CR 21x datalogger, as well as from two manual rain gauges. The ground thermal regime was measured continuously using thermocouple arrays at 0, 2, 5, 10, 25, 50 and

75 cm depths. Manual measurements of air temperature and peat temperatures (2, 5, and 10 cm) were also made with a portable thermocouple thermometer probe (±0.3°C) during CO_2 production and CH_4 flux sampling. CO_2 and evapotranspiration fluxes were measured continuously with a CSAT-3 3-D sonic anemometer and a LI-7500 open path infrared gas analyzer using the eddy covariance technique. Details of the equipment and analysis approach are outlined in Petrone et al. (2001). Water table levels were monitored hourly using Remote Data System (RDS) wells in addition to manual measurements. Five additional RDS wells were located throughout the peatland during the 2001 and 2002 field seasons. Water level of ponds and ditches were also monitored manually during CH_4 flux sampling. Soil moisture was determined at all collar sites using multiple level Campbell Scientific TDR's with tensiometer measurements taken throughout the peatland. The TDR was calibrated using peat cores from the site and their volumetric moisture contents used to refine the calibration equation. Photosynthetically active radiation (PAR) was measured continuously using a LI-COR quantum light sensor and manually with a PP Systems PAR sensor during CO_2 production measurements.

4.2.2 Gross Ecosystem Production

Net ecosystem CO_2 exchange (NEE) was measured several times a week at multiple sites representing moss (*Sphagnum* and *Polytricum* species) and vascular (*Eriophorum*) vegetation within the restored and cutover sites. A clear chamber connected to a PP Systems EGM-1 or EGM-2 infrared gas analyzer (IRGA) was used to measure CO_2 concentrations at one minute intervals. A series of shrouds were placed over the clear chamber to measure NEE under low light conditions. Total respiration

(R_{tot}) was measured using the same process but with an opaque chamber in place of the clear chamber. Fans inside the chambers ensured the air was well mixed for sampling. In addition, a cooling device was attached to the clear chamber circulating cold water, maintaining constant relative humidity and temperature inside the chamber. Gross ecosystem production (GEP) was determined as the difference between NEE and R_{tot}. GEP was modelled using the following relationship:

$$A = \frac{\O Q + A_{max} - ((\O Q + Amax)^2 - 4\O Q k A_{max})^{1/2}}{2k} \tag{2}$$

where A is the leaf net photosynthesis (μmol CO_2 m^{-2} s^{-1}), Q is photosynthetically active radiation (μmol m^{-2} s^{-1}), Ø is apparent quantum efficiency (AQE), A_{max} is the light saturated maximum, and k is convexity. Ø, k, and A_{max} parameters were determined from field collected GEP and PAR data using the software, Photosyn Assistant Ver 1.1.2 (Dundee Scientific). Continuously modelled GEP was calculated using the following equation:

$$A = \frac{T_w}{T_m} \times \frac{\O Q + A_{max} - ((\O Q + Amax)^2 - 4\O Q k A_{max})^{1/2}}{2k} \tag{3}$$

where T_w is the 7 day weighted air temperature and T_m is the mean air temperature and were applied to the half hourly PAR and temperature data recorded at the restored and cutover meteorological towers. Carbon uptake (NEE and GEP) was indicated by a positive value and R_{tot} as a negative value.

4.2.3 CH_4 Flux

CH_4 was measured biweekly from 1999-2001 at multiple sites representing ponds, ditches, vegetation, and bare peat located throughout the restored and cutover sites. An opaque climate controlled chamber was placed over a PVC collar set into the peat. Fans inside the chambers ensured the air was well mixed for sampling. CH_4 samples were taken at 10, 20 and 30 min intervals using syringes and were sent to the McMaster Ecohydrology Laboratory for analysis.

In the summer of 2002, CH_4 flux was partitioned into diffusive, plant mediated and ebullition components. Diffusive flux was measured as in 1999-2001 but on a weekly basis to better determine temporal variability. Plant mediated CH_4 flux was monitored by adding moss (*Sphagnum* and *Polytricum* species) and vascular (*Eriophorum*) vegetation sites and linking CH_4 flux to plant production. Ebullition was monitored over pools and ditches using a floating funnel chamber. The floating chambers were sampled and total gas volume recorded weekly. Negative flux values indicate a removal of CH_4 from the atmosphere (sink) while positive flux values indicate a source of CH_4 to the atmosphere. All collars were referenced to a common datum on July 10, 2002 using standard surveying techniques.

4.2.4 CH_4 Storage

Soil gases were sampled biweekly (2000-2002) at the restored and cutover sites with tygon tubing located at 2, 5, 10, 20, 30, 50 and 75 cm depths. An additional site located beneath vascular vegetation was added in 2002. Samples were extracted slowly using syringes which were sent back to the McMaster Ecohydrology Laboratory for analysis.

Piezometer transects installed in both the restored and cutover sites were sampled biweekly in the 2002 field season for porewater concentrations of CO_2 and CH_4. The restored and cutover transects contained four and five piezometer nests, respectively located in the west to east direction perpendicular to the ditch in zone 3 and field ten respectively (Figure 2.1). Piezometers, constructed of PVC pipes (2.5 cm ID), had a 10 cm slotted intake covered with nylon mesh. Piezometers were installed at average intake depths of 50, 75, 90, 100, 110 and 150 cm in the restored site and 50, 75, 100, 125, and 150 cm for the cutover site. Two peizometer nests were also located within the restored site under moss and vascular vegetation at average intake depths of 50, 70, 100, 125, and 150 cm. Piezometers were pumped 24 hr before sampling and porewater samples were taken using a modified syringe-tubing apparatus. In the lab, equal amounts of N_2 gas were drawn into the porewater syringes and degassing of the sample occurred by shaking of the sample vigorously for 5 min. CO_2 and CH_4 concentrations in the headspace were sampled and then analyzed. Wells and piezometers were referenced to a common datum on July 10, 2002 using standard surveying techniques.

4.2.5 CH_4 Analysis

All CH_4 samples were analyzed within 48 hours of sampling on a Varian 3800 Gas Chromatograph equipped with a Porapak N column, flame ionization detector (CH_4) and thermal conductivity detector (CO_2). A CO_2/CH_4 standard was used for calibration and a burnoff was executed periodically to ensure moisture was not accumulating within the GC. Statistical analyses were performed using ANOVA within years and student's t-test assuming equal variance between years with a significance level of $\alpha = 0.05$.

4.3 Results

4.3.1 Environmental Variables

Total precipitation (May 1 to August 31) was highest in 1999 followed by 2001, 2000 and 2002 (Figure 4.1 and Table 4.1). 1999 experienced few precipitation events during May and August while June, July and September were the only months over the four field seasons in which the total monthly precipitation exceeded the 30-year mean. 2000, 2001 and 2002 experienced low precipitation at the beginning of the field season while mid-season months experienced higher precipitation. August 2002 experienced drought like conditions, receiving only 27% of the normal amount of precipitation for that month.

Water table levels at the restored site ranged between 10 and 69 cm below the surface over the four study periods with the average water table position highest in 2001 (-30.4 cm), followed by 2000 (-31.5 cm), 2002 (-35.9 cm) and 1999 (-54.8 cm) (Figure 4.1). Minimum water table depths occurred at the beginning of each field season while maximum water table depths occurred in late July for 1999 and 2000, early August in 2001 and late August in 2002. In addition, the restored site experienced larger fluctuations in water table positions after rainfall events. The cutover site experienced water table levels ranging from 26 to 67 cm below the surface with the mean water table position highest in 2001 (-39.5 cm), followed by 2002 (-43.8 cm), 2000 (-46.0 cm) and 1999 (-51.4 cm) (Figure 4.1). As with the restored site, minimum water table levels

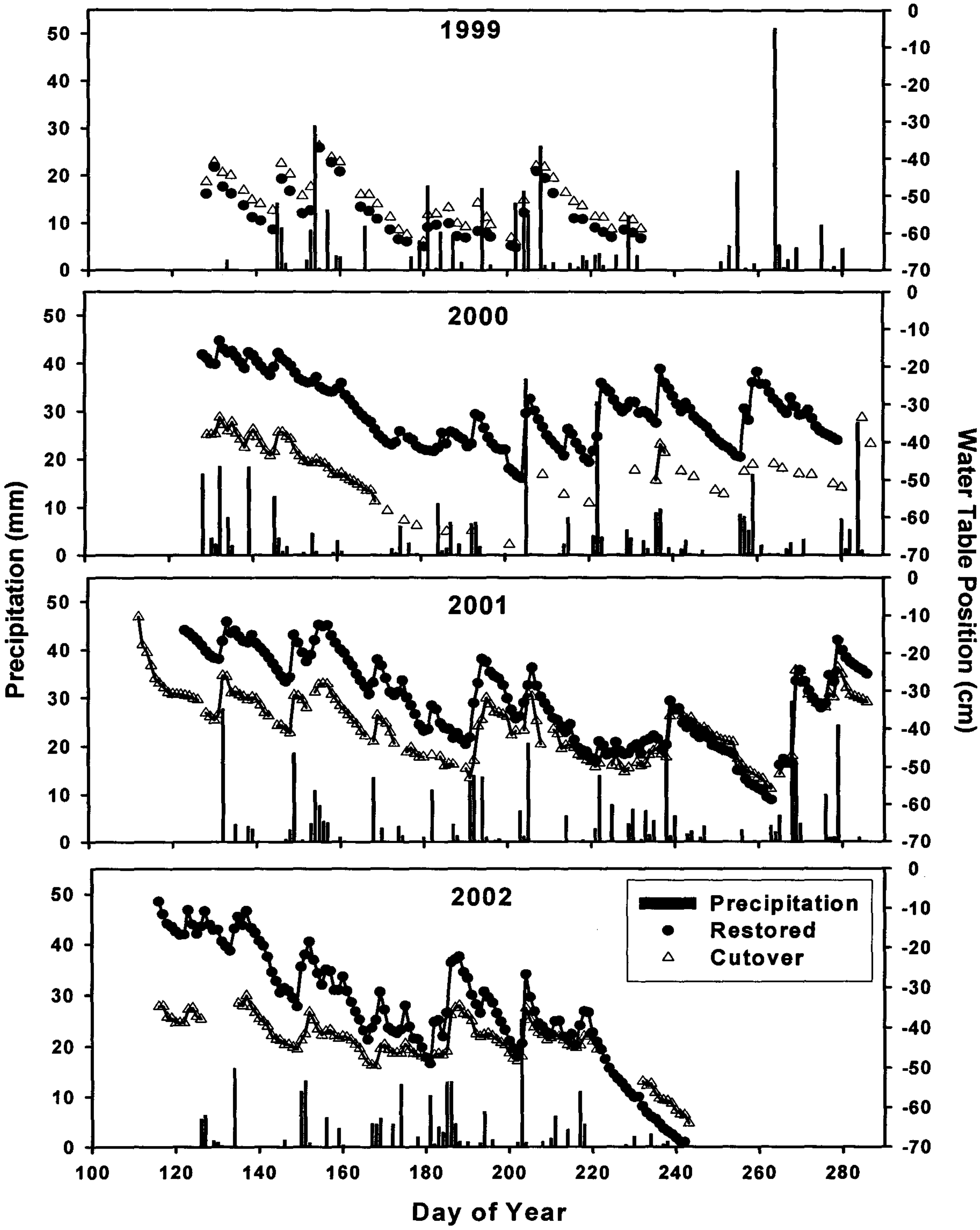


Figure 4.1 Daily precipitation (mm) and water table position (cm) at the restored and cutover sites over the four field seasons.

Table 4.1 Precipitation as a % of the 30-year mean for each month of the field season and for the total seasonal precipitation (May 1 to August 31).

Month	**1999**	**2000**	**2001**	**2002**
May	NA	100	68	63
June	110	23	62	63
July	116	82	95	94
August	33	91	86	27
September	104	55	78	NA
Total	79	71	78	61

occurred at the beginning of each field season and maximum depths occurred in late June for 1999, late July in 2000, late September in 2001 and late August in 2002. Water table levels at both sites closely followed the seasonal trend seen in precipitation over the four field seasons.

Air temperature was within 1°C of the 30-year summer mean for all years except 1999 which was 1.3°C warmer. May, June and September 1999, September 2000, May, August, and September 2001 and August 2002 were on average 2.7, 1.2 1.6 and 1.6°C warmer, respectively than the 30-year monthly mean. June 2002 was an exception with a 1.3°C cooler temperature than the 30-year monthly mean (Environment Canada 1993).

Average 10 cm soil temperature was highest in 1999 at 17.7°C compared to the three years post-restoration. Temperatures at the restored and cutover sites were similar in 2000 (13.4 and 13.6°C, respectively) and in 2001 (14.7 and 14.1°C, respectively). However in 2002, the restored site had ~3°C higher soil temperature compared to the cutover site. Maximum 10 cm soil temperatures ranged from 23.5 to 29.1°C and peaked in late July in 1999 and 2001 and in early August in 2000 and 2002.

4.3.2 Diffusive CH_4 Emissions

CH_4 flux from bare peat was fairly uniform during 1999 with both the pre-restored and cutover sites acting as small CH_4 sinks throughout the entire field season (Figure 4.2). Mean daily CH_4 fluxes from the pre-restored and cutover sites (Table 4.2) were not significantly different ($p < 0.05$), respectively.

Bare peat CH_4 flux in 2000 was more variable than 1999, acting as both a source and sink of CH_4 (Figure 4.2), however the average flux remained small for both the

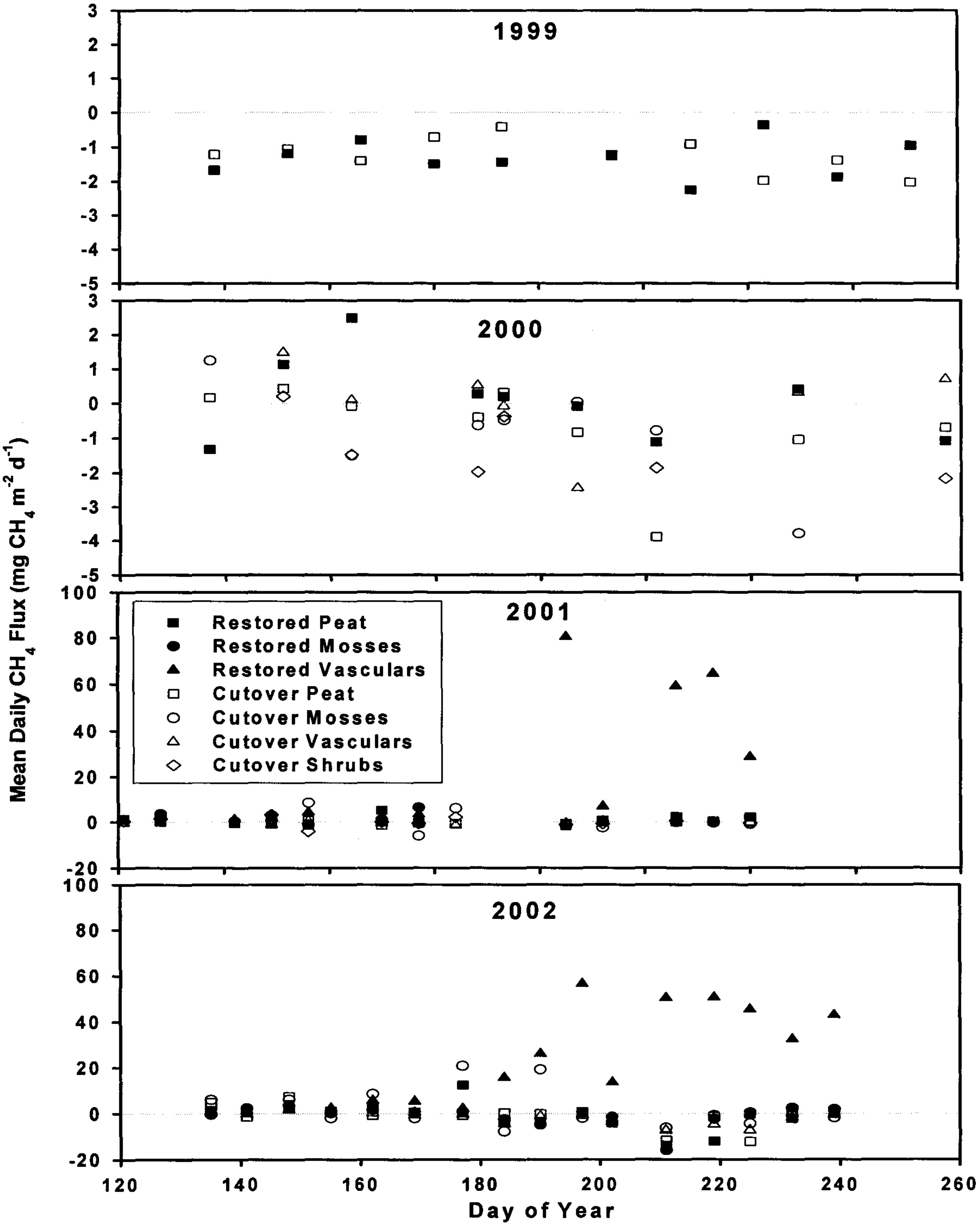


Figure 4.2 Mean daily CH_4 flux (mg CH_4 m^{-2} d^{-1}) of bare peat, mosses, vasculars and shrubs at the restored and cutover sites over the four field seasons. *Note the change in scale from 1999 and 2000 to 2001 and 2002.

Table 4.2 Seasonal CH_4 fluxes from bare peat, mosses, shrubs, vascular vegetation, ditches, and ponds from the restored and cutover sites for the four field seasons.

		Restored				**Cutover**			
Year	**Type**	**n**	**Minimum**	**Maximum**	**Mean (± SD)**	**n**	**Minimum**	**Maximum**	**Mean (± SD)**
1999	**Peat**	64	-16.4	17.5	-1.3 (± 4.9)	66	-16.2	15.3	-1.4 (3.8)
	Moss	NA	NA	NA	NA	NA	NA	NA	NA
	Shrub	NA	NA	NA	NA	NA	NA	NA	NA
	Vascular	NA	NA	NA	NA	NA	NA	NA	NA
	Ditch	12	-6.2	149.5	37.0 (49.0)	11	-2.6	49.6	10.4 (16.4)
	Pond	NA	NA	NA	NA	NA	NA	NA	NA
2000	**Peat**	50	-6.6	8.0	0.1 (2.6)	26	-10.9	1.0	-0.7 (2.3)
	Moss	NA	NA	NA	NA	7	-3.8	1.2	-0.8 (1.6)
	Shrub	NA	NA	NA	NA	6	-2.2	0.2	1.0 (-1.3)
	Vascular	NA	NA	NA	NA	7	-2.4	1.5	0.1 (1.2)
	Ditch	19	-1.3	132.5	11.2 (30.2)	17	-2.3	1285.1	154.9 (358.4)
	Pond	23	-2.6	2.4	-0.1 (1.4)	NA	NA	NA	NA
2001	**Peat**	48	-5.4	10.7	0.7 (2.9)	31	-3.3	4.2	0.1 (1.7)
	Moss	32	-5.1	10.9	1.4 (3.5)	10	-6.0	8.4	0.4 (4.1)
	Shrub	NA	NA	NA	NA	11	-4.1	3.3	0.1 (1.9)
	Vascular	11	0.5	80.4	22.8 (30.4)	10	-1.3	2.0	-0.1 (0.9)
	Ditch	51	-14.1	248.4	23.7 (50.7)	22	-3.0	278.0	52.5 (79.6)
	Pond	95	-8.6	904.1	55.3 (165.9)	NA	NA	NA	NA
2002	**Peat**	43	-17.1	49.7	-0.3 (9.1)	29	-15.4	13.3	-0.8 (5.1)
	Moss	98	-17.3	7.6	-0.3 (4.0)	42	-14.5	64.6	2.5 (15.1)
	Shrub	NA	NA	NA	NA	NA	NA	NA	NA
	Vascular	75	-7.0	122.2	23.4 (28.9)	46	-11.0	2.1	-1.6 (3.4)
	Ditch	65	-14.0	7664.5	473.8 (1101.8)	27	-13.6	1595.3	164.7 (422.2)
	Pond	49	-3.8	2447.1	279.8 (607.2)	NA	NA	NA	NA

restored and cutover sites (Table 4.2). CH_4 flux was high (source) during the beginning of the season and then decreased (became a sink) during the last half of the study period. Restored and cutover bare peat fluxes were not significantly different ($p > 0.05$) in 2000 but the 2000 restored site fluxes were significantly larger than 1999 fluxes ($p < 0.05$). Vascular, moss and shrub vegetation were also monitored for CH_4 emissions at the cutover site but were absent from the restored site as a result of the restoration process. Vascular, moss and shrub fluxes (Table 4.2) were not significantly different ($p > 0.05$) from bare peat values but vascular fluxes were significantly higher ($p > 0.05$) than shrub CH_4 fluxes.

In contrast to the 2000 season data, CH_4 fluxes during 2001 and 2002 became very large and highly variable from the restored site whereas the cutover site was only moderately variable with higher fluxes during 2002 (Figure 4.2). In 2001, bare peat and mosses for the restored and cutover sites were not significantly different (Table 4.2). However, only fluxes from bare peat were significantly higher than 1999 ($p < 0.05$) and 2000 values ($p < 0.05$). Fluxes remained low throughout the entire field season at the cutover site while at the restored site they remained low only during the beginning of the field season with high water table conditions. Fluxes from restored site mosses became larger and more variable during the last half of the field season, and as a result, the year was separated into wet (high average water table position from Julian day 121 to 200) and dry (low average water table position from Julian day 200 to 243) conditions and average fluxes were calculated. Bare peat showed no significant difference in mean CH_4 flux between wet and dry conditions whereas mosses had a higher flux under wet conditions (2.3 ± 2.6 mg CH_4 m^{-2} d^{-1}) compared to dry conditions (0.3 ± 1.0 mg CH_4 m^{-2} d^{-1}). Cutover shrub mean CH_4 fluxes were 0.1 ± 1.9 mg CH_4 m^{-2} d^{-1} and ranged from -4.1 to 3.3 mg CH_4 m^{-2} d^{-1}. Fluxes from shrubs were not significantly different between years or from cutover bare peat and mosses. Due to their minimal influence on CH_4 emissions and their very small areal coverage, measurement of shrub fluxes were omitted in 2002 in order to increase the number of moss and vascular sites measured and to measure ebullition and porewater CH_4 concentrations.

2001 vascular vegetation was significantly different between the restored and cutover sites (Table 4.2). Fluxes from restored site vascular vegetation were also significantly larger than both restored peat and moss fluxes but both sites were not significantly different between years. Breaking average flux values into wet and dry conditions found that restored vascular fluxes were significantly higher (47.9 ± 29.6 mg CH_4 m^{-2} d^{-1}) during dry conditions than wet conditions (2.0 ± 1.5 mg CH_4 m^{-2} d^{-1}).

In 2002, bare peat and mosses were again not significantly different between the restored and cutover sites or for previous years (Table 4.2). Breaking down the mean seasonal fluxes into wet and dry conditions found that restored and cutover bare peat had a significantly higher CH_4 flux under wet conditions (2.0 ± 4.6 mg CH_4 m^{-2} d^{-1} and 1.3 ± 3.2 mg CH_4 m^{-2} d^{-1}, respectively) than dry conditions (-4.4 ± 5.5 and -3.4 ± 5.4 mg CH_4 m^{-2} d^{-1}, respectively). Conversely, both restored and cutover mosses were not significantly different between conditions.

The magnitude of restored vascular fluxes was slightly lower (not significant) than 2001 however the variability was much less and became consistent through the last half of the study period (Figure 4.2 and Table 4.2). Restored vascular fluxes were significantly higher than both restored moss and bare peat values. Cutover vascular fluxes (Table 4.2) were not significantly different than previous years but were significantly lower ($p < 0.05$) than restored vascular fluxes. Breaking down fluxes into wet and dry conditions found cutover vascular vegetation significantly higher (1.3 ± 1.9 mg CH_4 m^{-2} d^{-1}) under wet conditions while restored vascular vegetation was significantly higher (39.8 ± 14.5 mg CH_4 m^{-2} d^{-1}) under dry conditions.

Fluxes from both the restored and cutover ditches were highly variable over the entire study (Figure 4.3). During 1999, restored ditch fluxes were significantly higher ($p < 0.05$) than cutover ditch fluxes (Table 4.2).

In 2000, restored ditch fluxes decreased while cutover ditch fluxes increased but were not significantly different to each other (Figure 4.3 and Table 4.2). Restored ponds were small sources of CH_4 (Table 4.2) and had minimal variability in emissions (Figure 4.3). 2001 fluxes were generally higher and much more variable from the restored ditches and ponds as well as the cutover ditches (Figure 4.3). Restored and cutover ditches were not significantly different however the restored ditches and pond fluxes were significantly higher than 2000 fluxes (Table 4.2).

Fluxes from restored ditches and ponds were significantly higher in 2002 compared to 2001 and were still highly variable over the season (Figure 4.3). Cutover ditches were higher but not significantly different than 2001, and were also highly variable (Table 4.2).

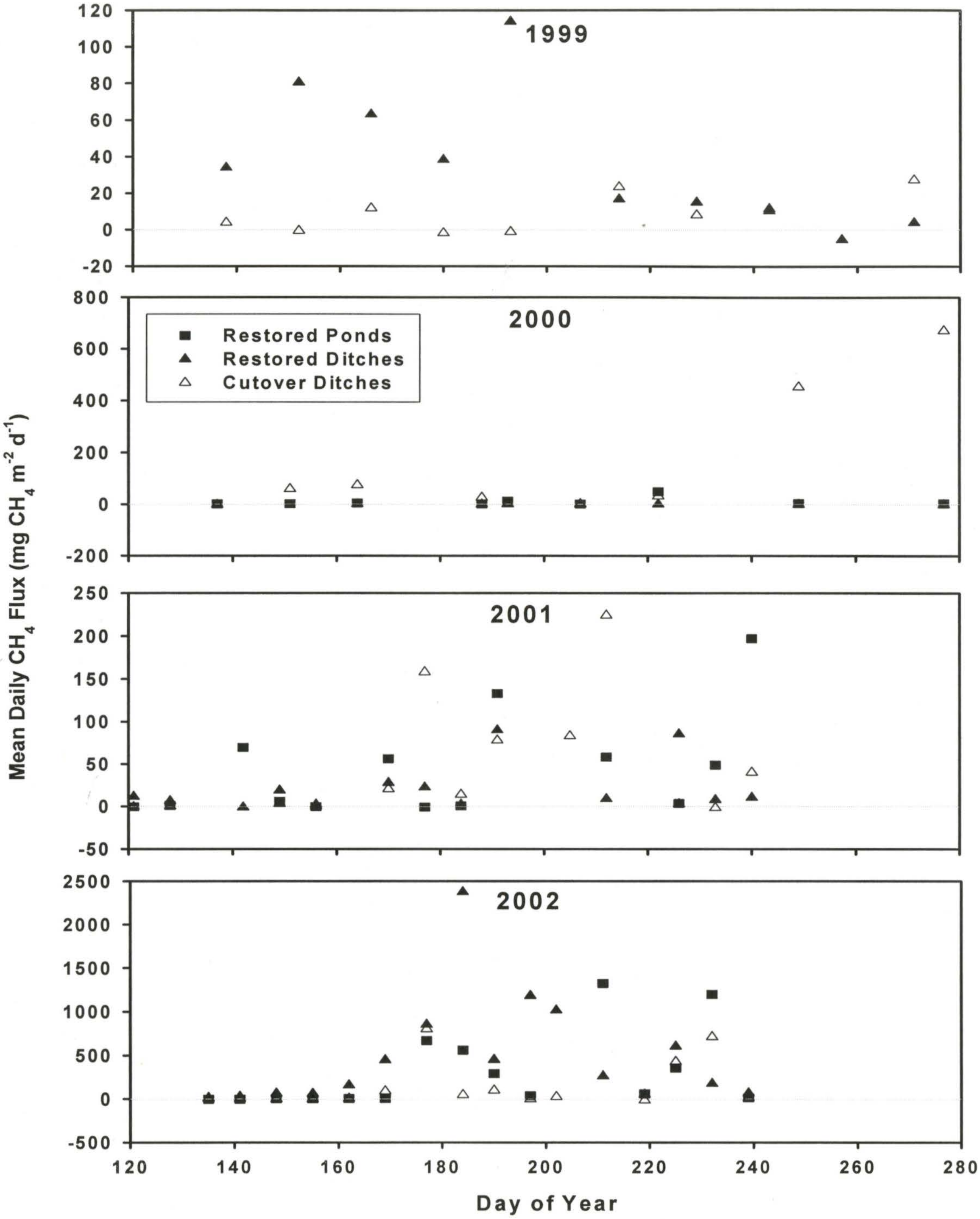


Figure 4.3 Mean daily CH_4 flux (mg CH_4 m^{-2} d^{-1}) of ponds and ditches at the restored and cutover sites over the four field seasons. *Note the change in scale for each graph.

4.3.3 *Episodic CH_4 Emissions*

Observations of episodic CH_4 release from restored ponds and ditches in 2001 (and absent in 1999 and 2000) led to the monitoring of ebullition in 2002. Mean ebullition from the restored ponds and ditches were 2.9 ± 2.5 and 10.7 ± 16.9 mg CH_4 m^{-2} d^{-1} respectively and ranged from 0.0 to 12.2 mg CH_4 m^{-2} d^{-1} for the ponds and from 0.0 to 74.3 mg CH_4 m^{-2} d^{-1} for the ditches (Figure 4.4). Ebullition ranged in importance from the ponds with the zone 2 pool having the lowest percent ebullition compared to diffusive CH_4 flux (0.5%) followed by zone 1 (1.6%), zone 4 (1.9%) and zone 3 (1.5%). For the ditches, the zone 1 ditch had the lowest percent ebullition (0.2%) followed by zone 4 (0.6%), zone 3 north (5.6%), zone 2 (4.6%) and zone 3 south (42.4%). Ebullition represented on average 10.6% of the CH_4 flux from the ditches and 1.4% from the ponds.

4.3.4 *Seasonal CH_4 Exchange*

Total seasonal CH_4 exchange was determined using the average seasonal flux for bare peat, mosses, vascular vegetation, shrubs, ditches and ponds at both the cutover and restored sites, number of days in the field season, and the % coverage of each component to determine the mass of CH_4 released or consumed. These values were summed to determine the total amount of CH_4 released by the peatland. Some assumptions were made for unavailable flux and coverage data and are listed in Table 4.3.

At the cutover site bare peat were net seasonal consumers of CH_4 with the exception of 2001 (Figure 4.5). Mosses were net consumers during 1999 and 2000 and were net producers during 2001 and 2002 while vascular vegetation exhibited the opposite trend. Shrubs were small sources of CH_4 for each year of the study. Restored

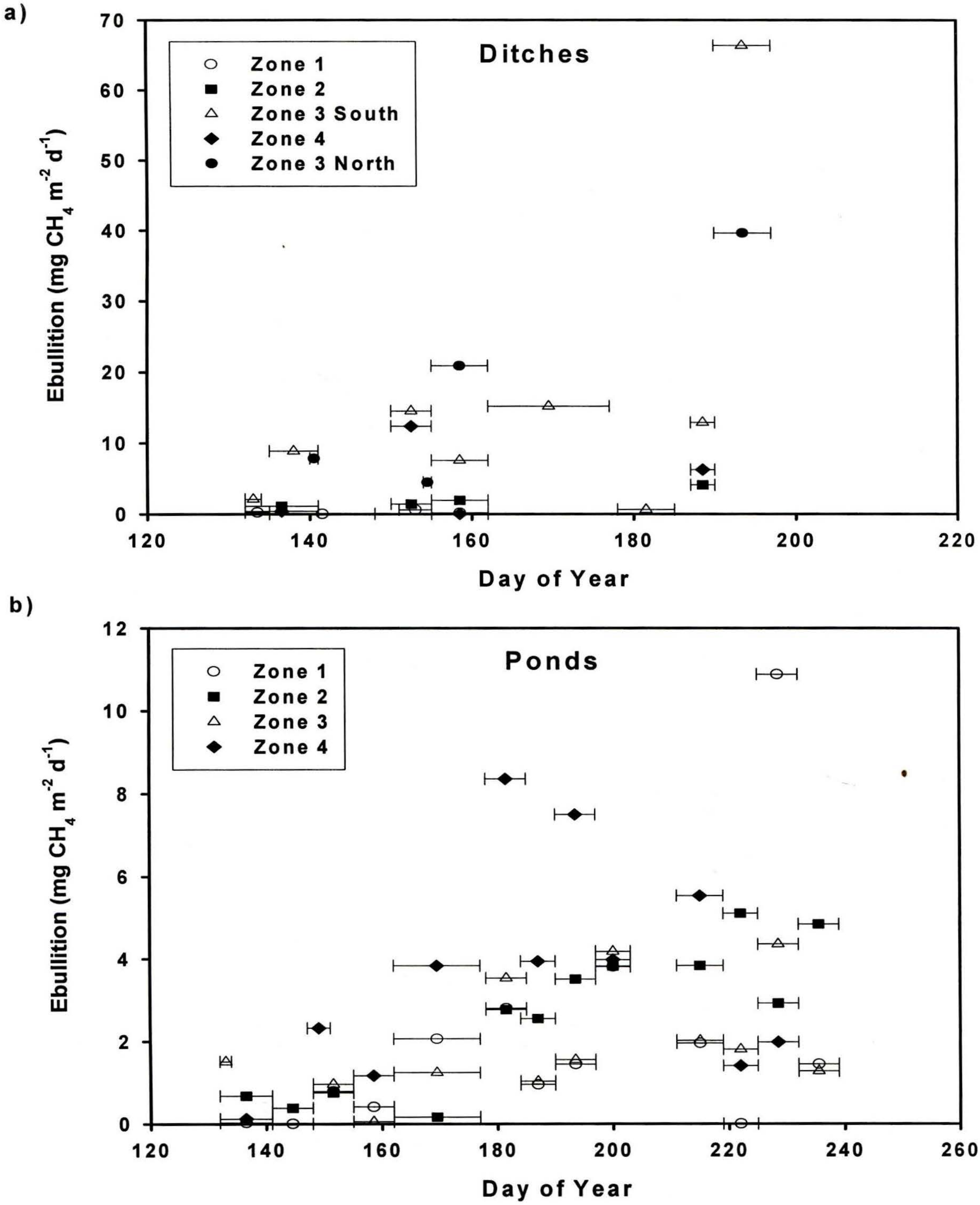


Figure 4.4 a) CH_4 ebullition (mg CH_4 m^{-2} d^{-1}) for ditches, and b) CH_4 ebullition (mg CH_4 m^{-2} d^{-1}) for ponds at the restored site. The horizontal lines indicate the temporal range of each ebullition measurement.

Table 4.3 Flux and coverage assumptions made in determining total seasonal CH_4 exchange.

Year	COMPONENT	ASSUMPTION
1999	Cutover Moss Flux	Set equal to measured 2000 moss values based on the assumption that the cutover CH_4 fluxes were not significantly different between years.
	Cutover Shrub Flux	Set equal to measured 2000 shrub values based on the assumption that the cutover CH_4 fluxes were not significantly different between years.
	Cutover Vascular Flux	Set equal to measured 2000 vascular values based on the assumption that the cutover CH_4 fluxes were not significantly different between years.
	Restored Moss Flux	Set equal 1999 cutover moss flux as restoration had not yet occurred and it was assumed that the restored site CH_4 fluxes were not significantly different than the cutover site CH_4 fluxes.
	Restored Shrub Flux	Set equal 1999 cutover shrub flux as restoration had not yet occurred and it was assumed that the restored site CH_4 fluxes were not significantly different than the cutover site CH_4 fluxes.
	Restored Vascular Flux	Set equal 1999 cutover vascular flux as restoration had not yet occurred and it was assumed that the restored site CH_4 fluxes were not significantly different than the cutover site CH_4 fluxes.
2000	Restored Moss Flux	Set equal to the mean of 1999 and measured 2001 moss CH_4 flux assuming that restoration is increasing CH_4 fluxes each year.
	Restored Vascular Flux	Set equal to the mean of 1999 and measured 2001 vascular CH_4 flux assuming that restoration is increasing CH_4 fluxes each year.
	Restored Shrub Flux	Set equal to 2000 cutover shrub CH_4 flux due to the limitation of the number of sites that could be monitored at the restored site and because shrubs have not been found to be large sources of CH_4 as a result of their limited transport capacity. It is expected that this assumption may underestimate CH_4 fluxes from restored shrubs but that the error involved is small.
2001	Restored Shrub Flux	Set equal to 2001 cutover shrub CH_4 flux due to the limitation of the number of sites that could be monitored at the restored site and because shrubs have not been found to be large sources of CH_4 as a result of their limited transport capacity. It is expected that this

		assumption may underestimate CH_4 fluxes from restored shrubs but that the error involved is small.
2002	Cutover and Restored Shrub Flux	Set equal to 2001 shrub CH4 flux as previous data showed no significant change between years and due to time constraints in the field they were removed from the sampling scheme. It is expected that this assumption may underestimate CH_4 fluxes from restored shrubs but that the error involved is small.

Year	**COMPONENT**	**ASSUMPTION**
1999	Peat, Moss and Vascular Coverages	Calculated based on vegetation surveys conducted at the site (Rochefort, unpublished data).
2000	Peat Coverage	Estimated based on visual observations converted to mapping estimates of coverage.
	Moss Coverage	Estimated based on visual observations converted to mapping estimates of coverage.
	Vascular Coverage	Equal to the residual of decrease in 20000 peat cover and the increase in 2000 moss cover.
	Shrub Coverage	Based on visual observations, areal coverage did not appear to change so the coverage was set to equal 1999 shrub coverage.
2001	Peat, Moss and Vascular Coverages	Calculated based on vegetation surveys conducted at the site (Rochefort, unpublished data).
2002	Peat Coverage	Estimated based on visual observations converted to mapping estimates of coverage.
	Moss Coverage	Estimated based on visual observations converted to mapping estimates of coverage.
	Vascular Coverage	Estimated based on visual observations converted to mapping estimates of coverage.
	Shrub Coverage	Based on visual observations, areal coverage did not appear to change so the coverage was set to equal 1999 shrub coverage.
All Years	Ditch and Pond Coverages	Total areas of ditches and ponds were calculated by determining the length and widths of each individual ditch and pond from a GIS theme of the site.

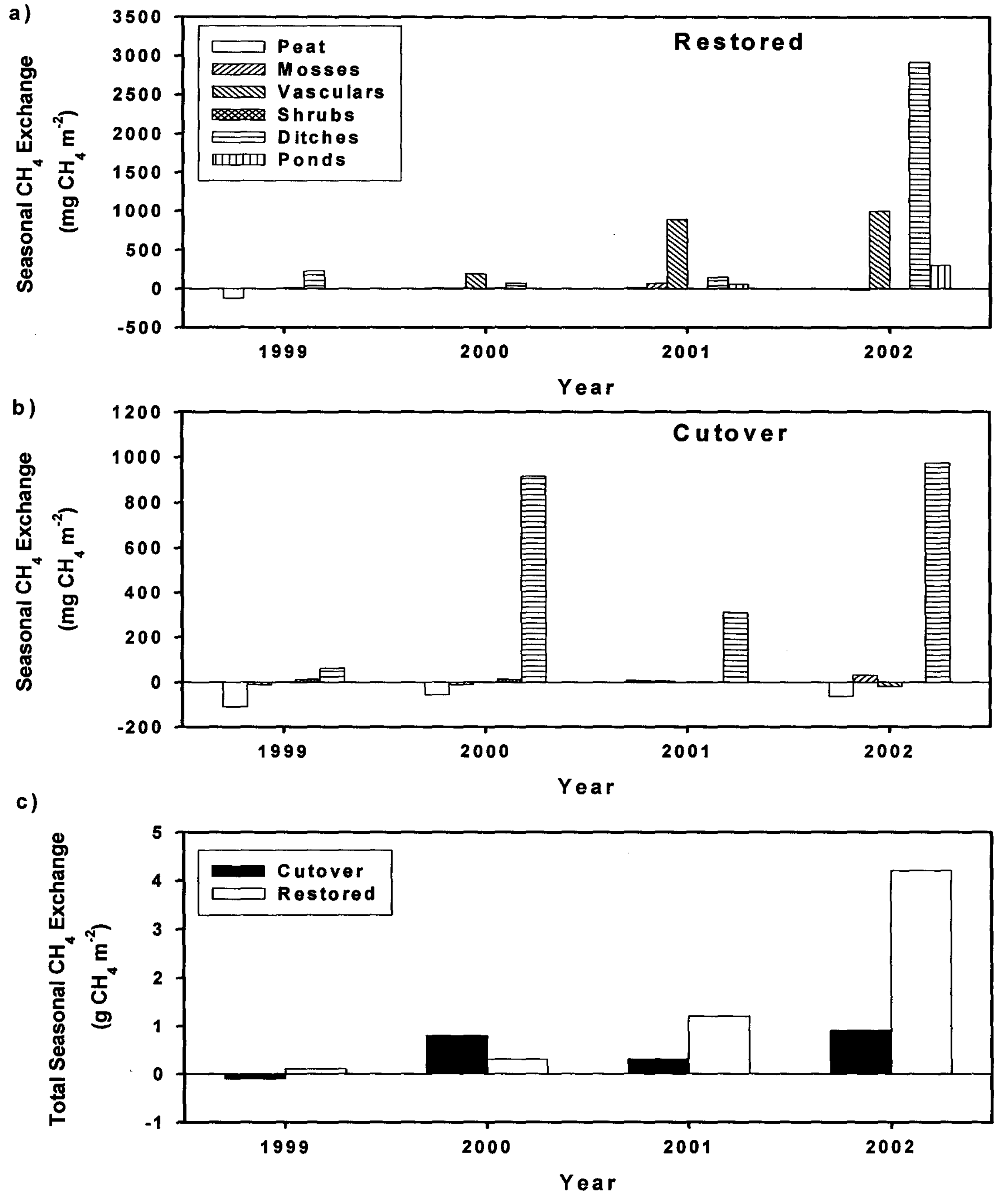


Figure 4.5 a) Seasonal CH_4 exchange (mg CH_4 m^{-2}) for bare peat, mosses, vascular vegetation, shrubs, ditches and ponds at the restored site, b) Seasonal CH_4 exchange (mg CH_4 m^{-2}) for bare peat, mosses, vascular vegetation, shrubs and ditches at the cutover site, and c) total seasonal CH_4 exchange (g CH_4 m ^{2}) for the cutover and restored sites over the four field seasons.

site bare peat and mosses were only net seasonal consumer of CH_4 during 1999 and 2002. Conversely to the cutover site, vascular vegetation were large net producers of CH_4 for each year of the study, while shrubs were again only small sources of CH_4.

Ditches at both the restored and cutover sites were net seasonal CH_4 producers however their patterns of seasonal CH_4 exchange were quite different. Restored site ditches increased in net seasonal CH_4 emission with each year post-restoration while fluxes from the cutover site showed no specific trend. In both cases, ditches were one of the major sources of total CH_4 released from each site.

Ponds created at the restored site were net seasonal CH_4 producers for each year with total seasonal CH_4 exchange increasing every year post-restoration, however values were not as significant as ditches or vascular vegetation. (0.3 g CH_4 m^{-2}). Conversely, total seasonal CH_4 exchange increased exponentially at the restored site from a net release (0.1 g CH_4 m^{-2}) in 1999 to a large CH_4 source (4.2 g CH_4 m^{-2}) in 2002 which was significantly larger (~122% higher) than the cutover site.

4.4 Discussion

4.4.1 Relationships to Environmental Variables

Regression analyses found that both the pre-restored and cutover site fluxes in 1999 were poorly correlated to water table position while a stronger relationship was found with the 10 cm soil temperature at the cutover site which was nonexistent at the pre-restored site (Table 4.4).

No strong relationships in 2000 were found with any environmental variables for either the restored or cutover peat fluxes. However, cutover shrubs and vascular

Table 4.4 R^2 (n) values of linear regressions of CH_4 vs. water table (WT), unsaturated zone soil moisture (SM), soil temperature at 2 (T2), 5 (T5), 10 (T10) cm, water temperature (Tw) and gross ecosystem production (GEP).

		Restored							Cutover						
Year	**Type**	**WT**	**SM**	**T2**	**T5**	**T10**	**Tw**	**GEP**	**WT**	**SM**	**T2**	**T5**	**T10**	**Tw**	**GEP**
1999	**Peat**	0.21 (7)	NA	NA	NA	0.01 (7)	NA	NA	0.29 (7)	NA	NA	NA	0.54 (7)	NA	NA
	Moss	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
	Shrub	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
	Vascular	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
	Ditch	0.30 (10)	NA	0.19 (10)	0.21 (10)	0.05 (10)	NA	NA	0.42 (9)	NA	0.20 (9)	0.14 (9)	0.01 (9)	NA	NA
	Pond	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
2000	**Peat**	0.01 (50)	NA	0.01 (50)	0.00 (50)	0.02 (50)	NA	NA	0.02 (17)	NA	0.04 (26)	0.00 (26)	0.06 (26)	NA	NA
	Moss	NA	NA	NA	NA	NA	NA	NA	0.14 (4)	NA	0.03 (7)	0.01 (7)	0.0 (7)	NA	NA
	Shrub	NA	NA	NA	NA	NA	NA	NA	0.00 (4)	NA	0.88 (6)	0.04 (6)	0.04 (6)	NA	NA
	Vascular	NA	NA	NA	NA	NA	NA	NA	0.67 (5)	NA	0.64 (7)	0.90 (7)	0.80 (7)	NA	NA
	Ditch	NA	NA	0.02 (17)	0.00 (17)	0.06 (19)	NA	NA	0.00 (11)	NA	0.22 (11)	0.14 (11)	0.03 (17)	0.02 (6)	NA
	Pond	NA	NA	0.01 (9)	NA	0.20 (14)	0.07 (23)	NA	NA	NA	NA	NA	NA	NA	NA
2001	**Peat**	0.00 (42)	0.01 (24)	0.05 (42)	0.03 (42)	0.01 (42)	NA	NA	0.02 (26)	0.21 (18)	0.05 (26)	0.05 (26)	0.06 (26)	NA	NA
	Moss	0.09 (21)	0.00 (20)	0.01 (32)	0.07 (32)	0.08 (32)	NA	0.05 (32)	0.07 (10)	0.05 (7)	0.21 (10)	0.34 (10)	0.46 (10)	NA	0.32 (9)
	Shrub	NA	NA	NA	NA	NA	NA	NA	0.09	0.00	0.00	0.01	0.02	NA	0.24

								(11)	(6)	(11)	(11)	(11)		(9)
	Vascular	0.25 (11)	0.05 (7)	0.15 (11)	0.23 (11)	0.20 (11)	NA	0.00 (10)	0.02 (10)	0.62 (6)	0.00 (10)	0.00 (10)	0.00 (10)	NA	0.14 (8)
	Ditch	0.11 (37)	0.01 (25)	0.03 (27)	0.03 (25)	0.09 (51)	0.00 (27)	NA	0.08 (22)	0.11 (10)	0.00 (10)	0.00 (10)	0.22 (22)	0.73 (10)	NA
	Pond	0.03 (80)	NA	NA	NA	0.00 (94)	0.01 (93)	NA	NA	NA	NA	NA	NA	NA	NA
2002	**Peat**	0.00 (42)	0.02 (43)	0.00 (43	0.01 (43)	0.02 (43)	NA	NA	0.04 (29)	0.05 (29)	0.04 (29)	0.10 (29)	0.21 (29)	NA	NA
	Moss	0.04 (98)	0.07 (98)	0.01 (98)	0.02 (98)	0.02 (98)	NA	0.06 (68)	0.06 (42)	0.03 (42)	0.10 (42)	0.08 (42)	0.02 (42)	NA	0.21 (41)
	Shrub	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
	Vascular	0.06 (75)	0.03 (75)	0.04 (75)	0.09 (75)	0.19 (75)	NA	0.02 (75)	0.08 (46)	0.02 (46)	0.16 (46)	0.20 (46)	0.33 (46)	NA	0.04 (44)
	Ditch	0.01 (56)	0.02 (51)	0.02 (47)	0.03 (47)	0.05 (65)	NA	NA	0.01 (25)	0.01 (16)	0.20 (16)	0.22 (16)	0.11 (16)	0.10 (11)	NA
	Pond	0.00 (46)	NA	NA	NA	0.14 (49)	0.11 (49)	NA	NA	NA	NA	NA	NA	NA	NA

vegetation were found to be strongly correlated to 2 cm and 5 cm soil temperature, respectively. Cutover vascular vegetation was also found to be related to the water table position.

In 2001 restored and cutover bare peat, restored moss and cutover shrub fluxes were not significantly correlated to soil temperature, unsaturated zone soil moisture or water table position but cutover moss flux was correlated to the 10 cm soil temperature and GEP. Even when separating the data into wet and dry conditions (defined previously) no good relationships were observed. Cutover vascular vegetation was correlated to unsaturated zone soil moisture while restored vascular vegetation was only weakly correlated. When breaking the study period into wet and dry conditions, the restored vascular vegetation was correlated to GEP under both wet and dry ($R^2 = 0.42$ and 0.61, respectively, $n = 5$).

2002 correlations showed no strong relationships for restored peat and mosses when determined over the entire study periods nor when separated into wet and dry conditions. Conversely, cutover mosses showed a weak correlation to GEP ($R^2 = 0.43$, $n = 18$) under wet. 2002 cutover vascular fluxes were correlated to 10 cm soil temperature flux over the entire season and under wet conditions ($R^2 = 0.30$, $n = 20$) but showed no strong correlations under dry conditions.

1999 restored ditches were weakly correlated to water table position while cutover ditches had a slightly stronger relationship. No significant correlations were found for 2000 for either restored ponds and ditches or cutover ditches.

2001 cutover ditches had a strong relationship to water temperature. However, when separating the season into wet and dry conditions, cutover ditches were correlated to 10 cm soil temperature ($R^2 = 0.30$, n = 14), water temperature ($R^2 = 0.49$, n = 9) and water table position ($R^2 = 0.30$, n = 14) under wet conditions.

Coinciding with 2001, no strong relationships were determined for restored ditches and ponds in 2002 while cutover ditches were correlated to 5 cm soil temperature under dry conditions ($R^2 = 0.24$, n = 10) and to 10 cm soil temperature under wet conditions ($R^2 = 0.28$, n = 13).

4.4.2 Bare Peat

Mean daily CH_4 emissions from bare peat at the restored and cutover sites fall within the low end of emissions determined for peat from natural peatlands 2.0×10^{-2} to 1.3×10^3 mg CH_4 m^{-2} d^{-1} (Glenn et al. 1993, Moore & Dalva 1993, Whalen & Reeburgh 2000, Frenzel & Karofeld 2000, Waddington & Price 2000). Mean daily CH_4 emissions were also similar to newly harvested sites 0.2 to 24.0 mg CH_4 m^{-2} d^{-1} (Sundh et al. 2000, Waddington & Price 2000), however the bare peat also experienced net CH_4 consumption, which was noted at an old harvested peatland site -2.4 to 7.2 mg CH_4 m^{-2} d^{-1} (Sundh et al. 2000, Tuittila et al. 2000c).

As in other studies (e.g. Glenn et al. 1993, Sundh et al. 2000), CH_4 emissions from bare peat experienced no strong seasonal patterns. As the rate of CH_4 production and oxidation are most likely the dominant processes controlling CH_4 emissions from peat, soil temperature influences the rate of CH_4 production and is reflected in the moderately strong correlations with CH_4 flux for restored and cutover peat. The rate of

CH_4 production could also explain the generally higher CH_4 flux at the restored site compared to the cutover site. Moreover, potential CH_4 production was higher at the restored site (0.03 ug g^{-1} d^{-1}) than the cutover site (0.02 ug g^{-1} d^{-1}) (see Chapter 3).

CH_4 fluxes increased with each year post-restoration at the restored site and each year, with the exception of 2002 at the cutover site. Mean seasonal CH_4 soil gas profiles for the restored and cutover sites (Figure 4.6) also show an increasing CH_4 concentration with each year post-restoration, including 2002, supporting the increase in the rate of CH_4 production with each year post-restoration due to: 1) a larger anoxic zone, 2) an increase in the methanogenic biomass, 3) warmer temperatures, and 4) a supply of labile carbon from the new vegetation. In 2000 and 2001 both the restored and cutover sites had surface soil gas concentrations less than atmospheric (~2 ppmv), with concentrations increasing with depth, but in 2001 concentrations equaled or exceeded atmospheric at 30 and 75 cm in the restored (3.1 ppmv) and cutover (2.1 ppmv) sites respectively. Concentrations less than atmospheric indicate that consumption of atmospheric CH_4 was occurring, supporting the consumptive CH_4 fluxes observed in 2000 for the cutover but not the restored site. The greater than atmospheric concentrations with depth in 2001 resulted in the small but positive CH_4 flux seen from both the restored and cutover sites. In 2002, soil gas concentrations ranged from 2.8 to 6.0 and from 4.5 to 16.9 ppmv for the cutover and restored sites, respectively, yet CH_4 fluxes from both sites were consumptive of atmospheric CH_4. In 2002, water table levels were significantly lower than previous years. This could potentially have limited the rate of CH_4 production by decreasing the anoxic zone to a depth in which no labile carbon was available and by increasing the zone

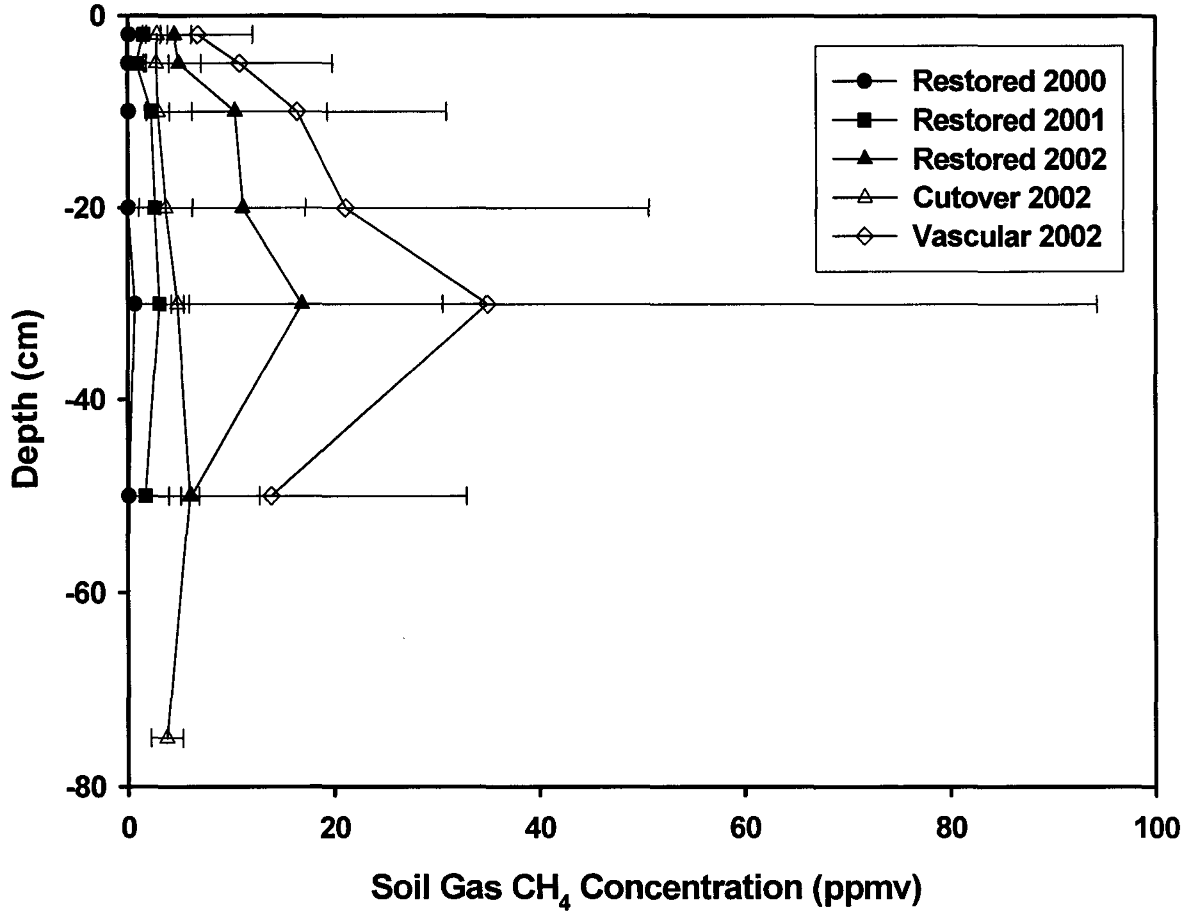


Figure 4.6 Mean seasonal CH_4 depth profiles of soil gas (ppmv) for the restored site, site for each season and for the cutover site.

in which CH_4 oxidation could occur. Using the water table position probability of exceedence graphs discussed in Chapter 3, and with an average water table position in 2002 for the cutover and restored sites of -44.4 and -37.5 cm, respectively, it can be estimated that the cutover site water table was lower than the depth in which CH_4 production is greater than oxidation (see Chapter 3) while the restored site was on the border but most likely also exceeding this boundary. Therefore, the low water table levels experienced in 2002 was responsible for the net CH_4 consumption emission for bare peat at both the restored and cutover sites.

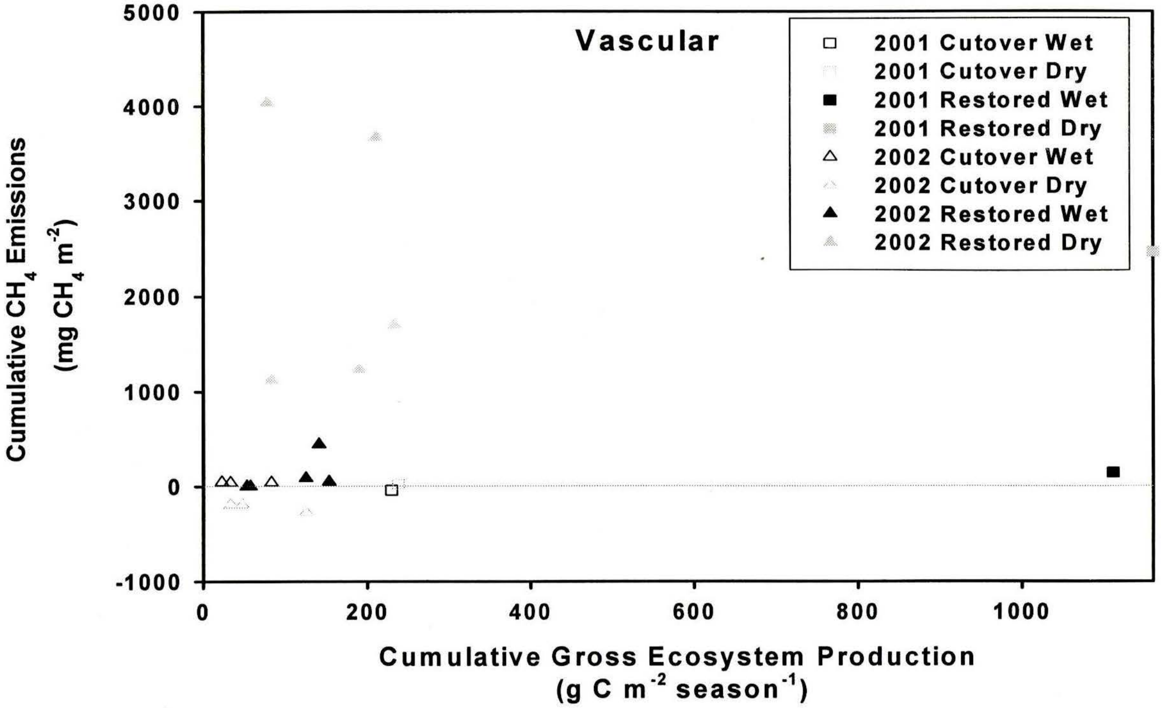
4.4.3 Vegetation

Mean daily CH_4 fluxes from the moss vegetation fall within the range from natural moss dominated peatlands ~-2 to 40 mg CH_4 m^{-2} d^{-1} (Whalen & Reeburgh 1988, Moore & Knowles 1989, Moore & Knowles 1990, Bartlett et al. 1992, Bubier et al. 1993, Savage et al. 1997, Granberg et al. 1997, Bellisario et al. 1999). Fluxes from drained/harvested sites were lower than those from natural sites for both this and other studies which ranged from -0.3 to 2 mg CH_4 m^{-2} d^{-1} (Roulet et al. 1993, Roulet & Moore 1995) and slightly higher from rewetted sites -2.4 to 4.8 mg CH_4 m^{-2} d^{-1} (Tuittila et al. 2000c)

CH_4 fluxes from vascular vegetation from this study fall within the range from natural sites with vascular vegetation of -73.6 to 2240 mg CH_4 m^{-2} d^{-1} (Whalen & Reeburgh 1988, Bartlett et al. 1992, Yavitt et al. 1993, Waddington et al. 1996, Komulainen et al. 1998, Frenzel & Karofeld 2000) but were more consistent with values from vascular vegetation at drained sites, 0 to 20 mg CH_4 m^{-2} d^{-1} (Tuittila et al. 2000b) and followed the same pattern of an increase in CH_4 flux after rewetting, 6.4 to 75 mg CH_4 m^{-2} d^{-1} (Komulainen et al. 1998, Tuittila et al. 2000b).

Many studies have shown that vascular plants can enhance CH_4 emissions through the supply of labile carbon and transport of CH_4 to the atmosphere (Chanton et al. 1992, 1993, Waddington et al. 1996, Shannon et al. 1996, Joabsson et al. 1999ab, Greenup et al. 2000, Joabsson & Christensen 2001, King & Reeburgh 2002, King et al. 2002) resulting in higher CH_4 fluxes than from natural moss dominated bog peatlands. However, few studies have looked at the impacts of peatland drainage and harvesting (Tuittila et al. 2000b) or restoration (Komulainen et al. 1998, Tuittila et al. 2000b) on vascular control of CH_4 emissions.

Restoration did not appear to have a significant effect on CH_4 emissions from mosses and showed no temporal pattern that could be significantly related to water table or peat temperature as in other studies (e.g. Roulet et al. 1993, Roulet & Moore 1995, Savage et al. 1997). CH_4 emissions from restored site vascular vegetation plots were 23 to 57 times higher than emissions from vascular vegetation plots at the cutover site. Fluxes from vascular vegetation plots at both the restored and cutover sites increased significantly after mid-June (Figure 4.2) when the vegetation began to grow. Strong positive correlations have been found between GEP and CH_4 flux (e.g. Whiting & Chanton 1993, Waddington et al. 1996) since higher vegetation GEP increases CH_4 flux through the larger aerenchyma and transport of CH_4 and the higher supply of labile carbon for methanogenesis. Restored site vascular vegetation had higher seasonal GEP than cutover site vascular vegetation (Figure 4.7), suggesting that the larger GEP of the



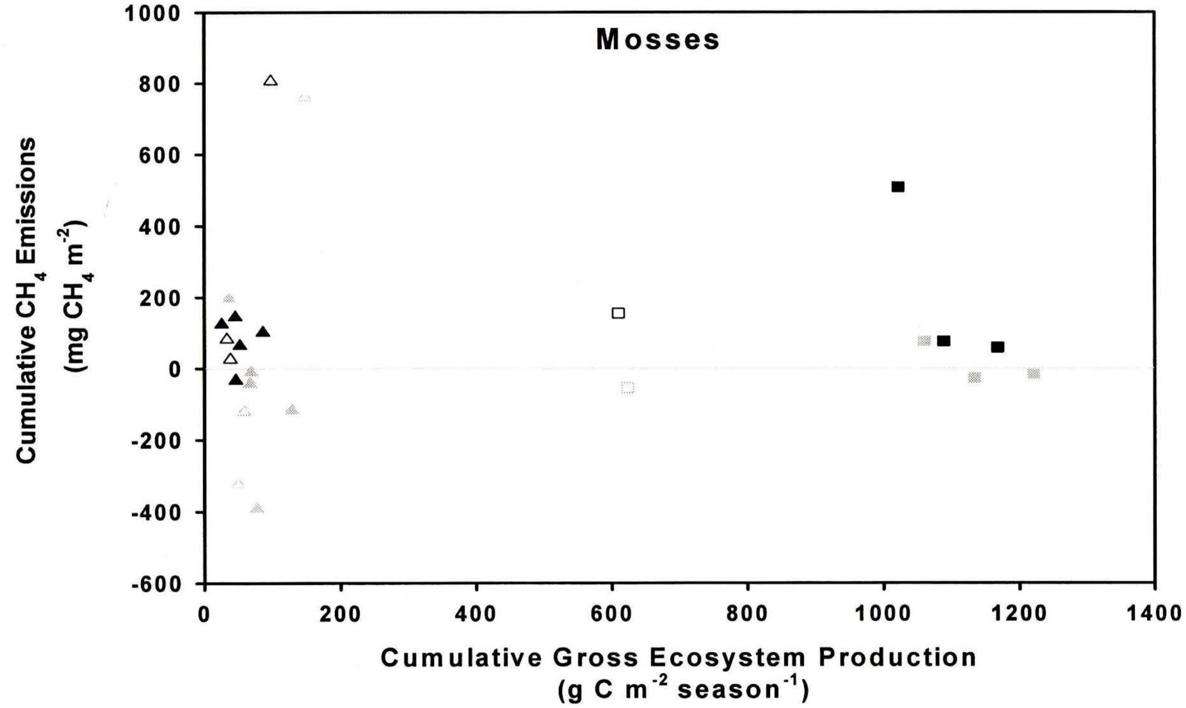


Figure 4.7 Cumulative seasonal GEP (g CO_2 m^{-2} d^{-1}) vs. cumulative seasonal CH_4 (mg CH_4 m^{-2} d^{-1}) for cutover and restored vasculars and mosses under wet and dry conditions.

restored vascular vegetation caused an increase in the supply of root exudates for CH_4 production and the ability of the plant to transport CH_4. Water is an essential component in photosynthesis, therefore the higher water table position in 2001 resulted in higher GEP and therefore larger CH_4 fluxes post-restoration. Furthermore, the higher water table allows more of the vascular roots to be within the zone of CH_4 production, thereby permitting more CH_4 to be transported and root exudates to be utilized for methanogenesis (Waddington et al. 1996). Tuittila et al. (2000b) also found that low water table levels resulted in low CH_4 emission from *Eriophorum* and that CH_4 emissions increased with an increase in water table levels.

However, differences in cumulative CH_4 emissions and GEP within years can not be explained by water table position alone as mean water table position was similar between the restored and cutover sites over the growing season (Julian day 200 to 243). Yet, when comparing the mean seasonal volumetric moisture content between the restored and cutover vascular sites, 66.9 and 40.6% respectively, the cutover site was much drier, indicating that a deficit of soil moisture can significantly impact the growth of the vascular vegetation and therefore its ability to provide root exudates and transport CH_4. Similar results were found by Joabsson et al. (1996b) where a decrease in GEP caused by shading (mimicking the results of the dry conditions at the cutover site), resulted in decreased dissolved organic acids and carbon flow from the roots and lower CH_4 emissions.

The areal coverage of vascular vegetation has increased consistently post-restoration and as a result has increased CH_4 fluxes from the site. The influence of vegetation on supplying labile carbon for methanogenesis and transport of CH_4 past the oxic zone are the primary processes increasing CH_4 production and emissions. Moss and vascular vegetation release carbon into the peat profile, either through root exudates or senescence, which is used by methanogens. Seasonal porewater CH_4 concentrations beneath restored site mosses (Figure 4.8) were higher than beneath cutover peat (mean 0.98 and 0.02 mg L^{-1}, respectively) indicating that mosses also potentially increased the amount of available labile carbon which increased CH_4 production and dissolved CH_4 concentrations. Yet dissolved CH_4 beneath the restored mosses was lower compared to literature values for natural moss peatland (0.0 to 19.3 mg L^{-1}) (Nilsson & Bohlin 1993, Lloyd et al. 1998, Frenzel & Karofeld 2000). Seasonal porewater CH_4 beneath restored site vascular vegetation was higher than mosses (mean 1.2 mg L^{-1}) suggesting that it has a stronger influence on carbon supply and CH_4 production. Similarly, dissolved CH_4 beneath restored vascular vegetation was smaller than literature values (0.0 to 32.1 mg L^{-1}) (Waddington et al. 1996, King & Reeburgh 2000) indicating that restoration has not yet returned CH_4 dynamics to the same magnitude as natural peatlands.

The GEP of restored mosses was higher in 2001 compared to 2002 due to higher water table levels (discussed above) and as such had higher CH_4 emissions. However, when separating GEP and CH_4 into wet and dry conditions, GEP was not significantly different but CH_4 fluxes were higher under wet conditions, suggesting that GEP of mosses does not affect CH_4 emissions. Therefore, CH_4 transport was not occurring through mosses. This is not surprising as mosses have no roots or aerenchymous tissue to act as conduits (Greenup et al. 2000). Similarly, GEP and CH_4 emissions of restored

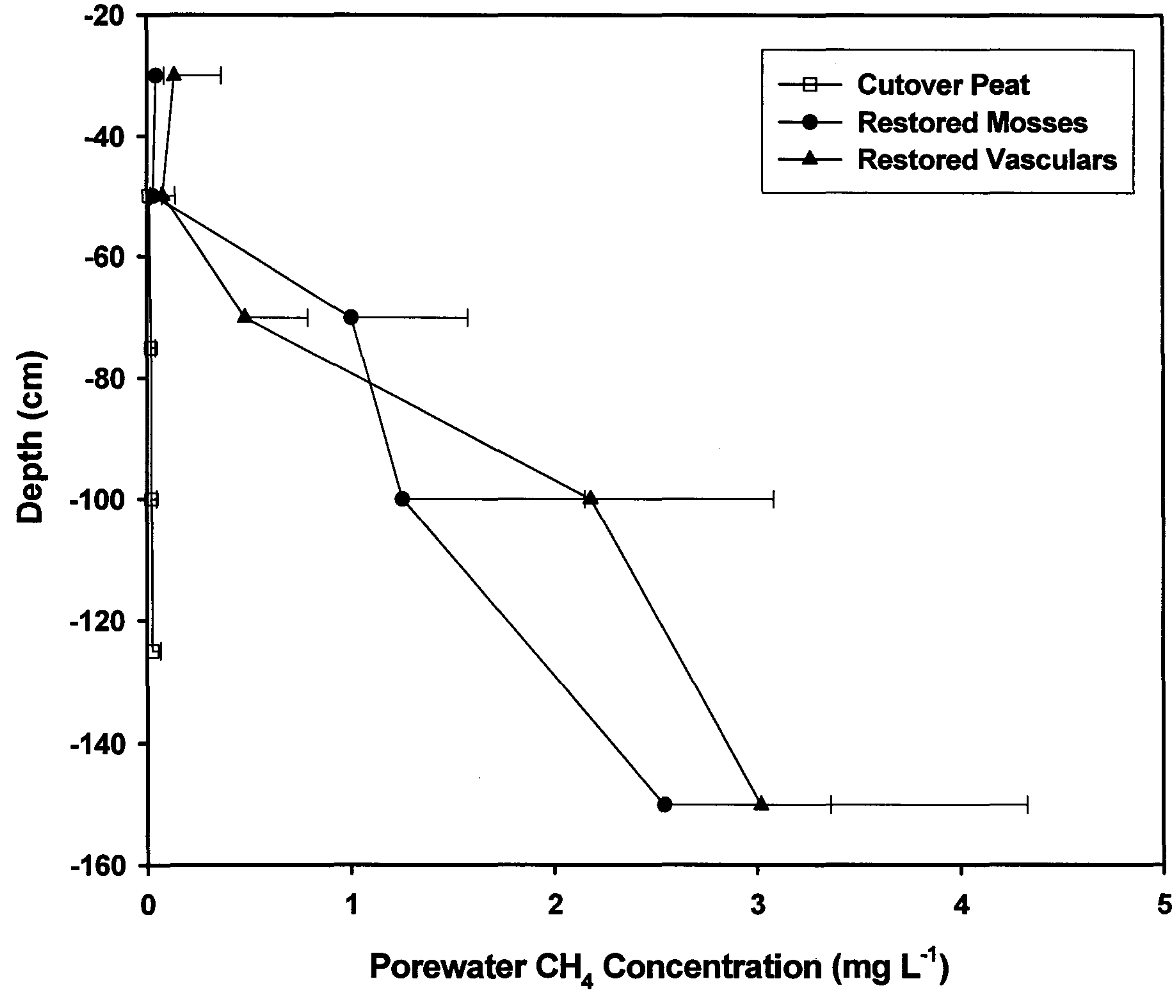


Figure 4.8 Mean seasonal CH_4 depth profiles of porewater (mg L^{-1}) for 2002 of the restored site mosses and vasculars with cutover peat as a comparison.

vascular vegetation was highest in 2001, however GEP and CH_4 from vascular vegetation was greater under dry conditions than wet conditions indicating that increases in vascular GEP increased the conduit potential of the plant to transport CH_4, thereby increasing CH_4 emissions. Similar results from a two-year post-restoration vascular site were found by Komulainen et al. (1998) where CH_4 emissions increased five to ten times after the wet season. The influence of vascular transport of CH_4 is further substantiated by the changes in dissolved CH_4 through the season. During the beginning of the season dissolved CH_4 concentrations were moderately high (mean 1.2 mg L^{-1}), peaking at the beginning of June (mean 1.6 mg L^{-1}) and began to decrease around early to mid July, remaining low throughout the rest of the field season (mean 0.9 mg L^{-1}), similar to results found by Waddington et al. (1996). The lower dissolved CH_4 at the end of July, when soil temperatures were warmest and carbon supply from plant growth was larger, resulted from the removal of CH_4 by plant transport being greater than the rate of CH_4 production. Minkkinen et al. (1997) and Frenzel & Karofeld (2000) attributed the absence of ebullition from vascular vegetation to the transport mechanism depleting CH_4 concentrations within the peat and preventing bubble formation and release. The lack of observations of episodic events from vascular vegetation plots at the restored site is also likely due to the depletion of dissolved CH_4 by vegetation.

4.4.4 Ditches

The mean daily CH_4 flux from ditches was similar to that reported in the literature for drained peatlands (0.0 to 595.0 mg CH_4 m^{-2} d^{-1}) (Roulet & Moore 1995, Minkkinen et al. 1997, Sundh et al. 2000) for 1999 to 2001 but 2002 CH_4 flux values exceeded this range by up to ~400 %.

CH_4 fluxes from ditches were consistently higher than the adjacent peat in all years. Time series profiles of dissolved porewater CH_4 (Figure 4.9) at ~100 cm beneath the peat surface, from the ditch and field, show that concentrations are much higher beneath the ditches compared to peat located 2.5 m from the ditch at both the restored and cutover sites. This suggests that there is a larger supply of labile carbon for methanogenesis within the ditches and therefore a larger rate of CH_4 production, resulting in the larger fluxes from the ditches compared to the adjacent peat. Furthermore, the concentrations of dissolved CH_4 at the restored site changed throughout the field season with highest concentrations at the end of May/beginning of June, coinciding with wet conditions, warm temperatures and high rates of CH_4 production. CH_4 concentrations then decreased to the lowest values measured on the 26 July due to large ebullition events (Figure 4.4a), large CH_4 fluxes (Figure 4.3), and vegetative transport depleting the pool of dissolved CH_4. Dissolved CH_4 increased in concentration until the end of the season despite the low water table conditions and was much lower than at the beginning of the season. These lower concentrations may have resulted in the lower CH_4 fluxes from the ditches near the end of the season. Concentrations of dissolved CH_4 were significantly lower at the cutover site than the restored site (Figure 4.9) with the highest concentrations occurring on 12 July while all other dates were very similar in their profiles with extremely low (0 to 0.23 mg L^{-1} beneath the peat and 0 to 0.43 mg L^{-1} beneath the ditch) concentrations.

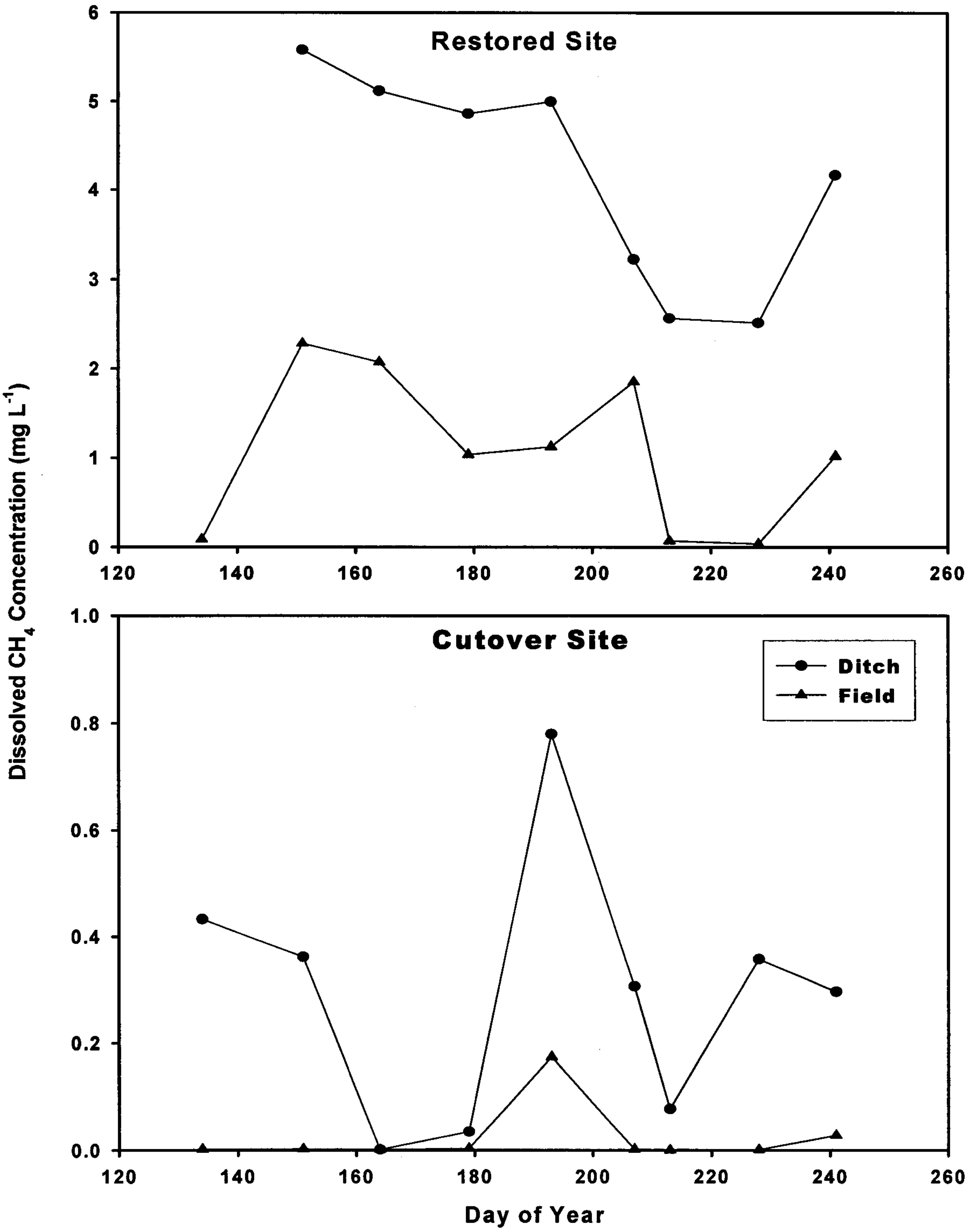


Figure 4.9 Time series profiles of dissolved CH_4 (mg L^{-1}) from the ditch and field in 2002 for the restored site and cutover site.

Time sereis profiles of redox (Figure 4.10) ~60 cm beneath the peat surface, from the ditch and field, show that redox gradients generally increased with depth and were the same beneath the ditch and 2.5 m from the ditch at both the restored and cutover sites. In fact, redox conditions not suitable for methanogenesis were found beneath the restored site ditch yet still had high concentrations of dissolved CH_4 and high CH_4 emissions. Conversely, redox conditions suitable for methanogenesis were found within the peat at 2.5 m from the ditch on 26 July, suggesting that CH_4 production from the peat at 2.5 m should be similar to the ditch, which was not observed. Consequently, CH_4 flux at 2.5 m from the ditch is likely limited by a supply of labile carbon (Figure 4.9) and not redox conditions. In addition, at 2.5 m from the ditch, the amount of oxic peat above the water table is larger than at the ditch which generally remained saturated. Therefore, CH_4 that is produced at depth at 2.5 m from the ditch would be oxidized as it diffused through the oxic peat layer resulting in the smaller CH_4 flux, whereas the oxic layer at the ditch only occurred at the end of the season causing a decrease in the CH_4 flux from the ditch (Figure 4.3).

Similar processes occurred at the cutover site with the exception of carbon supply being more recalcitrant within the ditches and peat than at the restored site, resulting in the lower concentrations of dissolved CH_4 and thereby lower CH_4 fluxes.

CH_4 flux from the ditches generally increased with each year post-restoration with the exception of 2000, the first year after the restoration process. Prior to restoration, the ditches were similar to that of the cutover site, that is, they were contributing water to the outflow and were vegetated mainly with shrubs and some *Typha*. After restoration, the

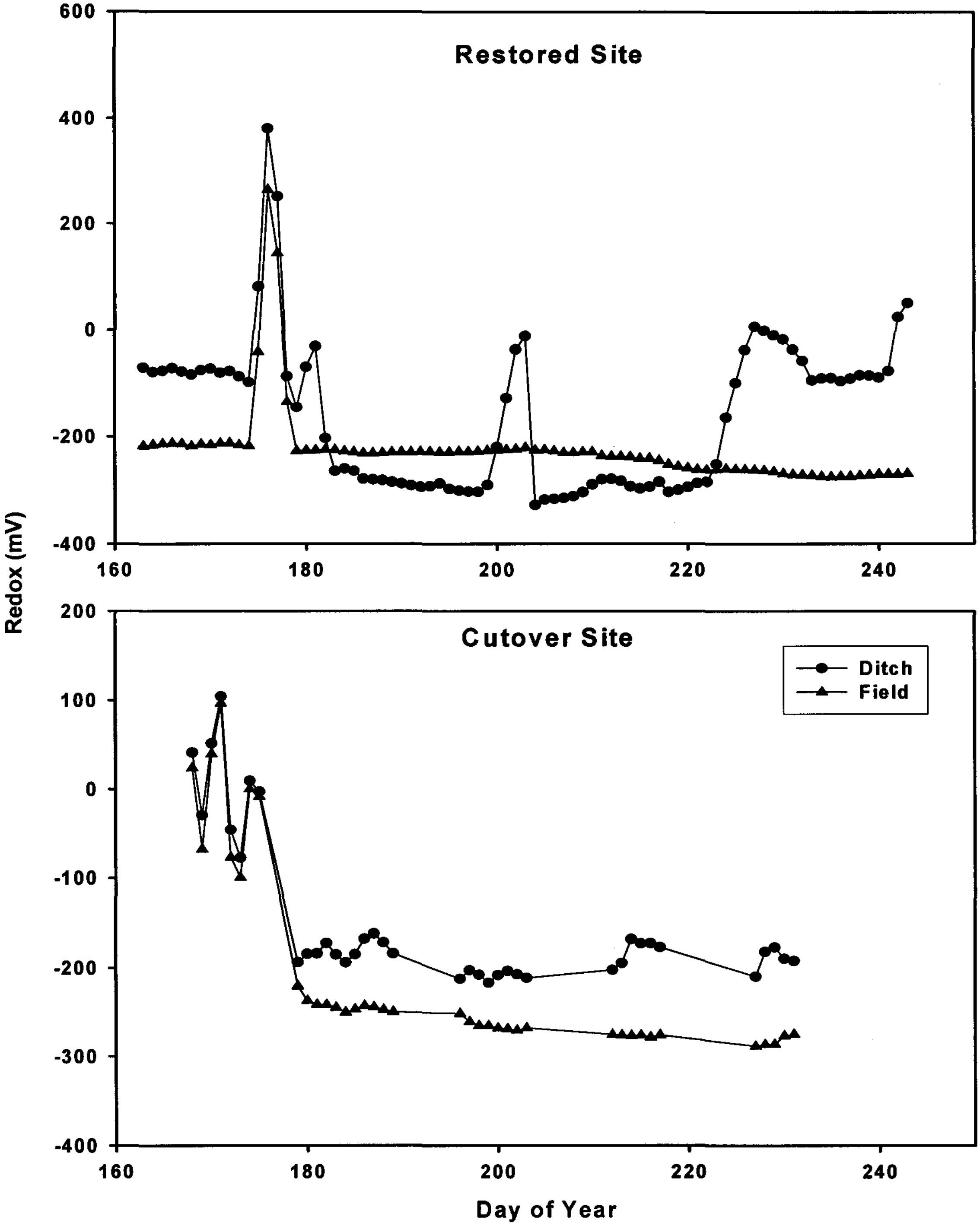


Figure 4.10 Time series profiles of redox (mV) from the ditch and field in 2002 for the restored site and cutover site. *Note -240 mV is the redox value in which methanogenesis occurs.

ditches were partially filled in with brush (shrubs and trees) removed from the fields and covered over with peat removed through the construction of the ponds. The ditches were no longer visible and stagnant pools of water were not present. Accordingly, it can be assumed that the same processes discussed for the peat 2.5 m from the ditch were also present in the ditches in 2000 and produced the low CH_4 fluxes observed. Significant peat slumping occurred over the end of the 2000 field season and at the beginning of 2001, changing the profile of the ditches to a concave feature which possessed stagnant pools of water without an overlying oxic layer of peat. This change in ditch morphology likely resulted in higher CH_4 fluxes in 2001 during May and beginning of June of the field season compared to 2000.

During 2001 and 2002, CH_4 fluxes increased significantly around mid-June, coinciding with the start of significant vegetation growth. An increase in vegetation growth within the ditches enhanced the supply of labile carbon for methanogenesis (Figure 4.9), increasing CH_4 production, thereby increasing porewater CH_4 concentrations and CH_4 fluxes. Measurements of CH_4 fluxes from the ditches did not include plants (due to size constraints with the static chambers used) therefore estimates for flux from the ditches could be underestimated as transport by vascular vegetation, such as *Typha*, was not determined. To further support the influence of vegetation on CH_4 fluxes from ditches, 2002 fluxes were highest from the zone 4 ditch (data not shown) and occurred when a mat of algae was present at this site. Algae was not observed in the other ditches. Minkkinen et al. (1997) and Sundh et al. (2000) also found that high emissions were correlated with the presence of green algae and attributed the large fluxes to the supply of labile carbon provided by the growth of the algae.

Bubble fluxes from the ditches were within the range reported by Minkkinen et al. (1997) of 3.0 to 37.0 mg CH_4 m^{-2} d^{-1} for drained peatland ditches. Ebullition accounted for 10.6% of CH_4 fluxes while other studies found ebullition to account for <10% of CH_4 fluxes (Minkkinen et al. 1997). Total mean daily flux from ditches (diffusive + bubbles) was ~500 mg CH_4 m^{-2} d^{-2} (with bubbles accounting for 2.1% of the total flux), ~1.7 times larger than that reported for a boreal beaver pond ~300 mg CH_4 m^{-2} d^{-1} (Dove et al. 1999).

4.4.5 Ponds

Fluxes from the ponds in 2000 and 2001 were similar to values found for other pool and wetland ponds of 5.6 to 74.0 mg CH_4 m^{-2} d^{-1} (Bartlett et al. 1988, Harriss et al. 1988, Moore et al. 1990, Waddington & Roulet 1996, MacDonald et al. 1998, Frenzel & Karofeld 2000) with the exception of Dove et al. (1999) which found a higher mean flux, 139.2 mg CH_4 m^{-2} d^{-1}, at a beaver pond. In 2002, pond fluxes were much higher and closer to the values found for vegetated sites of a beaver pond (187.45 mg CH_4 m^{-2} d^{-1}) by Dove et al. (1999) compared to open water sites.

Low CH_4 fluxes in the first two study seasons may have been a result of the limited carbon supply for methanogens as degradation of peat at the bottom of the pond was the main carbon supply process. Foster et al. (1983) found that CH_4 formed at the peat-water interface of a pond was from very old peat and was dated at 2700 years B.P. As the peat in BDB ponds are ~2 m below the original bog surface, it is expected that the peat would be very recalcitrant in nature and therefore the rate of CH_4 production would be limited by the rate of peat degradation. Therefore, low CH_4 production in the ponds in 1999 and 2000 would result in low dissolved CH_4 concentrations and thus low CH_4 fluxes and minimal to no ebullition.

Water column profiles of dissolved oxygen (O_2) (Figure 4.11) indicate that the ponds had no gradient and low concentrations of O_2 at the beginning of the season but quickly became stratified and depleted in O_2 at depth by the end of May. These low O_2 levels were probably caused by consumption of O_2 by decomposers and the slow rate of O_2 diffusion through water (Dove et al. 1999). Low O_2 levels can limit CH_4 oxidation within the water column thereby resulting in larger fluxes from these sites. Consequently, the lower O_2 concentrations in the zone 2 pool may be responsible for the larger fluxes from this pond compared to that of the zone 4 pool (data not shown), while the low fluxes from the ponds at the beginning of the season (Figure 4.3) may be a result low temperatures limiting CH_4 production as O_2 conditions were also low within the water column.

An increase in the presence of *Sphagnum* within the ponds in 2002 could be responsible for the higher fluxes during this study season. Increased plant growth within the pond would result in a supply of labile carbon for methanogenesis. This is supported by the large proportion (48 to 83%) of highly labile dissolved organic carbon within the ponds during 2001 (Tóth 2002), increasing CH_4 production and dissolved CH_4 concentrations. Furthermore, the mean CH_4 flux measured at the peat-water interface in 2001 was 2.2 mg CH_4 m^{-2} d^{-1} while at the water-air interface it was 14.4 mg CH_4 m^{-2} d^{-1},

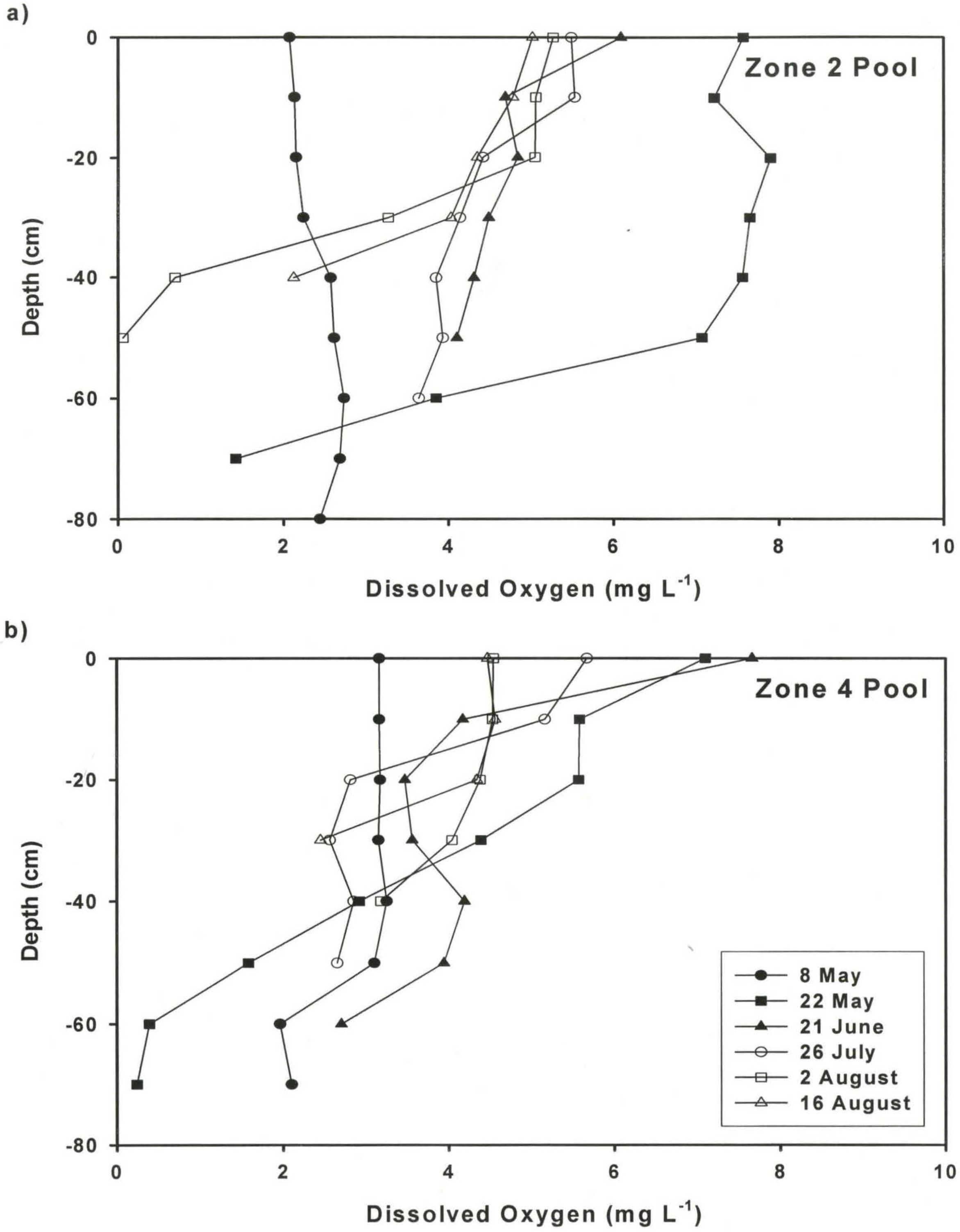


Figure 4.11 Dissolved oxygen (mg L^{-1}) depth profiles from the water surface for a) zone 2 pool and b) zone 4 pool throughout the 2001 field season.

suggesting that CH_4 is being produced from sources (labile DOC) other than pond bottom peat.

Profiles of dissolved CH_4 indicate that dissolved CH_4 concentrations changed significantly through the 2002 season and generally peaked at depths closest to the peat-water interface. Profiles for both ponds had low concentrations on July 9 (0.4 to 6.3 and 0.4 to 2.8 mg L^{-1} for zone 2 and zone 4 pools respectively), which increased significantly on August 20 (1.9 to 40.2 and 163.1 to 301.9 mg L^{-1} respectively) and then decreased again to their lowest levels on August 29 (0.00 to 0.02 and 0.1 to 0.3 mg L^{-1} respectively). CH_4 fluxes from the ponds were high prior to July 9, possibly depleting dissolved CH_4 concentrations, resulting in the low to moderate fluxes from the ponds on this day. CH_4 emissions remained low, allowing dissolved CH_4 to increase, resulting in a large episodic event on August 20 coinciding with the lowest water levels observed the ponds. Continued large flux events further depleted dissolved CH_4 concentrations, resulting in the lowest dissolved CH_4 concentrations observed on August 29 and the low CH_4 fluxes observed just prior to this date.

Bubble fluxes from the ponds fall within the range of values reported in other studies 0.3 to 226.4 mg CH_4 m^{-2} d^{-1} (Dove et al. 1999, Frenzel & Karofeld 2000). Ebullition equalled 1.4% of CH_4 fluxes while other studies found ebullition to account for 20 to 65% of CH_4 fluxes (Chanton et al. 1989, Weyhenmeyer 1992, Dove et al. 1999). Large ebullition events rarely occurred on days with large CH_4 fluxes. The majority of CH_4 fluxes measured the same time as large ebullition events were omitted due to their poor R^2 values and may be a result of the episodic event altering the general linear relationship of CH_4 diffusion. Total mean daily flux from ponds (diffusive + bubbles) was ~304 mg CH_4 m^{-2} d^{-2} (with bubbles accounting for 1.0% of the total flux), similar to results found by Dove et al. (1999) which reported 320 mg CH_4 m^{-2} d^{-1} for open water sites.

4.4.6 Seasonal CH_4 Exchange

The cutover site experienced an increase in CH_4 flux from the site, with the exception of 2002, and experienced a net consumption of CH_4 in 1999 (Figure 4.5c). Restored site seasonal CH_4 fluxes were significantly larger (4 to 150 times greater) than the cutover site, with the exception of 2000, and increased exponentially from 1999 to 2002. Changes in the ecohydrological conditions at the restored site provide partial explanations for this trend. Water table levels were lowest in 1999 followed by 2002, leading to greater CH_4 oxidation and a lower mass of CH_4 lost in 1999 but not in 2002. Conversely, the water table position was highest in 2000 and 2001, suggesting that more CH_4 would be produced and less oxidized, thereby increasing the mass of CH_4 lost. Furthermore, from 1999 to 2002, peat coverage decreased while moss and vascular areal coverages increased. Other studies (e.g. Waddington et al. 1996) suggest that vascular plants can enhance CH_4 flux to the atmosphere through 1) supply of labile C and 2) transport of CH_4 to the atmosphere, bypassing the aerobic zone in the peat. Consequently, vascular plants likely enhanced the mass of CH_4 lost in 2001 and 2002, despite the dry conditions in 2002.

Mean seasonal CH_4 flux increased with time post-restoration from the ponds and ditches; however the flux remained fairly constant from vascular, moss and peat. The increase in flux from ponds and ditches is mainly a function of changes in the saturated/anoxic conditions and the supply of labile carbon. During the restoration process, dead vegetation was pushed into the ditches providing a "hot spot" for CH_4 production. In addition, the emergence of new vegetation within and around the ponds increased dissolved CH_4 concentrations in the ponds (2.8 mg L^{-1} early July to 301.9 mg L^{-1} late August) as well as the quantity and quality of DOC (Tóth 2002). Although the ditches (2.6 to 49.1 mg CH_4 m^{-2} d^{-1}) and ponds (0.2 to 45.2 mg CH_4 m^{-2} d^{-1}) are significant sources of CH_4, when weighting fluxes to their areal coverage, vascular plants exerted the strongest influence (23.4 to 93.5%) on CH_4 flux from the site, followed by ditches (-0.2 to 70.6%), ponds (2.2 to 7.6%), mosses (-1.2 to 5.8%), and peat (-0.3 to 1.9%).

4.5 Implications

The process of restoration has changed the Bois-des-Bel peatland from a small CH_4 sink and/or source, depending on climatic conditions, to a large source of CH_4. The change in the overall CH_4 function of the peatland was directly related to the increase in CH_4 emissions from vascular vegetation, remnant ditches and newly constructed ponds. Restoration significantly altered the carbon processes at the peatland, changing the dominant CH_4 controls under harvested conditions from temperature and hydrology, to more ecohydrological (i.e. vegetation and hydrology). When comparing CH_4 emissions from this site (~4 g CH_4 m^{-2} a^{-1}) to natural peatland systems (~10 g CH_4 m^{-2} a^{-1}), it is evident that the site is still a much smaller source of CH_4 and only represents ~1% of the total carbon emissions. However, in terms of global warming potential, CH_4 represents

14% of the total CO_2-equivalent losses from the site. It is evident that carbon and CH_4 process are still changing as the pool of labile carbon increases (develops). Vegetation succession is still occurring and more time and monitoring is needed in order to determine if this site will return to similar CH_4 functions as natural peatlands.

The goal for the restoration of peatlands differs and is dependent on the needs of the industry/organization. If a site is being restored with the establishment and increase in cover of *Sphagnum* mosses as the goal, then monitoring of carbon dynamics (DOC, CO_2 and CH_4) are unnecessary, however, if the purpose of restoration is to return the natural carbon sink function, then the carbon processes and dynamics altered by the restoration process need to be understood for appropriate peatland restoration management and assessment.

The main goals for restoration of Bois-des-Bel were both the establishment and growth of *Sphagnum* mosses and the return of the natural carbon sink function. This study has determined that in order to reduce carbon emissions from the site in the form of CH_4, removal of vegetation from and/or completely filling in of the ditches would reduce and possibly eliminate the "hot spot" potential for CH_4 production at these locations. Ponds were created in order to retain meltwater and maintain water levels. The need for creating ponds as part of the restoration process has to be carefully considered as they were the third largest source of CH_4. In order to reduce the potential of CH_4 emissions from ponds, it is suggested that they are kept small in areal extent (as in the BDB peatland) so that their contribution to the total CH_4 emission is minimal. They should also be shallow in depth to maintain high dissolved oxygen concentrations in the water column which oxidizes CH_4 before it is emitted to the atmosphere. As a result of their areal extent, vascular vegetation was the largest source of CH_4 from the peatland. However, measures taken to control the growth of vascular vegetaiton may be detrimental to the establishment for *Sphagnum*. Studies have shown that vascular vegetation such as *Eriophorum*, can alter microclimatological conditions to those favourable for Sphagnum growth (Tuittila et al. 2000b, Rochefort et al. 2003). Furthermore, with time, *Sphagnum* establishment causes changes in the geochemical conditions within the peat (Rochefort et al. 2003), making it intolerable for vascular vegetation, resulting in a successional change to a *Sphagnum* moss dominated ecosystem. Thus, the long-term best course of action is likely no action.

As CH_4 fluxes from mosses were not significantly different between the restored and cutover sites two and three years post-restoration, but were smaller than values observed at natural peatlands, perhaps moss plots on restored sites can be used as indicators of when peatland processes and conditions are similar to natural systems. For example, continued monitoring of mosses until a significant difference in CH_4 fluxes between the restored and cutover sites and insignificant differences between restored and natural site moss CH4 fluxes occur, could be used to estimate the sites' progress back to a natural CH_4 source. This in turn would reduce the costs and time incurred by monitoring, providing a valuable management tool. However, it is likely that a return to natural CH_4 dynamics at this site will not occur until water table fluctuations are constrained to the upper levels of the peatland (i.e. in the acrotelm). For this to occur the peatland requires a sufficiently thick acrotelm (moss thickness). Once this occurs it is likely that subsurface CH_4 dynamics that regulate water loss and surface levels (e.g. Price 2003) will help regulate restored peatland hydrology.

CHAPTER 5

SUMMARY

5.1 Conclusions

Ratification of the Kyoto Protocol and increasing public interest in peatland conservation has created a demand for peatland restoration to reduce CO_2 emissions. Peatlands are important in terms of their long-term sequestration of atmospheric carbon (Gorham 1995), and human induced changes such as harvesting and drainage for horticultural purposes can significantly alter a peatland's role from a net accumulation of atmospheric carbon to a net source of carbon. The expanding knowledge on peatland restoration practices has encouraged the peat horticultural industry, in particular, to restore long abandoned sites which are significant sources of CO_2. The impact of peatland restoration at a large scale on CH_4 fluxes and processes is not well understood. Consequently, the main focus of this research was to determine the effect of peatland restoration on ecosystem scale CH_4 emissions from a cutover peatland.

Results from a potential CH_4 production experiment (in Chapter 3) found that harvesting and drainage reduced potential CH_4 production and total depth integrated CH_4 production and that these factors continued to decrease with time post harvest. This was likely the result of respiration depleting the pool of labile carbon and oxic conditions reducing the methanogenic biomass. Conversely, restoration increased potential and total depth integrated CH_4 production by increasing anoxic conditions, and likely the methanogenic biomass, and producing a source of labile carbon from the growth of bryophyte and vascular vegetation. Water table position probability exceedence graphs showed that the water table position was higher for a longer period of time at the restored site compared to the 20-yr cutover site. The critical water table depth at which net CH_4 production below exceeded net CH_4 oxidation above was the same at both the restored and 20-yr cutover sites. However, the restored site exceeded this depth about two times more often than the 20-yr cutover site, indicating that CH_4 fluxes would likely be higher from the restored peatlands.

Field measurements (Chapter 4) found that CH_4 fluxes from bare peat and mosses were not significantly different three years post-restoration compared to pre-restored and cutover conditions. Conversely, fluxes from vascular vegetation, ditches and ponds increased significantly with each successive year post-restoration. Porewater concentrations beneath vascular vegetation plots and ditches were higher compared to bare peat while the ponds had predominantly highly labile carbon generally produced by fresh vegetation. Therefore, higher fluxes from these sites were directly attributed to an increase in methanogenesis provided by labile carbon from vegetation. As a result of the high fluxes from the vascular vegetation, ditches and ponds, the total seasonal CH_4 exchange from the restored site increased with each successive year while the cutover site fluctuated between a small net sink and a small net source of CH_4 as a direct result of the variability in annual climatic conditions. CH_4 fluxes in 1999 and 2000 were correlated to soil temperature while water table position, pond water levels, unsaturated soil moisture and GEP had stronger relationships with CH_4 flux in 2001 and 2002, switching CH_4 emissions from temperature to more ecohydrologically dependent.

CH_4 fluxes from ditches and ponds suggest that these features are the largest sources of CH_4 from the peatland. However, when weighting the fluxes to the areal extent of each feature, ditches become secondary to vascular vegetation in total CH_4 emissions while the ponds had a minimal impact on the amount of CH_4 emitted from the peatland. Furthermore, ebullition from ditches and ponds were insignificant in comparison to the diffusive fluxes.

As mentioned above, vegetation was found to have significant impacts on the subsurface storage of CH_4. Both moss and vascular vegetation had higher porewater concentrations than bare peat, indicating that vegetation was increasing labile carbon supply and thereby the rate of CH_4 production. However, vascular vegetation also had a negative effect on dissolved CH_4 concentrations. Time series profiles of dissolved CH_4 showed a distinct decreasing trend in concentration after mid July. Higher rates of CH_4 transport by vascular vegetation than CH_4 production likely caused the low concentrations near the end of the season. The absence of CH_4 ebullition was directly linked to vascular vegetation as the low concentrations of dissolved CH_4 prevented the formation of CH_4 bubbles.

Applying the data from this study to a conceptual model of changes in hydroclimate and carbon cycling conditions pre- and post-peatland restoration (see Waddington & Price for details) (Figure 5.1) indicates that the effect of restoration on CH_4 emissions was previously underestimated. Indeed, CH_4 emissions increased quicker post restoration than Waddington & Price (2000) hypothesized, however fluxes are not

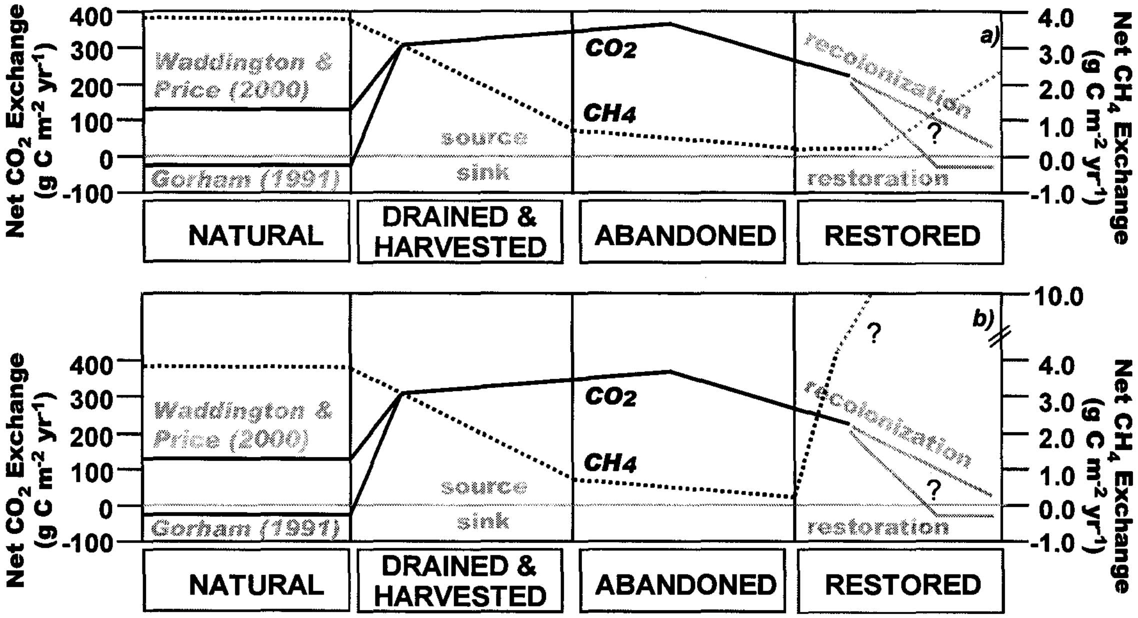


Figure 5.1 Conceptual model (adapted from Waddington & Price 2000) illustrating the effects of peatland drainage, harvesting, abandonment and restoration on net CO_2 and CH_4 exchange a) before this study and b) including this study.

yet as large as those from natural peatlands. Assuming total seasonal CH_4 exchange continues on the current increasing exponential trend observed, we can expect CH_4 emissions from the Bois-des-Bel peatland to equal natural peatlands approximately five years post-restoration.

It remains to be seen whether the restoration of CH_4 dynamics within restored peatlands will begin to alter peatland hydrology (e.g. compressibility, buoyancy, and hydraulic conductivity). It is hypothesized that as the acrotelm continues to develop and quality of carbon continues to increase, hydrology and CH_4 dynamics will become more coupled at Bois-des-Bel, as is common in natural systems. This coupling may help regulate water retention and enhance plant productivity.

CHAPTER 6

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